INTERNATIONAL WORKSHOP on TROPICAL CYCLONES

Topic 3.3: Intensity change: Operational Perspectives

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Abstract:

This review summarizes techniques used by operational centers to forecast tropical cyclone intensity change. Recent advances and major changes over the past four years are presented, with a special focus on forecasting rapid intensity changes. Although intensity change remains one of the most difficult aspects of tropical cyclone forecasting, objective guidance has shown some improvement, and operational forecast centers have been able to leverage these advances to increase forecast skill, albeit incrementally. The greatest improvements are realized when consensus methods are utilized, especially those that blend statistical-dynamical based guidance with dynamical ocean-coupled regional models. These models become even more skillful when initialized with inner core observational data. It is noteworthy that the realization of a recommendation from IWTC-8, to adapt guidance initially developed for the North Atlantic and North-East Pacific to other basins, has led to improved forecast skill of some agencies. Recent worldwide difficult cases are presented so that the research community can further investigate, potentially leading to improved intensity forecasts when similar cases are observed in the future. Continued improvement and availability of intensity guidance along with associated forecaster training are expected to deliver improvements in the forecast in the future.

3.3.1 Introduction

The IWTC-8 session on intensity guidance (Sampson and Knaff, 2014) provided this assessment of intensity forecasting: "*Over the last 15 years, intensity forecasting at the operational centers have shown little improvement (…) the mean errors in the intensity guidance available to forecasters is gradually decreasing at the rate of 1-2 % per year at 24-72h and if this trend continues, the official forecasts could also start to improve along with the guidance*."

This report presents an updated picture of operational intensity forecasting. Rapid intensification (RI) is a particular focus given the potentially catastrophic consequences when RI occurs just prior to landfall. Section 2 provides an update on selected intensity guidance available, or planned to be soon available to the operational agencies. Section 3 provides the recent progress of intensity forecasting by selected operational agencies along with current practices and guidance employed. Section 4 summarizes and provides recommendations for the research and operational communities for the next 4 years.

3.3.2 Recent advances in intensity guidance

The following section is aimed to highlight recent advances in intensity guidance, stratified into five model categories as described below.

3.3.2.1 Statistical models

As stated in the previous report, statistical models are primarily used as skill baselines for both operational and model forecasts. Several operational centers used an equivalent of SHIFOR (Jarvinen and Neumann, 1979) to benchmark their forecast skill.

Since the IWTC-8 in 2014, some TC intensity forecast improvements have been achieved with an analog approach for the North-West Pacific, which has been developed from historical best tracks by selecting a number of closest analogs to the target cyclone track and initial intensity (Tsai and Elsberry, 2014, 2015 and 2018). A recent result from the ONR Tropical Cyclone Intensity (TCI) Directed Research Initiative has been development of a 7-day combined, three-stage Weighted Analog Intensity Pacific (WAIP) intensity prediction and intensity spread guidance product (Tsai and Elsberry 2018). This new combined WAIP has special treatments (including intensity bias correction) for the pre-formation stage, the intensification stage, and the ending storm stage (hence the three-stage). In addition, WAIP also provides a quantitative value of the intensity forecast uncertainty (calibrated to include 68% of the verifying intensities), which was one of the recommendations from IWTC-8.

This 3-stage WAIP will be operationally tested at JTWC during the 2019 season, and the 3-stage WAIA for the North Atlantic is in final development and will be tested at the NHC later in the 2018 season. Another good point with WAIP/WAIA is that it can be produced on a desktop computer in a few minutes given only the official track forecast and the initial intensity, and thus similar techniques could in principle be developed in other TC basins.

Also available at JTWC is a seven-day North-West Pacific track and intensity forecasts that is created using a combination of persistence and climatological trajectories to estimate track and a LGEM (Logistic Growth Equation Model, DeMaria 2009) approach integrated over climatological SST fields along the forecast track. This model, “Trajectory CLIPER” (TCLP) is operationally available at JTWC (Sampson and Knaff, Personal Communication).

3.3.2.2 Statistical-Dynamical models and probabilistic guidance

Statistical-dynamical guidance such as Statistical Hurricane Intensity Prediction Scheme (SHIPS; DeMaria et al. 2005) have proven to be reliable objective intensity guidance and later on the Logistic Growth Equation Model (LGEM; DeMaria 2009) are the most known models.

A recent advance is the installation of Rapid Intensification Prediction Aid (RIPA) at JTWC (Knaff et al., 2018), based on predictors from the environment (from the SHIPS developmental dataset), IR imagery and the best-track / advisory-based data. Two statistical methods are used to create probabilistic forecasts for seven intensity thresholds including 25-, 30-, 35-, and 40-kt changes in 24 h; 45- and 55-kt in 36 h; and 70-kt in 48 h. These forecast probabilities are further used to create an equally weighted probability consensus that is then used to trigger deterministic forecasts equal to the intensification thresholds once the probability in the consensus reaches 40 %. The deterministic forecasts are incorporated into an operational intensity consensus forecast as additional members, resulting in an improved intensity consensus during rapid intensification period (independent verification during the 2016 and 2017 typhoon season). Experimental running of these aids in the Indian Ocean and Southern Hemisphere have been rather successful capturing the attention of forecasters at JTWC and at the Australian Bureau of Meteorology. These aids have proven skillful enough to be incorporated into the JTWC intensity consensus (ICNW). Feedback thus far has concerned overprediction in cases when the TC is relatively weak and the creation of deterministic forecasts when the TC is making or is expected to make landfall.

