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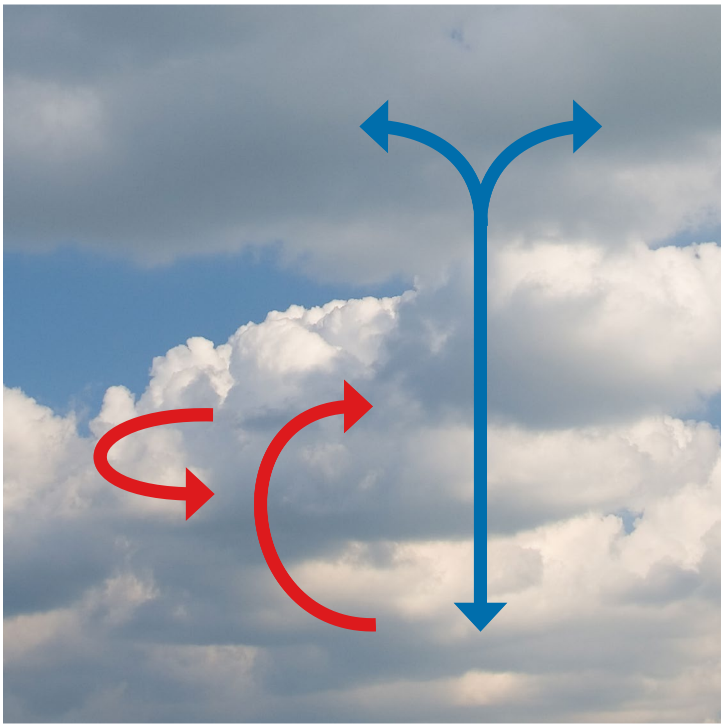
METEOROLOGY

Enhancing tropical cyclone wind forecasts



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Enhancing tropical cyclone wind forecasts

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This article highlights two developments that have enhanced the usefulness of tropical cyclone wind forecasts in ECMWF's newly upgraded Integrated Forecasting System (IFS Cycle 47r1). The first is a change in the model specification for momentum exchange at the sea surface. This development is the result of internal ECMWF work informed by discussions with scientists at Météo-France and the US National Centers for Environmental Prediction (NCEP). It goes some way towards resolving the longstanding issue that predicted tropical cyclone maximum surface wind speeds are generally too low, in particular for intense tropical cyclones. The second development is the production of new forecast parameters which specify the maximum distance from the centre of the cyclone to locations where the surface wind speed reaches 34, 50 and 64 knots (wind radii). This will help users to assess the risk of wind-related hazards.

The maximum wind speed problem

Both minimum central pressure and maximum 10 m wind speeds are used as measures of tropical cyclone (TC) intensity. There have been several improvements recently in predicting minimum central pressure and overall cyclone tracks (Haiden et al., 2019). However, prior to IFS Cycle 47r1, ECMWF forecasts generally severely underestimated maximum wind speed for intense tropical cyclones even given the correct central pressure (Figure 1a). While there are many different factors that could account for this behaviour, we have found it to be closely linked to the parametrization of momentum exchange at the ocean surface.

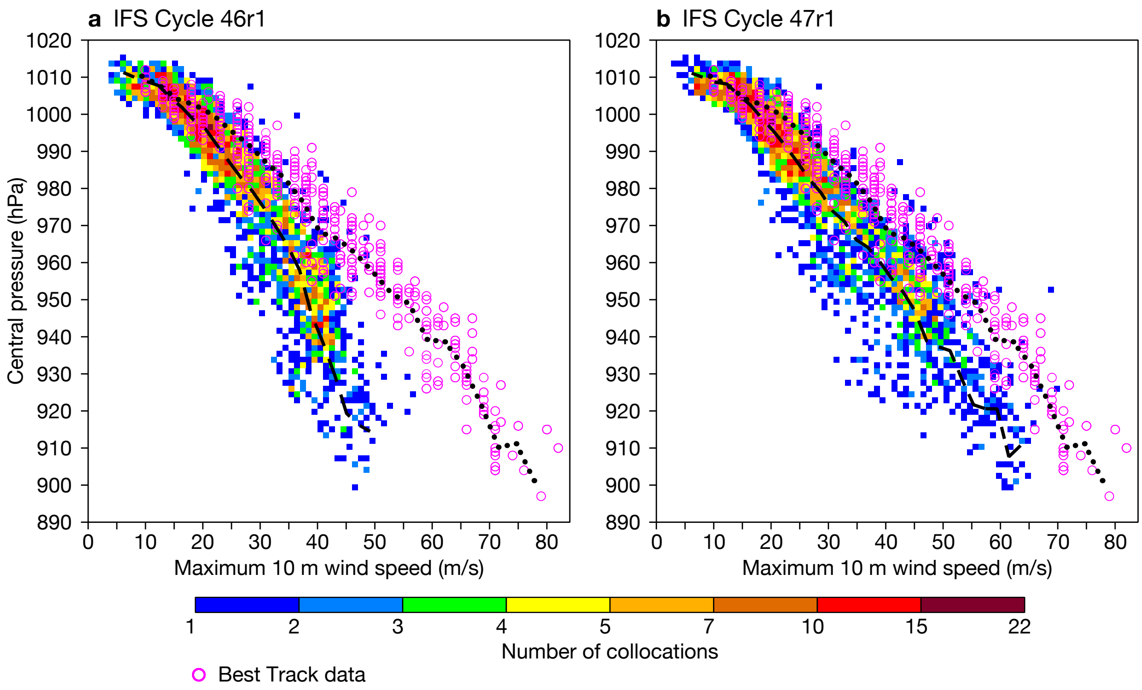

Figure 1 Scatter plots for maximum 10 m wind speed and corresponding minimum mean sea level pressure for all 10-day forecasts at TCo1279 resolution (corresponding to a grid spacing of about 9 km) from 00 UTC for the period 25 August 2019 to 1 January 2020 (coloured squares; the dashed line indicates mean central pressure for a given wind speed), and corresponding reported values (6-hourly Best Track data; purple circles; the dotted line indicates mean central pressure for a given wind speed), for 20 tropical cyclones, showing results for (a) IFS Cycle 46r1 and (b) IFS Cycle 47r1 with the new parametrization of unresolved roughness.

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This momentum exchange is generally expressed in terms of the drag coefficient (Cd), which connects the magnitude of the surface stress to the square of the wind speed at a certain height above the surface. In the IFS, there is an active two-way coupling between the atmosphere and ocean waves, which results in an extra dependency of Cd on the sea state (waves). Figure 2a shows the distribution of Cd values in IFS Cycle 46r1 plotted against wind speed for Hurricane Irma in September 2017. There is a large spread of possible Cd values for most wind speeds, in part due to the sea-state effect, with a tendency for the drag coefficient to take larger values for stronger winds.

Over the last decade, it has been suggested that the drag coefficient should tail off for strong winds. Recent wave model developments have tried to address this issue. Since IFS Cycle 43r1 (November 2016), maximum wave spectral steepness criteria have been imposed on the evolution of the wave spectra, resulting in reduced Cd values for high winds (Magnusson et al., 2019). Moreover, with the introduction in IFS Cycle 46r1 of a new parametrization of wind input and whitecap dissipation (June 2019), a further reduction of large Cd values, with a slight decrease for high winds, was achieved. However, a mismatch between predicted and observed maximum winds persisted, and a recent paper by Donelan (2018) indicated that the drag coefficient should decrease quite significantly for hurricane-force winds.