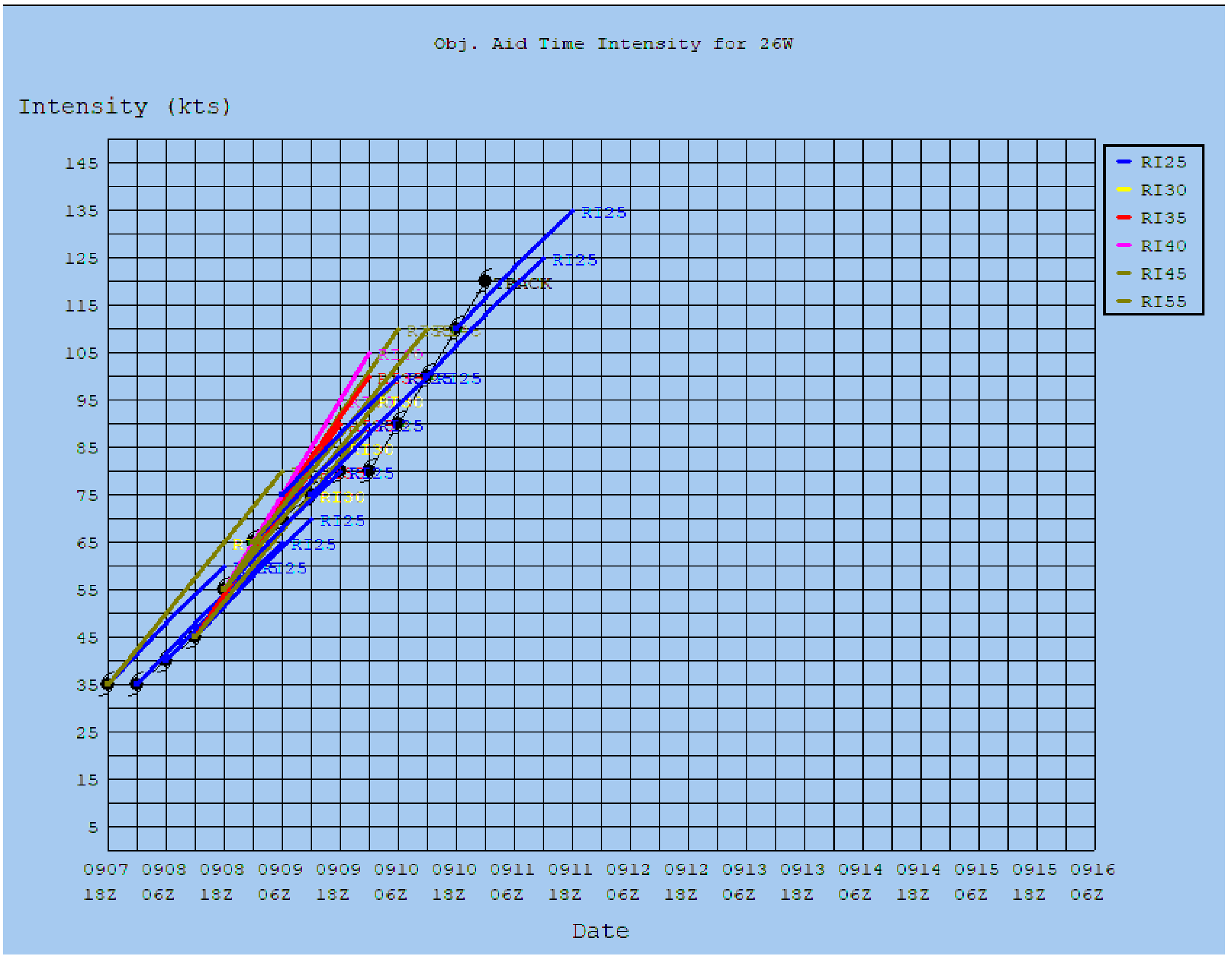
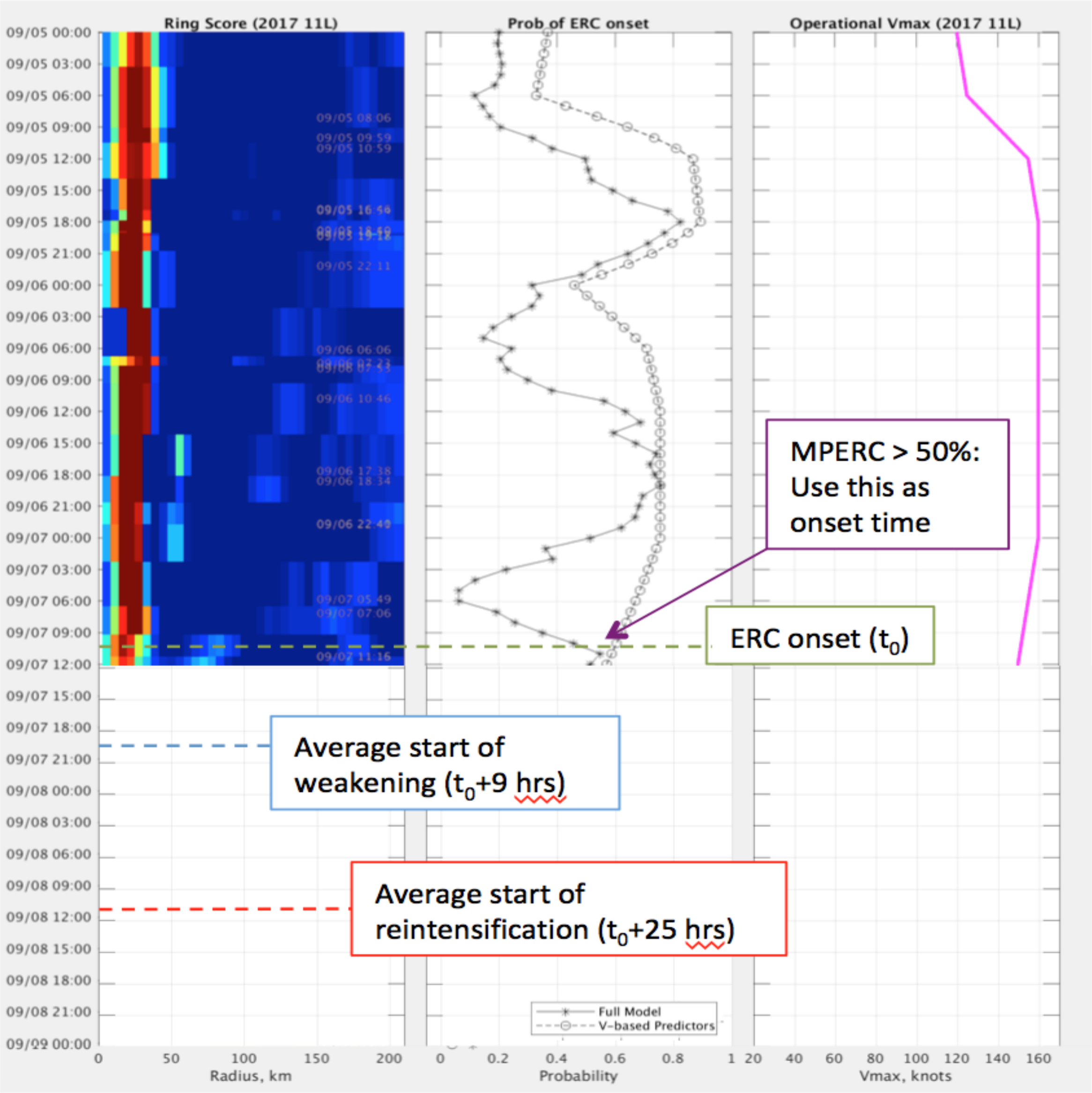


Figure 3.3.2.1. An example of the RI aid at JTWC for typhoon Mangkut (2018).

Recently DTOPS has been developed for NHC to forecast the likelihood of RI (Onderlinde and DeMaria, 2018). This uses IFS, GFS, HWRF, LGEM, and SHIPS. The intensity change forecasted by these models along with several other geographic (e.g., storm latitude) or multi-model parameters were compiled for numerous cases from 2011 – 2017 in the Atlantic and East-Pacific basins. These forecasts were compared to Best Track intensity change, and binomial logistic regression was used to derive coefficients for each model or parameter. These coefficients then were used for the multi-model logistic prediction scheme. The largest improvements (when compared to SHIPS-RII) occurred in the Atlantic basin where substantial Brier Skill Scores improvements were obtained. DTOPS has been run experimentally at the NHC during the 2017 and 2018 hurricane seasons and has been referenced in operational products during this time.

A challenging case for intensity forecasting also comes when an Eyewall Replacement Cycle (ERC) is taking place. This inner core mechanisms are associated with intensity fluctuations that sometimes can be quite significant. Until very recently, the skill to anticipate and quantify those intensity variations was rather limited. CIMSS have developed the M-PERC guidance (Microwave-based Probability of Eyewall Replacement Cycle) based on observational studies with aircraft data done previously (Sitkowski et al., 2011 and 2012; Kossin et al., 2012), M-PERC uses an azimuthal ring score from ARCHER derived with microwave imagery and calculates a probability forecast of the onset of an ERC. The timing and the amplitude of intensity fluctuations through the ERC can be assessed from the observational studies cited previously (Figure 3.3.2.2).

This new probabilistic guidance appears very promising as it is available to all TC forecasters in real-time on the CIMSS web site. Further improvements of this guidance are also likely within the next few years.



MPERC > 50%: Use this as onset time

ERC onset (t_0)

Average start of weakening (t_0+9 hrs)

Average start of reintensification (t_0+25 hrs)

Figure 3.3.2.2. The M-PERC guidance.

Following recommendations from IWTC-7 and IWTC-8, guidance available in the North Atlantic and North-East Pacific have continued to be implemented in other centers. In 2015, a version of STIPS has been developed at the Korea Meteorological Administration (KMA) using ocean-coupled potential predictors (Kim et al. 2018) associated with Land-STIPS to improve TC landfalling intensity prediction. For lead times up to 48h, the KMA version of STIPS shows the smallest MAEs relative to operational dynamical models (JMA-GSM, GFS and HWRF) in 2016 and 2017. Further improvement towards RI prediction is underway with the inclusion of a new predictor that has TC-induced vertical mixing and parametrization of the air-sea exchange process.

From 2015 to mid-2016, the Meteorological Research Institute (MRI) at Japan Meteorological Agency (JMA), developed the RSMC Tokyo version of SHIPS (Statistical Hurricane Intensity Prediction Scheme, DeMaria and Kaplan 1994; DeMaria and Kaplan 1999; DeMaria et al. 2005) with great support from SHIPS developers in the US (Yamaguchi et al. 2018). This version, named as TIFS (Typhoon Intensity Forecast scheme based on SHIPS) at RSMC Tokyo, predicts central pressure (Pmin) as well as maximum 10-min sustained wind speed (Vmax) for the North-West Pacific basin. Figure 3.3.2.3 shows root mean square errors (RMSEs) and biases of TIFS forecasts for both Pmin and Vmax. TIFS has considerable forecast skill relative to the GSM and a climatological statistical model (Statistical Hurricane Intensity FORecast, SHIFOR, Jarvinen and Neumann 1979; Knaff et al. 2003). Accordingly, the trial use of TIFS has greatly improved accuracy of RSMC Tokyo official intensity forecast as discussed in section 3.