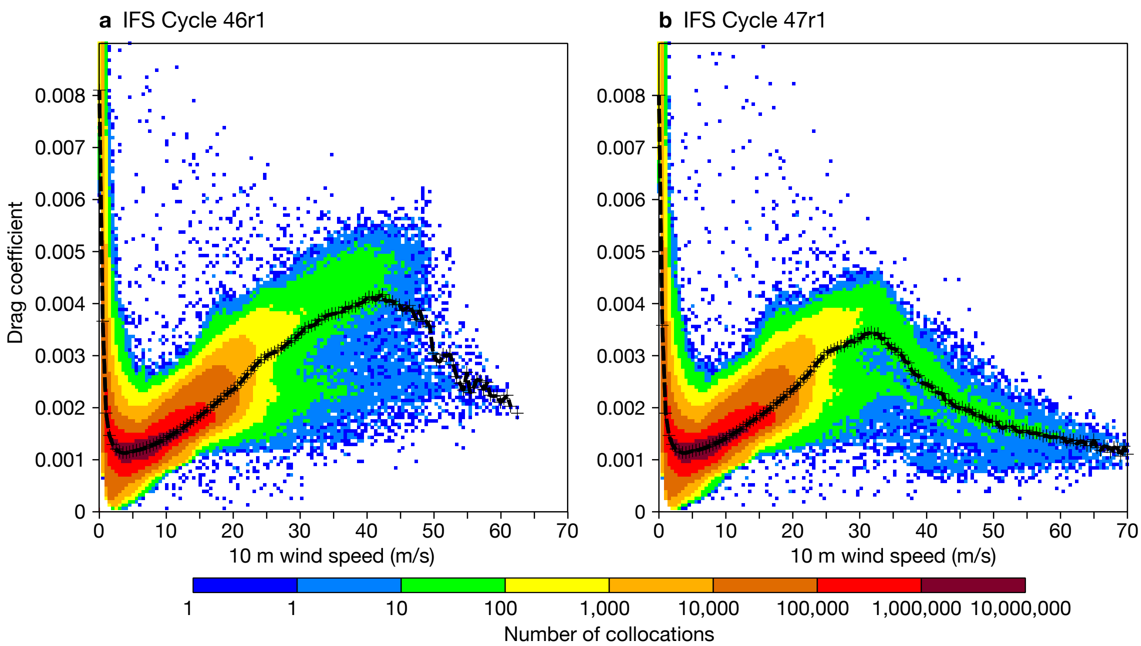

Figure 2 Scatter plots for the drag coefficient and corresponding 10 m wind speed for TCo1999 10-day forecasts initialised from the operational analysis of 00 UTC on 4 September 2017 (during Hurricane Irma), showing results for (a) IFS Cycle 46r1 and (b) IFS Cycle 47r1 with the new parametrization of unresolved roughness. All model grid points over the oceans were used every 6 hours. The black crosses show mean Cd values for given wind speeds.

Improving maximum winds

In the IFS, the momentum exchange with the sea surface is modelled via a dependency of the roughness length (z_0) on the surface stress. This expression accounts for both low and high wind regimes. At low wind speed, the sea surface becomes aerodynamically smooth and z_0 is determined by viscosity. At high wind speed, Charnock's relation is used, in which z_0 is expressed as a function of surface stress, air density, gravitational acceleration and a sea-state-dependent Charnock parameter. In ECMWF's wave model, the Charnock parameter depends on the state of development of the resolved waves and a tuneable parameter (α_b) which represents the impact of unresolved short waves (background roughness beyond the highest frequency resolved by the model) on the overall surface stress. Until IFS Cycle 47r1, this parameter had a constant value.

Observational evidence that the drag coefficient should be much lower for high winds suggests that the coupling between the ocean surface and the wind above becomes less efficient at transferring momentum for strong winds. For this to happen, it was realised that the Charnock parameter should be considerably smaller in the case of strong winds (above 35 m/s). This was achieved by reducing α_b for high 10 m wind speeds.

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This simple reduction was implemented in IFS Cycle 47r1. As expected, the drag coefficient is sharply reduced for winds above 35 m/s. Figure 2 illustrates how this affects the frequency of high winds in tropical cyclone forecasts. In particular, it can be seen that there are many more instances of very high winds, up to about 70 m/s, than without the reduction in α_b.

The results shown in Figure 2 were obtained for forecasts at the experimental resolution of TCo1999 (corresponding to a horizontal grid spacing of about 5 km) in order to test the limit of this new parametrization. For the current operational resolution (TCo1279, about 9 km), we have looked at a range of tropical cyclone forecasts and found that, generally, the new parametrization yields a much better maximum wind speed – minimum pressure relation (Figure 1b). However, compared to observational estimates, forecasts continue to underestimate some of the most intense cases.

Computation of wind radii

To assess wind-related hazards associated with tropical cyclones, it is useful to see the areas where winds are predicted to exceed certain thresholds. In IFS Cycle 47r1, this has been made possible by introducing a new wind radii parameter. The parameter indicates the maximum distance from a TC centre within which the surface wind speed is predicted to exceed certain thresholds. The thresholds have been set at 34, 50 and 64 knots, in line with the values used by global tropical cyclone warning centres. To compute the wind radii, a specific module taken from the Vortex Tracker package (Biswas et. al., 2018) developed at the Geophysics Fluid Dynamics Laboratory (GFDL) is used. It was chosen for two main reasons: first, the GFDL Tracker has been extensively tested by research and operational communities; second, the GFDL and ECMWF trackers use the same programming language, which facilitated porting the module into the ECMWF operational system.