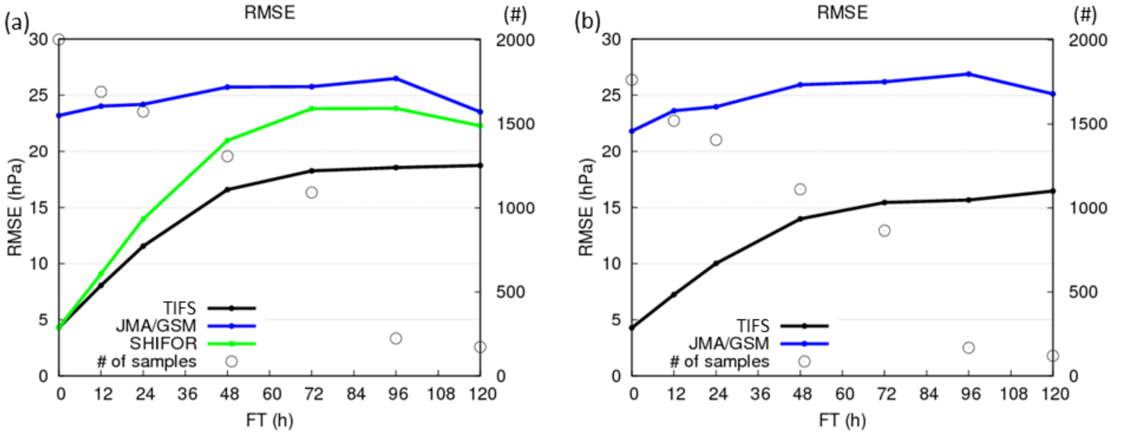


Figure 3.3.2.3: Root mean square errors (RMSEs) of (a) Pmin (hPa) and (b) Vmax (kt) forecasts. TIFS, JMA/GSM, and SHIFOR (Pmin only) are black, blue, and green lines, respectively. Black open circles show the number of samples corresponding to y-axis on the right. RMSEs are based on RSMC Tokyo's best track data. Forecast samples are from 2013 to 2015 for the WNP basin. This figure is from Yamaguchi et al. (2018).

Shimada et al. (2018) incorporated TC rainfall and structural predictors into TIFS to examine the impact of the predictors on the accuracy of TIFS. Results show some substantial improvement of the TIFS forecast but the latency of the rainfall product prevents operational implementation of TIFS with the rainfall predictors. Microwave satellite-based data with a high-temporal resolution and little latency are desirable to further improve the accuracy of statistical-dynamical models.

Some statistical-dynamical tools were also developed and evaluated recently at RSMC La Réunion, in order to meet the needs of the forecasters for specific guidance on that matter (pending publication from Leroux), using atmospheric and oceanic synoptic parameters (mostly from ERA-Interim data during the learning phase but with data from IFS in operation). The first one uses the Multivariate Adaptive Regression Splines (MARS) method, which allows simple non-linear behaviors. Its goal is to forecast the intensity changes (for 10-min maximum winds) within the next 24h. The second one is a decision tree developed to predict the occurrence of a RI during the next 24h. These tools are complementary because the first statistical model is not suited for extreme variations. They should become available for the forecasters in the near future.

The Indian Meteorological Department (IMD) uses an integrated Cyclone Prediction System (CPS) based on statistical-dynamical guidance as described at IWTC-8. The three intensity components are: (i) Intensity prediction by SCIP model, (ii) prediction of probability of rapid intensification by RI-Index, and (iii) decay of TCs after landfall by decay model.

3.3.2.3 Dynamical models

NWP models are still an area of great effort and great improvement in tropical cyclone intensity forecast. Hereafter we highlight some recent or planned improvements for some selected global and regional models

a) Recent or planned improvement with some selected global models

Although the skill of global models is less than that of the high-resolution regional models for intensity prediction, and especially so for RI, global models have improved considerably in recent years. It was not long ago that global model intensity forecasts were considered unskilful and were essentially ignored by forecasters. It is now admitted that these models nonetheless provide very useful guidance to operational forecasters since they often provide clues as to TC development and intensity trends.

In July 2017, an improvement in the ensemble data assimilation system along with adaptative quality control and observations errors for dropsondes, lead to a better handling of tropical cyclones at initial time for the global model IFS (Integrated Forecast System) at the European Centre for Medium-Range Weather Forecast (Vitard et al., 2018). A major upgrade was implemented in the operational version in June 2018 (CY45r1) with ocean and sea-ice models coupled in the high-resolution forecast. The change of SST from the Ocean near real time analysis (OCEAN5) is added to the initial OSTIA SST 1/20 degree for 4 days and then relaxed to 0 gradually from day 4 to day 8 for a full coupling thereafter. Verification of this implementation shows a small statistically-significant improvement in the intensity error at medium-range (figure *3.3.2.4*).

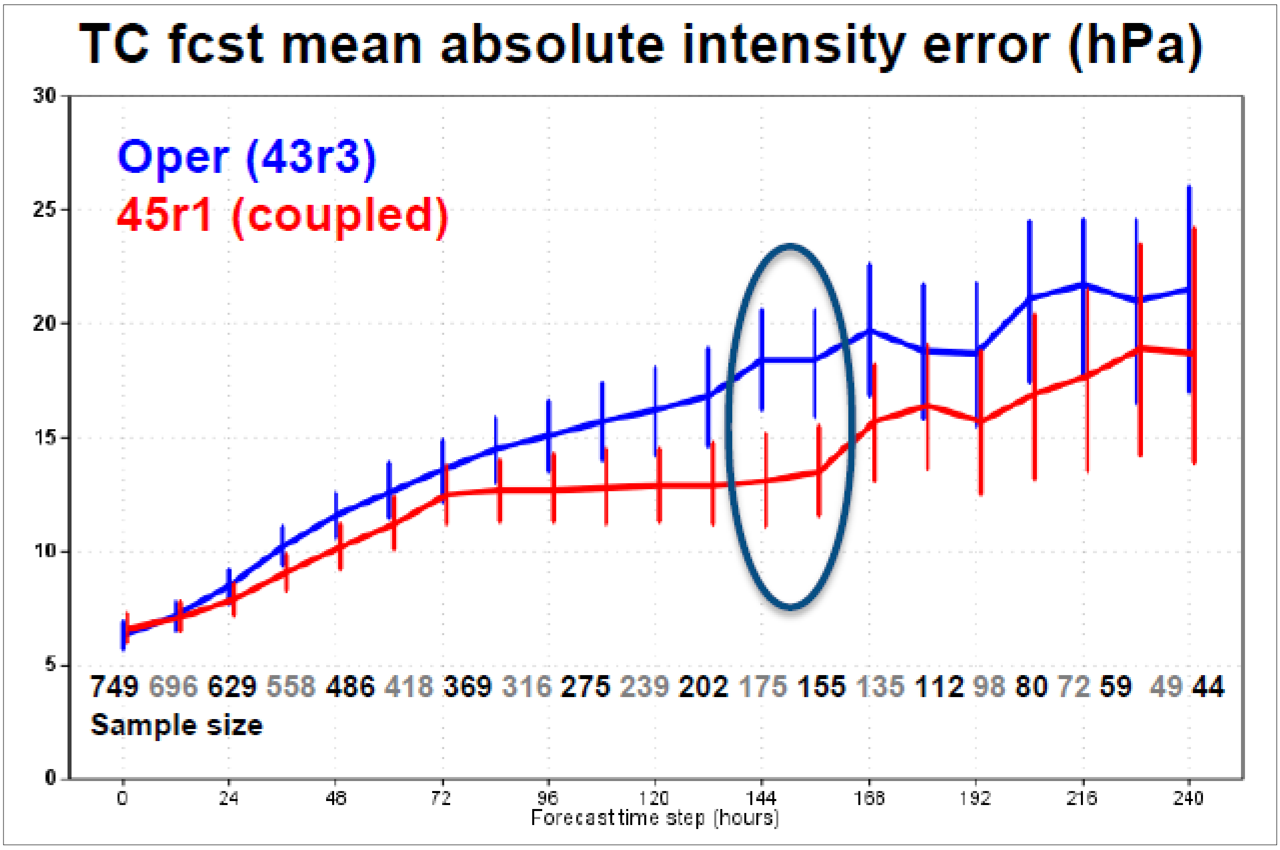


Figure 3.3.2.4. Intensity verification of the IFS (ECMWF) 2018 operational model. From: *https://www.ecmwf.int/en/about/media-centre/news/2018/ifs-upgrade-improves-extended-range-weather-forecasts*

In 2014 and 2015, two changes were made to the Met Office Global Model (MOGM – sometimes referenced as UKMO or UK in the followings sections of the report) which had a significant impact on tropical cyclone predictions (Heming and Vellinga, 2018). Global Atmosphere 6 (GA6) 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. In 2017, the MOGM horizontal resolution was increased again. Longer lead time forecasts of TCs 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 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 model. Operational implementation is planned for 2020. 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.

The GFDL Finite-Volume Cubed-Sphere (FV3), dynamical core was selected for the US NWS's Next-Generation Global Prediction System (NGGPS), has been transferred to NCEP, and is scheduled to become operational at NCEP in January 2019 as the replacements for the NWS’s Global Forecast System (GFS). An improved version of the model was recently developed at GFDL (referred to as fvGFS) and has been run daily in real time since 2 July

2018. The intensity performance of fvGFS is significantly improved with the new 2018 version of the GFDL fvGFS model compared to the 2017 version (degraded scores compared to operational GFS). The new model had the lowest intensity errors of all available operation guidance at 3 to 5 days (figure *3.3.2.5*), even beating the high-resolution regional hurricane models HWRF and COAMPS-TC.

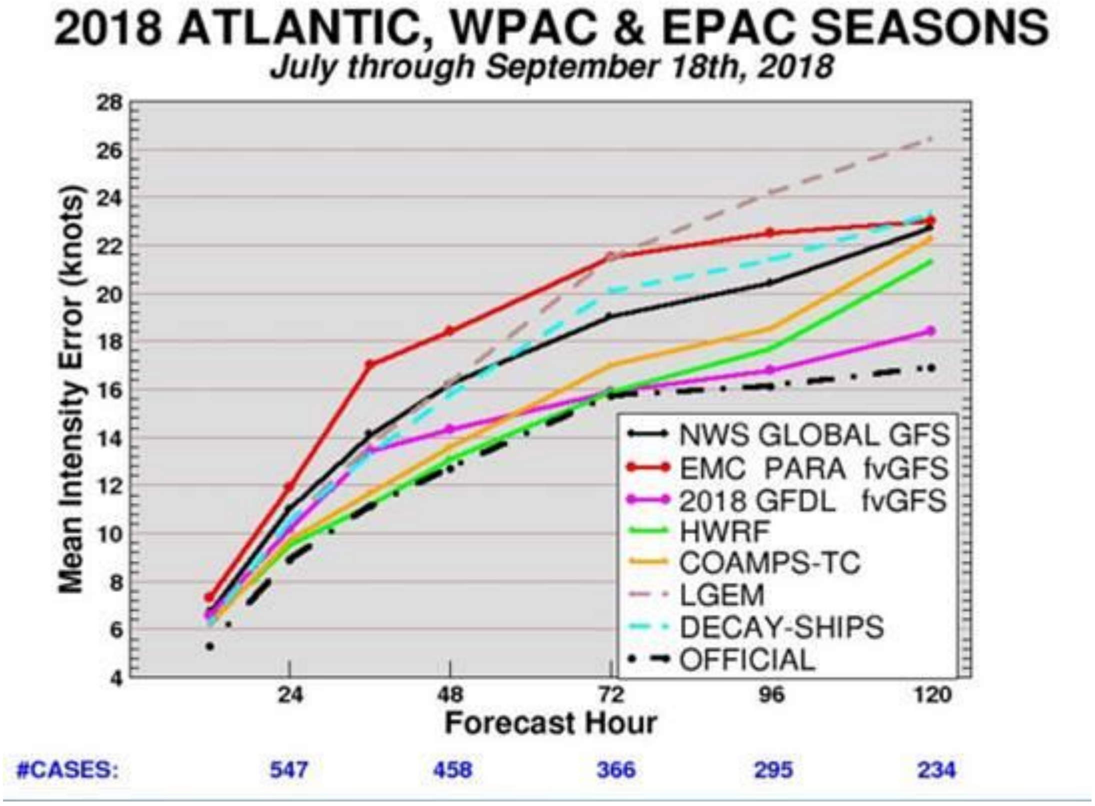


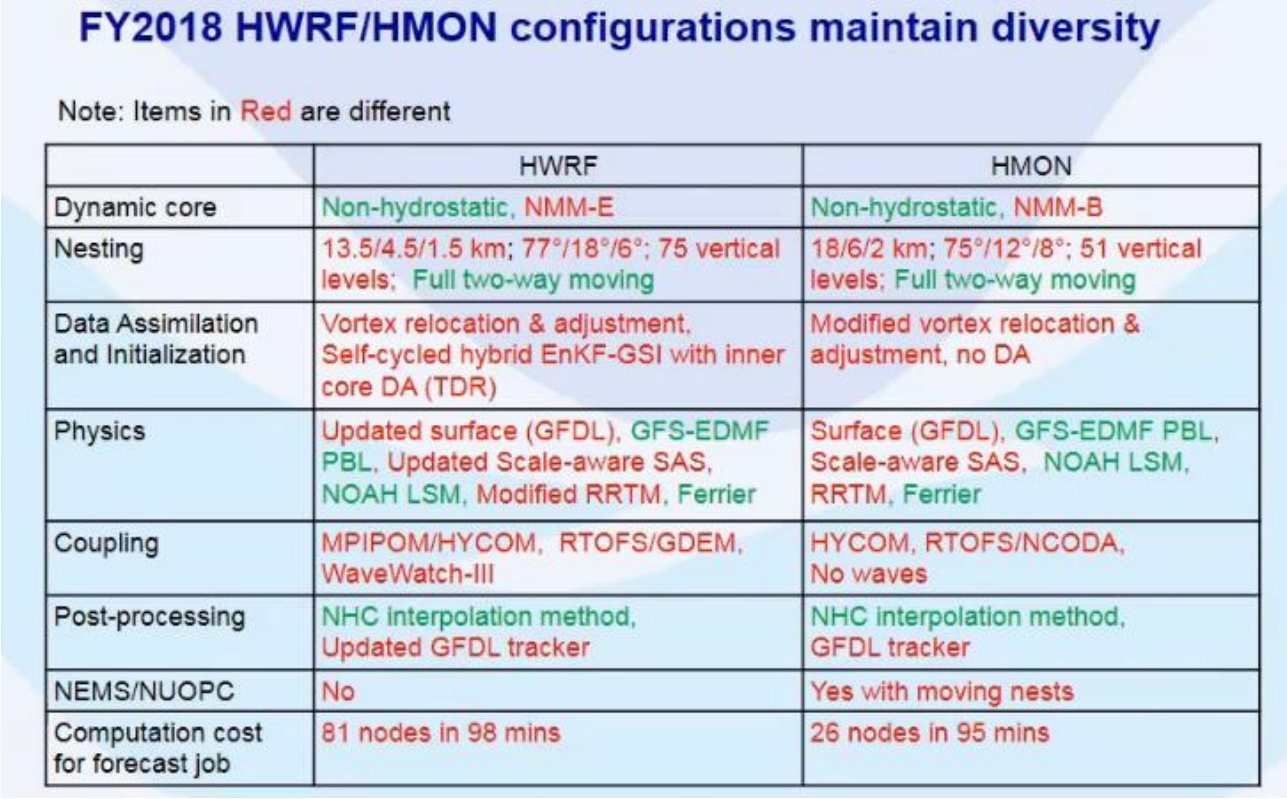
Figure 3.3.2.5. Average intensity errors (knots) for a portion of the 2018 tropical cyclone season (July 2-18 September), for the North Atlantic, North-East Pacific, North-West Pacific, and the combined 3 ocean basins, comparing the operational GFS (black) with other operational models including the EMC version of fvGFS (FV3-GFS, red) and the new 2018 experimental version of fvGFS (purple), developed at GFDL and run in near real time. Results are for the interpolated models and compared with the official forecast (black dot-dashed line).

Taking advantage of the nesting and grid stretching capability developed in the FV3 core, a high-resolution version of the model (hfvGFS) was adapted for the entire Atlantic hurricane basin (figure 3.3.2.*6*). The hfvGFS model uses the 13-km global domain with a 3-km, two-way interactive nest covering the tropical North Atlantic, and is run to 126 hours. Real time tests during the very active 2017 hurricane season over the North Atlantic, showed a reduction in mean absolute errors at almost all lead times, mostly due to a smaller negative bias at all forecast hours. It is anticipated that the development of this high-resolution version of fvGFS could eventually find a path to transition into NOAA's next generation hurricane model which will take advantage of the unified modelling approach that the FV3 modeling system was uniquely designed for.

b) Recent or planned improvement with some selected regional models

Regional Hurricane modeling systems implemented at NOAA’s NWS/NCEP operations are now used for forecasting guidance in all ocean basins of the world (Mehra et al., 2018). HWRF has made significant improvements to the state of the art in numerical forecast guidance. Verification shows that early guidance of this model was the best performer over the North Atlantic in 2017 at all lead times and for short lead times (< 48h) over the Eastern Pacific. Further improvements of HWRF in 2018 include increasing horizontal resolution (1.5km at the inner core), improvement of the data assimilation system (including the admission of new data sets like GOES16 AMW’s, NOAA 20, SFMR, Dropsondes drift and Tail Doppler Radar from the G-IV) and the physics. Improvements are also planned for the non-NHC basins with an increase in the vertical resolution and ocean coupling (HYCOM) for the southern hemisphere basins. Early verification over the North Atlantic suggests similar or slightly better performances than the 2017 version.