The wind radii computation is performed after the ECMWF TC tracker has completed the identification of cyclonic features for both high-resolution forecasts (HRES) and ensemble forecasts (ENS). It is carried out for all TCs that are present from analysis time and also those that develop during the forecast. To start, the algorithm establishes four sectors (NE, SE, SW and NW quadrants) centred on each TC's predicted positions. Within these sectors, the only model grid points considered are those whose distance from the TC centre is shorter than a predetermined radius, this radius being the distance beyond which winds are ordinarily below 34 knots. In each sector the distances of those grid points from the TC centre are then ranked, and 10 m wind speeds are checked at each grid point against the 34-, 50- and 64-knot thresholds. The wind radii then represent, for each sector, the maximum extent from the storm centre at which those wind thresholds are exceeded.

If the distance of a point where the wind speed is at least 34 knots is very close to the initial predetermined radius, then an iterative process follows: the predetermined radius is increased slightly and the scheme starts again until a more accurate 34-knot wind radius is reached. This iterative process is important to deal with situations where the storm is large and 34-knot winds are spread out far from the TC centre.

Finally, the upgrade to IFS Cycle 47r1 was an opportune time to remove the ad hoc factor converting 10-minute wind speeds to pseudo 1-minute wind speeds in the output files of the TC tracker (i.e. wind speed in m/s was multiplied by 2.1 to convert into knots until IFS Cycle 46r1, instead of using the standard conversion factor of 1.9). Historically, when models had very coarse horizontal resolutions and consequently TCs were too weak in forecasts, this conversion factor provided more realistic values. However, substantial progress made in recent years (including several model resolution upgrades) has improved the accuracy of TC forecasts, and tests confirmed that it could be removed without reducing forecast quality. Users should not expect an overall reduction in 10 m winds due to the removal of the ad hoc factor. On the contrary, 10 m wind speeds should be higher, at least for hurricane-force winds. Direct model output 10 m wind forecasts are not affected by removing the ad hoc factor.

Forecasting the size of Hurricane Dorian

Figure 3 shows an example of an HRES wind radii forecast starting from 12 UTC on 30 August 2019. Storm Dorian, which formed in the Atlantic basin on 24 August 2019, was elevated to hurricane category on 28 August while passing east of the island of Puerto Rico. Two days later, Dorian became a major hurricane before moving towards the Bahamas. The HRES 34-knot wind radii forecast is represented by circle sectors for each quadrant in 12-hour time steps. It means that 34-knot winds are predicted anywhere within those sectors. Similar charts are available for 50- and 64-knot wind radii if such wind speeds are present in the forecast.

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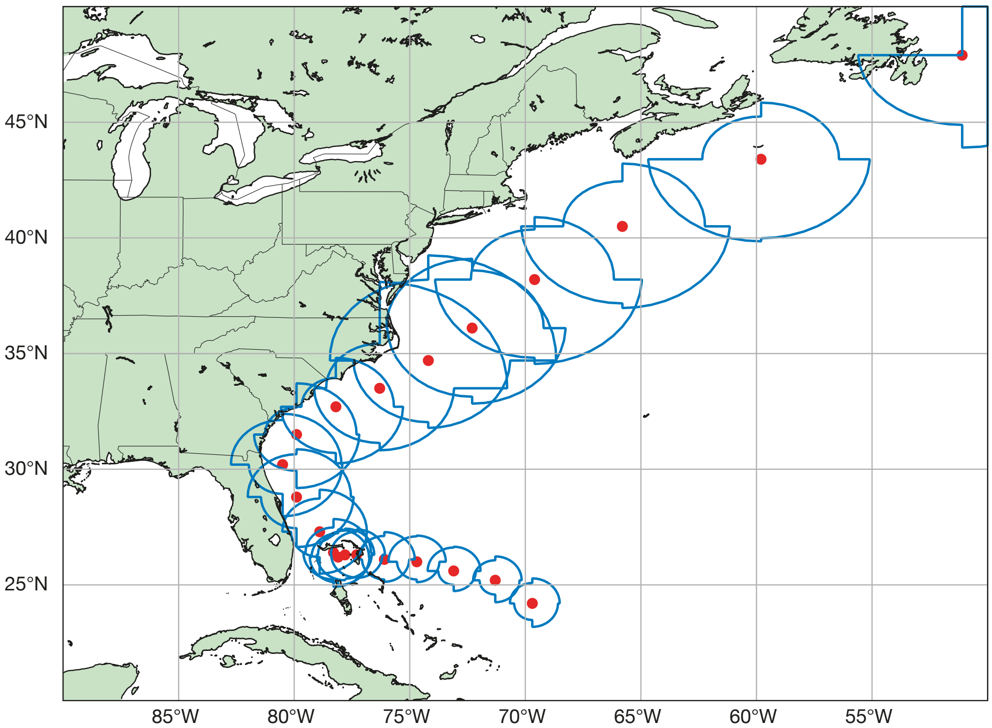