The Environmental Modelling Center hurricane team has also developed another non-hydrostatic hurricane model in NOAA Environmental Modeling System (NEMS) framework known as HMON (Hurricanes in a Multi-scale Ocean-coupled Non-hydrostatic) model which was implemented at NCEP operations this past year over the North Atlantic and Eastern Pacific. HMON came in to implement a long-term strategy at NCEP/EMC for multiple static and moving nests globally with one- and two-way interaction and coupled to other models (ocean, wave, land, surge, inundation, etc). Validation of the skill of the model during the 2017 hurricane season shows the skill lags behind HWRF, mainly due to a better modeling configuration for HWRF than HMON (figure 3.3.2.7). Development of HMON is consistent with, and a step closer to developing NGGPS chosen FV3 dynamic core based global to local scale coupled models in a unified modeling framework.



FY2018 HWRF/HMON configurations maintain diversity

Note: Items in Red are different

	HWRF	HMON
Dynamic core	Non-hydrostatic, NMM-E	Non-hydrostatic, NMM-B
Nesting	13.5/4.5/1.5 km; 77°/18°/6°; 75 vertical levels; Full two-way moving	18/6/2 km; 75°/12°/8°; 51 vertical levels; Full two-way moving
Data Assimilation and Initialization	Vortex relocation & adjustment, Self-cycled hybrid EnKF-GSI with inner core DA (TDR)	Modified vortex relocation & adjustment, no DA
Physics	Updated surface (GFDL), GFS-EDMF PBL, Updated Scale-aware SAS, NOAH LSM, Modified RRTM, Ferrier	Surface (GFDL), GFS-EDMF PBL, Scale-aware SAS, NOAH LSM, RRTM, Ferrier
Coupling	MPIPOM/HYCOM, RTOFS/GDEM, WaveWatch-III	HYCOM, RTOFS/NCODA, No waves
Post-processing	NHC interpolation method, Updated GFDL tracker	NHC interpolation method, GFDL tracker
NEMS/NUOPC	No	Yes with moving nests
Computation cost for forecast job	81 nodes in 98 mins	26 nodes in 95 mins

Figure 3.3.2.7: 2018 HWRF and HMON configurations.

Since February 2016, Meteo France has significantly improved its numerical modelling capabilities for the overseas French territories (La Réunion, Mayotte, Martinique, Guadeloupe, French Guiana, New-Caledonia and French Polynesia). AROME, a non-hydrostatic fine scale spectral model (2.5 km of horizontal resolution) initialised by the IFS analysis runs now 4 times per day up to 42h in each French territories domains (figure 3.3.2.6). In 2017 (Faure et al., 2018), a 1D ocean coupling and reduction of the spin-up time has been implemented. 1D ocean-coupling allows the model to represent cooling in TC wake even with no observations.

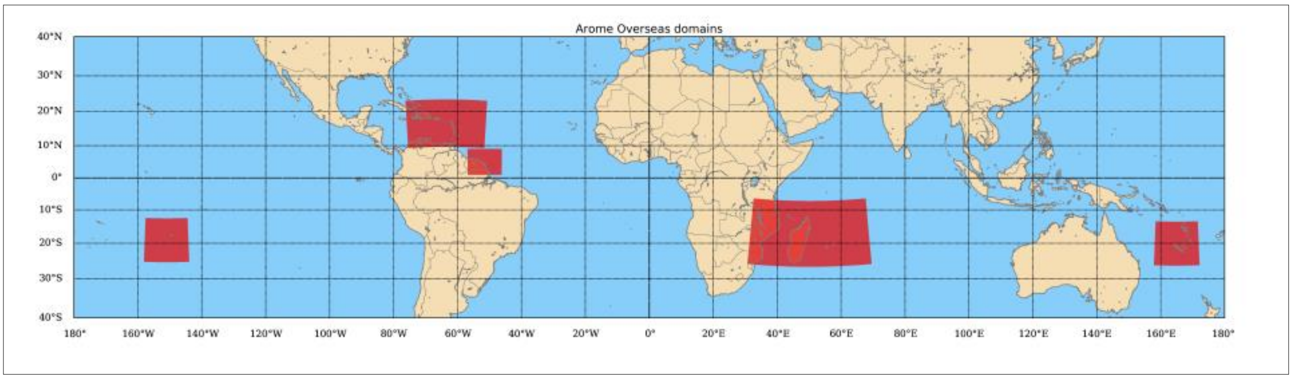


Figure 3.3.2.6. In red, Meteo-France non-hydrostatic AROME regional model domains associated with French overseas territories.

The results in terms of short-range forecasts are already supportive for both intensity and structure, along with excellent track forecast scores that remains near IFS valuable guidance. At RSMC La Réunion, AROME has successfully forecast a number of TC events including the rapid demise of TC Hellen in March 2014 (further information below), the explosive initial development of TC Bansi in January 2015 (AROME trial period), and the Eyewall Replacement Cycle of TC Fantala in April 2016. In the North Atlantic, AROME forecast has been verified against available observations (radar, recon, RSMC analyses, …) during IRMA and MARIA in September 2017 as those systems were crossing the lesser Antilles (Dupont et al., 2018). The model demonstrated its excellent ability to forecast realistic structures, tracks and intensities.

Many additional improvements are possible within the next few years including; better initial state through an own 3D-Var scheme and assimilation of cloudy microwave radiances and radar data, 3D ocean coupling, improved wind-pressure relationship and increased horizontal resolution or a high-resolution ensemble system.

Indian Meteorological Department (IMD) have adapted Hurricane-WRF model HWRFV 3.7+ from NCEP for the North Indian Ocean. The model runs with nested domain of 18 km, 6 km and 2 km horizontal resolution and 61 vertical levels. The model provides 6 hourly track and intensity forecasts along with surface wind and rain swaths valid up to 120 hours. The model uses IMD GFS-T1534L64 analysis/forecast for initialisation.

2.4 Consensus and ensemble-based guidance

Consensus methods are extensively used for track forecasting but the systematic use of a consensus for intensity matters are less widespread, potentially due to a lack of specific tools in some agencies to properly visualize full-resolution intensity forecast guidance.

The ‘ICNW’ approach to combine SHIPS and LGEM with high resolution models HWRF, COAMPS and HMON as well as the RIPA index, has led to significant improvements in the quality of objective guidance at JTWC. For example, at mid-typhoon season 2018, the ICNW outperformed JTWC from day 1 to day 4. Figure 3.3.2.7 shows the steady improvent of this consensus guidance.

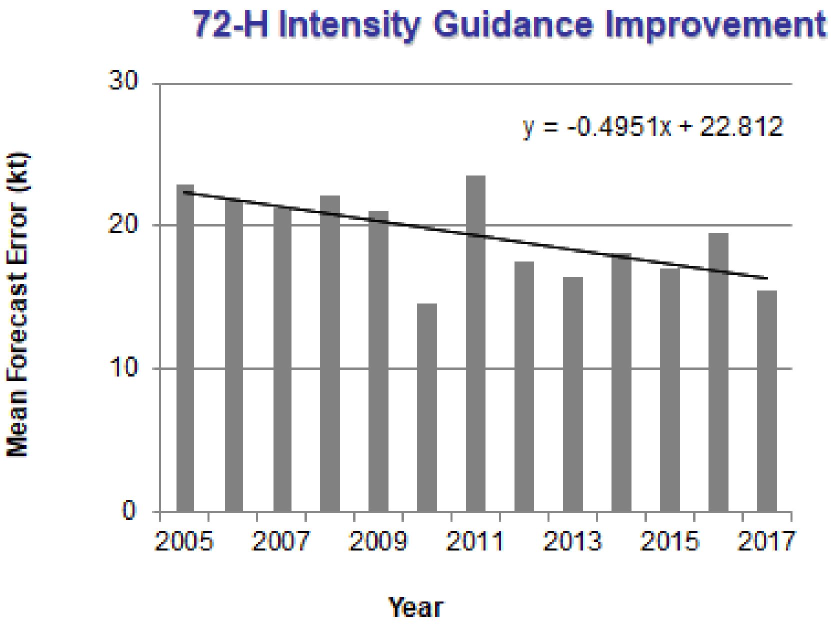


Figure 3.3.2.7. The 72-h intensity skill trend in the JTWC consensus for NWPac, 2005-17 showing approximate improvement of 5 kt in the last 10 years. (credit: Sampson)

In the framework of the Hurricane Forecast Improvement Program (HFIP), a Corrected Consensus Approach (HCCA) for tropical cyclone track and intensity forecasts has been developed at the NHC (Simon et al. 2018). The HCCA technique relies on the forecasts of separate input models for both track and intensity and assigns unequal weighting coefficients based on a set of training forecasts. HCCA uses Decay-SHIPS, LGEM, GFS, UKMO, IFS, COAMPS TC, HWRF, GEFS and EPS to derive a track and intensity consensus. The HCCA track and intensity forecasts for 2015 were competitive with some of the best-performing operational guidance at the NHC. The relative magnitudes of the intensity coefficients were more varied but the most important input models for HCCA intensity forecasts are HWRF and COAMPS-TC model initialized from the GFS. Several updates were incorporated into the HCCA formulation prior to the 2016 season. Verification results indicate HCCA continued to be a skillful model in both basins (North Atlantic and North-East Pacific).

Recent work at RSMC La Réunion has designed a technique to generate weighted ensemble predictions around the official track and intensity forecast (Quetelard et al. 2018) by combining 5-years statistical errors of RSMC forecasts and ECMWF ensemble forecast spread, allowing a situation-dependent quantification of official intensity forecast as recommended during IWTC-8.

Bureau of Meteorology have applied an intensity bias-correction to increase the ECMWF ensemble forecast intensity based upon differences in model performance and best tracks. This enables the production of point-based probabilistic wind output (and wave via linkages with a wave model) for key users. Such an approach carries an overhead to recalibrate the difference with ongoing model upgrades.

3.3.3 Intensity forecast by operational agencies

Although it was not manageable to include all operational agencies that issue tropical cyclone forecasts, a significant number of them contributed to this report, including notably all RSMCs. Thus, the pictures described in the following section regarding intensity forecast performances and current operational procedure, is expected to be well representative of the state of the art.

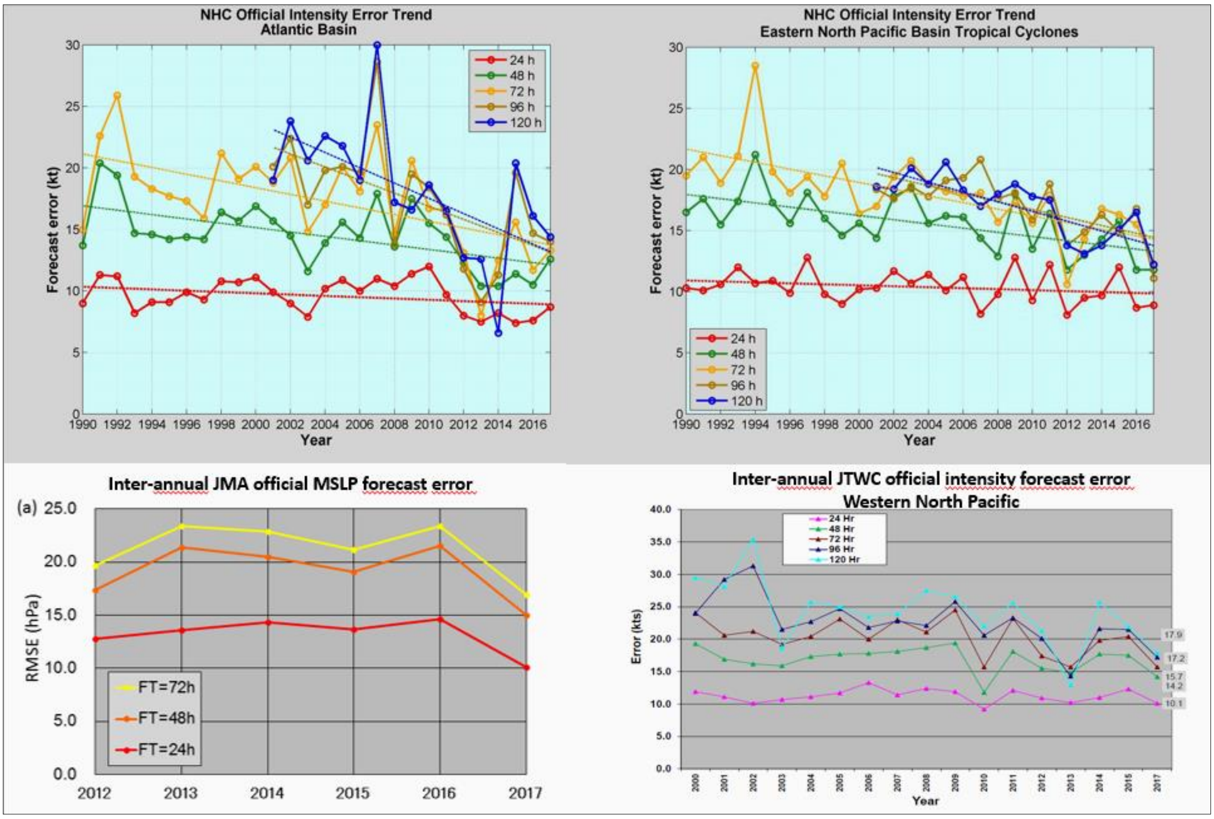
3.3.3.1 Inter-annual intensity forecast error trend

Over the last 4 years and for the first time, reports of intensity forecast skill from operational agencies are split into two categories: a small number of agencies (3) report a decrease in intensity forecast errors along with a concurrent increase in skill, while a continuous generally stationary trend is noted amongst other agencies. Figure 3.3.3.1 show the scores of operational agencies reporting those improvements. Although the progress has not been steady over recent years, improvements are remarkable at the NHC, especially for forecasts beyond 48 hours for both the North Atlantic (NA) basin and to a lesser extend the North-East Pacific. For the NA, the 2011-2013 official intensity forecast skill that was around 10-15 % for the 12-36 hours lead-times and near 0 % for longer lead times (previous IWTC report), have increased on average between 25-45 % at all lead-times for the period 2014-2017. The NHC reports that until recently, the statistical/dynamical models DSHIPS and LGEM were generally the most reliable guidance for intensity prediction. In recent years, however, consensus models such as the equally weighted variable-member consensus (IVCN) and the HCCA, along with the dynamical HWRF model, have become the best intensity guidance for the Atlantic basin. In fact, HWRF has been the best-performing individual model for intensity in the Atlantic for the past 3 years. Another promising aspect of the HWRF model is its ability to assimilate data such as aircraft-observed Doppler radar velocities in the TC inner core.

Over the North-West Pacific, The JMA has upgraded intensity guidance as seen in the previous section, with mainly the development of the RSMC Tokyo version of SHIPS, TIFS. RSMC Tokyo started using TIFS on a trial basis as one of the TC intensity forecast models since the middle of 2016. RSMC Tokyo is planning to operationalize TIFS from the 2019 typhoon season along with the extension of intensity forecasts from 3 days to 5 days. Accordingly, the trial use of TIFS has greatly improved the accuracy of RSMC Tokyo intensity forecasts. RMSE of the RSMC Tokyo official intensity forecast (Pmin forecast) decreased greatly in 2017 (figure 3.3.3.2) and skill has increased since 2016 passing from below 10 % to 15-20 % for lead-times 24, 48 and 72 hours.