Figure 3 HRES wind radii forecast (IFS Cycle 47r1) for the 34-knot wind threshold up to 240 hours ahead, initialised at 12 UTC on 30 August 2019. The red dots indicate the predicted centre of Hurricane Dorian at 12-hour intervals.

Time series of the wind radii forecasts from the HRES can be compared with observation-based information (a combination of satellite passive microwave data, surface observations, and reconnaissance aircraft when available). Figure 4 shows the evolution of mean wind radii over all four quadrants based on a method using infrared satellite imagery (Knaff et al., 2016) and the HRES mean wind radii forecast for Hurricane Dorian from the same start date as before. Overall the model tends to underestimate the size of the wind structure around Hurricane Dorian for all wind thresholds. This suggests a problem in handling a medium-size system experiencing rapid intensification. As predicted by the forecast (Figure 3), Hurricane Dorian never made landfall in the Florida peninsula. We recommend using the wind radii from the ENS in order to quantify the risk of wind-related impacts, in particular in the medium range. Users are also advised to always combine TC track forecasts with the wind radii forecasts.

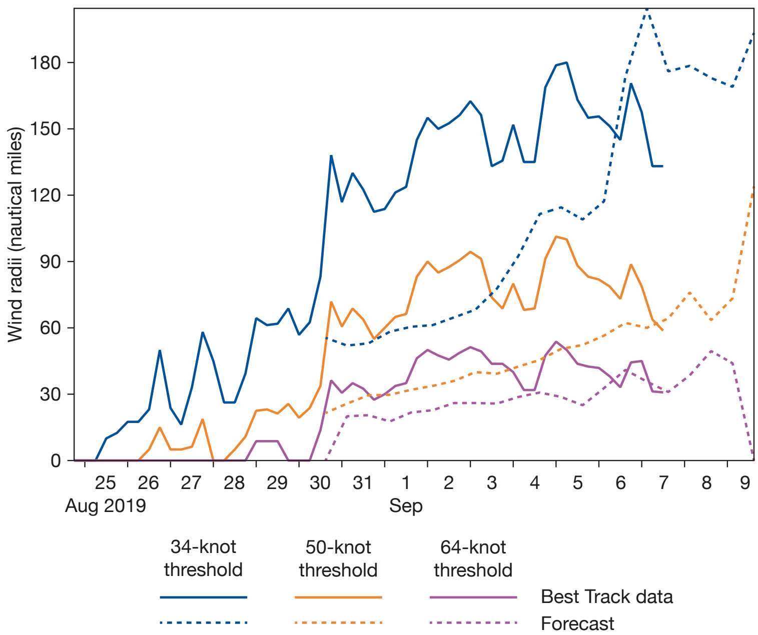

Figure 4 Mean HRES wind radii forecasts (dotted lines) for the 34-, 50- and 64-knot wind thresholds produced using IFS Cycle 47r1 and initialised at 12 UTC on 30 August 2019, and Best Track data (solid lines) for Hurricane Dorian.