Since 2000 JTWC report a gradual improvement in intensity at 48 and 72 hours with no significant change at 24 hours. However, a more pronounced improvement is evident in the very recent years at the 96-hour and 120-hour verification points. JTWC has recently implemented significant enhancements to the forecast intensity guidance suite to include:

- Rapid Intensification Forecast Aids (Knaff 2018) – deterministic forecasts (RI25, RI30, RI35, RI40, RI45, RI55 and RI70) incorporated into the intensity consensus (ICNW)
- M-PERC
- CIRA / RAMMB Eye Probability
- Weighted Analog Intensity (WANI) Guidance (Tsai and Elsberry 2015)


NHC Official Intensity Error Trend
Atlantic Basin

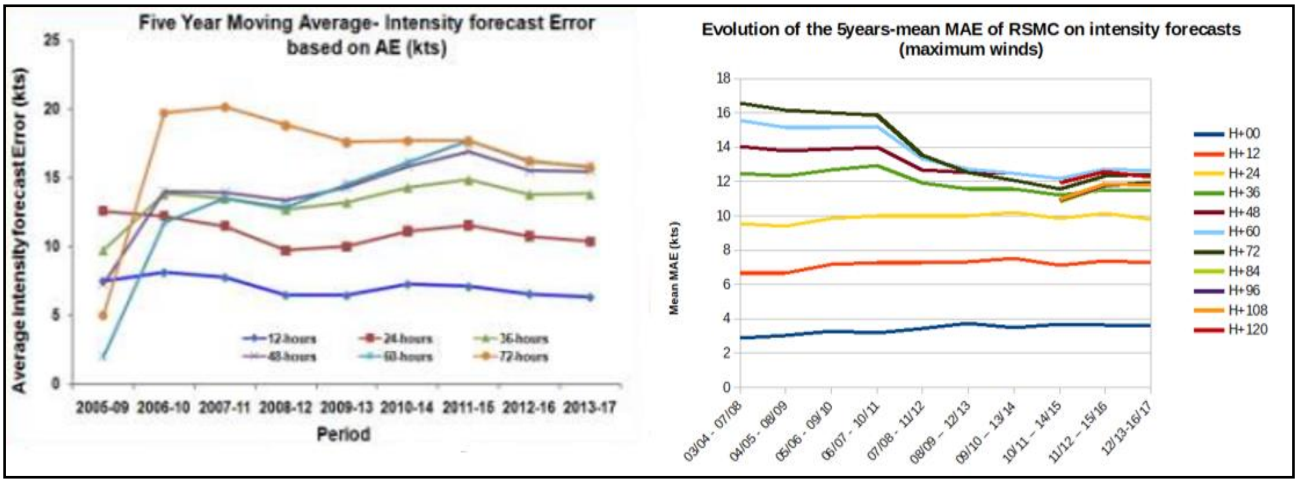
NHC Official Intensity Error Trend
Eastern North Pacific Basin Tropical Cyclones

Inter-annual JMA official MSLP forecast error

Inter-annual JTWC official intensity forecast error
Western North Pacific

Figure 3.3.3.1 Intensity verification at NHC for the North Atlantic and North-East Pacific, JMA and JTWC North-West Pacific.

In all the other selected agencies that contributed to this report, intensity forecast scores shows no or little recent significant improvement as illustrated in figure 3.3.3.2 with the example of the Indian Meteorological Department (IMD or RSMC New-Delhi) and Meteo France La Réunion.


Five Year Moving Average- Intensity forecast Error based on AE (kts)

Evolution of the 5years-mean MAE of RSMC on intensity forecasts (maximum winds)

Figure 3.3.3.2 *Intensity verification at IMD Arabian Sea and Bay of Bengal, and Meteo France South-West Indian Ocean*.

3.3.3.2 Operational intensity procedures

All selected operational agencies have shared an update of their intensity forecast process. A common feature is that the intensity forecast process follows the determination of the analysis fix and forecast track and its inherent uncertainty. As steering levels change with intensity, the intensity forecast is tightly connected with the track forecast, both being interdependent. All selected agencies based their intensity forecast process on an understanding of the current large-scale environment (upper level flow, vertical wind shear, low to mid-level moisture, ocean heat content, low level inflow and proximity to land factors) and the analysed intensity and trend over the past 24 hours or so along with inner core structural changes seen on micro-wave imagery. The intensity process then requires examination of the expected changes to the large-scale environment as indicated by NWP as well as the examination of key differences between NWP. Consideration is also given to continuity to avoid large changes from one forecast cycle to the next. A summary of specific procedures in each agency is provided below in no particular order.

a) RSMC Tokyo

TIFS, SHIFOR, JMA/GSM (JMA global model), JMA/MSM (JMA mesoscale regional model), HWRF, and cyclone phase space (CPS) based on JMA/GSM are used for intensity forecasts. JMA/MSM is used when TCs approach Japan. In general, mesoscale regional models are good at forecasting intensity changes associated with topography. JMA/GSM forecast is reliable when TCs are in the incipient stage or the extratropical transition stage. HWRF forecast is monitored to consider a possibility of RI. An intensity change scenario, including intensity change rate, peak intensity and its timing, and extratropical transition, is constructed based mainly on TIFS forecast with some modifications. For the incipient stage, TIFS intensity change rate is revised downward in most cases accounting for the bias of TIFS to over forecast intensity (e.g., Shimada et al. 2018). For the subsequent intensification stage, TIFS intensity change rate may be adjusted upward or downward to reach forecast peak intensity, depending on the discrepancy between the past TIFS forecasts and the latest Dvorak analysis. For the weakening or landing stage, forecast intensity is modified so as to gradually approach JMA/GSM forecast intensity.

b) The Korea Meteorological Agency (KMA)

For 120 h intensity forecast, KMA used the STIPS based on statistical-dynamic model and dynamical model results of HWRF and TRUM (KMA Typhoon Regional Unified Model). The decision whether a decaying TC transforms into an extratropical cyclone or not is mainly based on Cyclone Phase Space diagram and KMA operational extratropical cyclone transition manual (KMA, 2007). KMA intensity forecast is relied on the results from the STIPS.

c) The Bureau of Meteorology (BoM)

An initial intensity forecast estimate is typically considered in a Dvorak T-no. framework. For example, D for 0-24h, D+ 24-48h, D-/S 48-72h, W+ 72-96h etc. where D represents an increase of 1.0 T-no. per day. This is followed by a review of the objective NWP intensity forecasts and statistical-dynamic models. The Bureau follows research by NRL to improve objective statistical-dynamic intensity guidance. The latest version of the SHIPS approach, 'ICNW' is used routinely by BoM along with the Rapid Intensification Index RII. It is limited by not including some models such as IFS and UK.

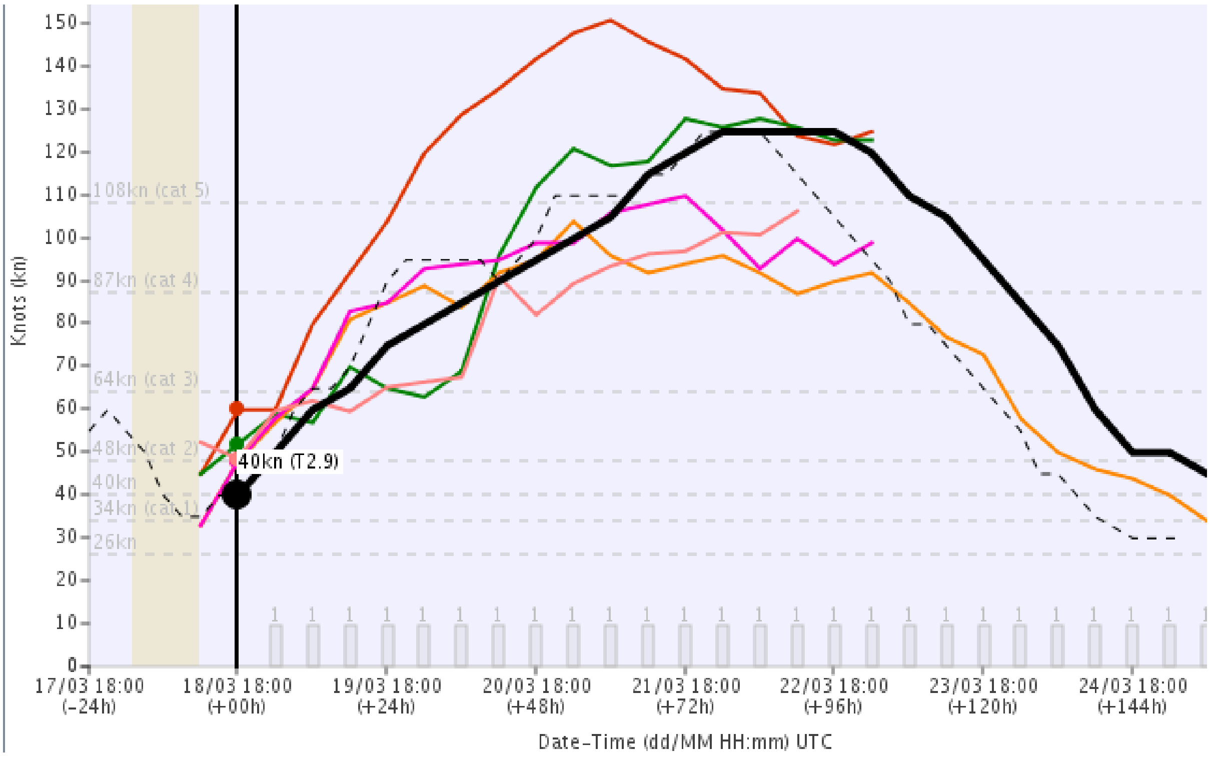


Figure 3.3.3.3: BoM's tool for the operational intensity forecast for Marcus (2018). To assimilate the range of NWP intensity estimates including ensemble outputs with the analysis and previous forecasts, BoM developed the intensity tool with the operational software package TCModule. This also allows the forecast to be automatically generated and edited onscreen and includes the standard inland decay rate.