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Verifying wind radii forecasts is difficult due to the lack of surface wind observations, which are critical for obtaining an accurate wind structure of the storms (Cangialosi & Landsea, 2016). This is why TC forecasting centres are still reluctant to publicly release on a regular basis verification metrics of TC size forecast performance. Despite these limitations, we have performed systematic verification for the northern hemisphere using the International Best Track Archive for Climate Stewardship (IBTrACS) dataset. Figure 5 shows the systematic errors of wind radii for the 34-, 50- and 64-knot wind speed thresholds of the HRES based on experiments carried out using IFS Cycle 47r1. Verification of ENS wind radii will be carried out once a sufficiently large sample is available. The HRES results suggest a tendency to underestimate the wind structure of TCs for all forecast lead times (consistent with the example of Hurricane Dorian shown in Figure 4). The systematic biases (mean errors) vary little with lead time except for the radius bias for the 34-knot wind speed threshold. Absolute wind radii errors are similar for 34- and 50-knot winds and nearly twice as big as the errors for the 64-knot wind speed threshold.

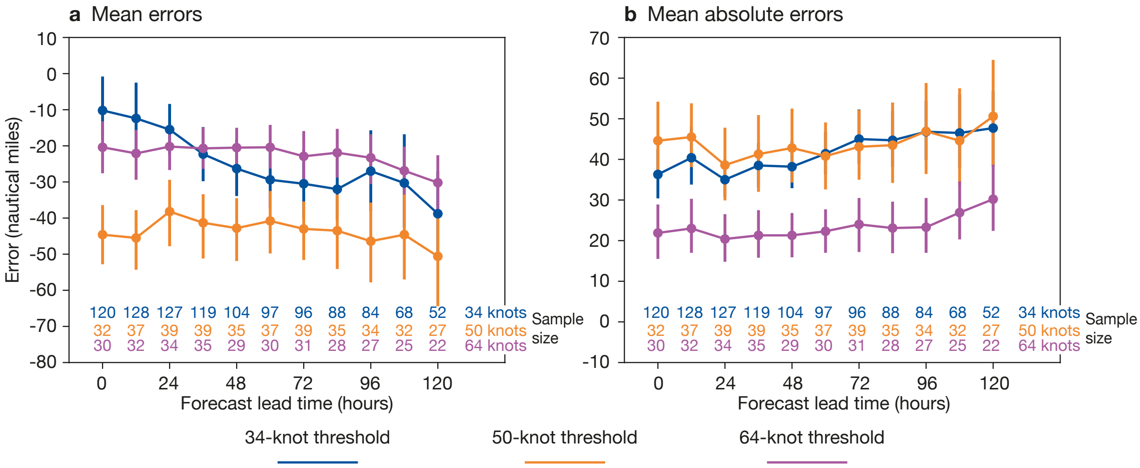

Figure 5 The charts show (a) the mean error of mean wind radii forecasts for 34-, 50- and 64-knot thresholds compared to Best Track data as a function of lead time up to 120 hours ahead and (b) the same but for mean absolute errors. Sample size is indicated at the bottom of the plot. The results were obtained for the TC basins in the North Atlantic and the Eastern Pacific (extended to the Western Pacific only for the 34-knot wind speed threshold) between July and November 2019. The vertical bars show 95% confidence intervals.

Product availability

To disseminate the wind radii product, changes had to be made in the publicly available tropical cyclone track BUFR files to accommodate this supplementary data. Three additional data descriptors were included in the BUFR messages: ‘wind speed threshold’, ‘bearing/azimuth’ and ‘maximum radius for a given wind threshold’. To decode the TC product files, users will need a specific version of ecCodes or they can download the BUFR table version 33 of the BUFRDC. More information can be found on this web page: *https://confluence.ecmwf.int/display/FCST/New+Tropical+Cyclone+Wind+Radii+product*.

Outlook

Progress has been made in improving the relationship between predicted maximum wind speed and predicted minimum mean sea level pressure for intense TCs. This has been achieved by introducing a change to the parametrization for the momentum transfer in IFS Cycle 47r1. The current approach relies on reducing the Charnock parameter when the 10 m wind is above a threshold value. Ongoing research aims to revise the parametrization based on an improved representation of the impact of ocean waves on high winds.

In addition, a new metric providing information on the surface wind speed structure and thus the size of a TC for the HRES and ENS is now available to users. It opens the way to adding other TC structure metrics in the future, in line with the recommendations of the World Meteorological Organization working group on tropical cyclones. Doing so will support forecasting centres and it will also provide additional metrics for model verification.

These two developments are expected to help forecasting centres around the world to provide better warnings of hazards related to high-impact TCs.

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Further reading

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