Consistency between dynamical models and from run to run are important considerations with bias given to the better performing and higher resolution models. The highest-resolution model, HWRF, is recognized as the most likely model to indicate rapid intensification. BoM also consider trends in the ECMWF and UK ensemble intensity output. The trends in model intensity are given greater consideration rather than the absolute values as NWP have historically underestimated the intensity. However, this is changing as model resolution increases.

Guidance from these forecast aids are combined with a subjective assessment of potential environmental influences and recent intensity changes to determine forecast intensity. A combination of synoptic assessment and persistence is usually weighted most heavily for the short term (to +24 h), after which increasing weight is given to objective guidance and consistent trends in dynamical models. Consistency over a series of model runs is also considered to avoid fluctuating from one forecast to the next.

Finally, the forecast intensity is compared to the previously issued forecast for policy consistency and adjusted accordingly. This is especially the case when there is high uncertainty. For example, if there is a significant change from what was issued previously the official forecast may be adjusted closer to the previous issue estimates until the evidence for the change becomes stronger. Rapid intensity changes especially at longer lead times are typically avoided as it is so difficult to pick the timing of such changes.

Forecasters appreciate tools that make it easy to visualize and intepret the range of guidance. It is an ongoing frustration that multiple sources have to be viewed to enable guidance to be compared. This has led to the development of the intensity tool in the TCModule software package (figure 3.3.3.3). Web displays such as the CIRA multi-model display (figure 3.3.3.4) are also well used as it includes displays of wind shear, SST and RH, but doesn't have the full range of guidance.

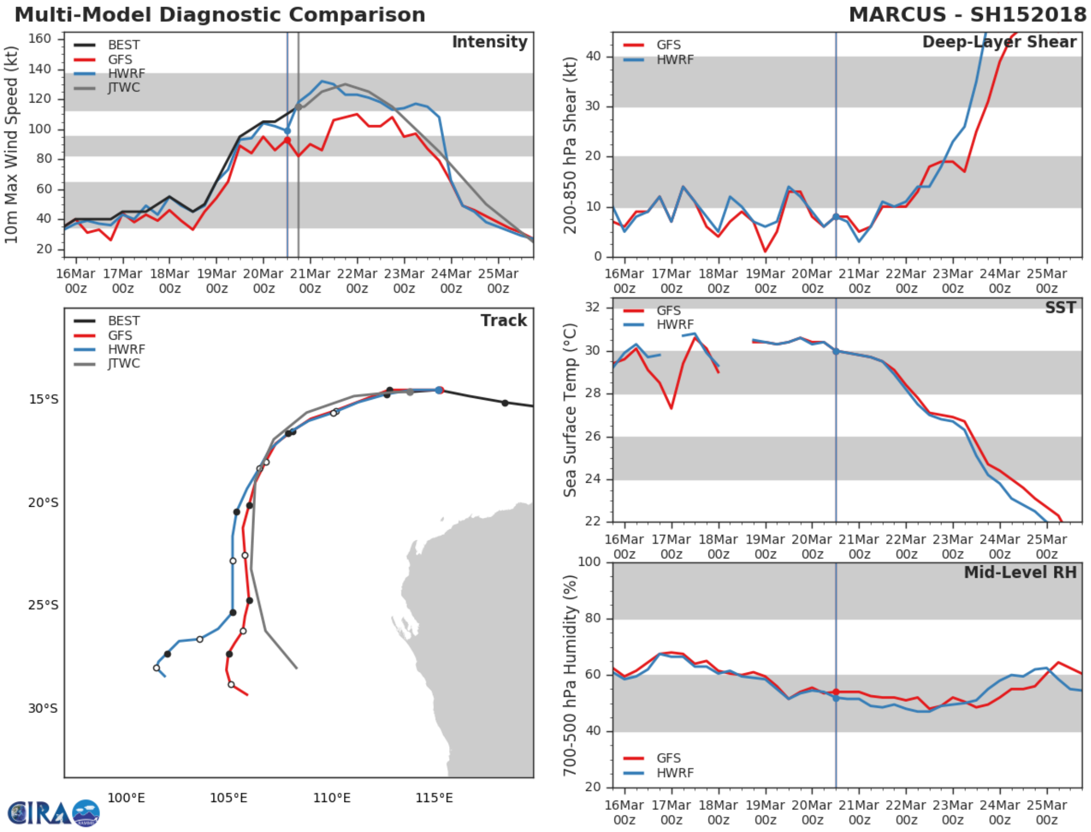


Figure 3.3.3.4: BoM forecasters use CIRA's multi-model display showing intensity guidance with track, shear, SST and RH information.

d) RSMC New-Delhi (IMD)

The intensity forecast has been issued by RSMC, New Delhi from deep depression stage (MSW: 28-33 kt) onwards since 2009 for 12, 24, 36, 48, 60 and 72 h forecast periods (Mohapatra et al, 2013). The TC intensity forecast is issued 4 times a day at the interval of six hours, i.e. based on 00, 06, 12 and 18 UTC observations with every three hourly updates and validity period extended up to 120 hrs since 2013. The forecasts are issued about three hours after the above-mentioned observation time. The tools and methods used by IMD for intensity forecasting of TCs over the NIO includes satellite, radar and synoptic guidance, as well as guidance from various global and regional deterministic models like IMD-GFS, NCMRWF(India)-GFS, IFS, UKMO, JMA, ARP (Meteo-France), IMD-WRF, WRF run at Indian Institute of Technology - Delhi, NCMRWF-WRF, HWRF, NCEP-HWRF and probabilistic predictions from ensemble prediction systems like NCMRWF-GEFS, ECMWF-EPS etc. (Mohapatra et al, 2013b). In addition, outputs from the Dynamical-statistical Cyclone Prediction System (CPS) are used routinely at IMD.

e) RSMC La Réunion (Meteo-France)

The short-range intensity forecast process is mainly influenced by the identification of ongoing internal / external influences detected at initial time. For the longer ranges, forecasters make environmental conditions assessments that are generally derived from analyses of environmental fields and chiefly from the main numerical guidance: IFS and GFS deterministic models constituting the main reference. With the progressive increase in resolution of numerical models, some raw parameters like maximum winds, central MSLP … are also looked at more closely by the forecasters. They appear very valuable for the post-tropical phase and to a lesser extent during cyclogenesis. Among the usual models, IFS and GFS deterministic data are the most popular but ECMWF EPS, GEFS, UKMO, ARP (Meteo-France global model) and aids received from JTWC (NVGM, HWRF, GFDN, CONW) are also frequently considered.

In the recent years, one main evolution was the implementation of the Meteo-France AROME-IO model in 2016. The tendency in this fine scale model to over-intensify was less apparent during last season (2017/2018) – probably owing to the inclusion of the ocean coupling – whereas some rapid intensification events were correctly forecast. These promising results along with expected valuable improvement of the model in the coming years should lead to increase use of this model for the short-term forecast.

f) The Joint Typhoon Warning Center (JTWC)

The JTWC forecaster only has about 1-1.5 h to synthesize forecast track, intensity, and wind distribution guidance before issuing a tropical cyclone forecast. The following forecast intensity practices and strategies are applied:

- Since HWRF is considered a reliable model for predicting intensity change rates, forecasters generally hedge close to or above HWRF guidance.
- Forecasters may also hedge above COTC / ICNW when output is consistent.
- Leverage Dvorak’s (Velden 2006) climatological intensification model
    - In a very favorable environment, the intensification rate may exceed 1.5 T-numbers per day
    - In an unfavorable environment, it may be well below one T-number per day
- Identify annular structure using EIR imagery.
- Identify eyewall replacement cycles, primarily through analysis of microwave satellite data and M-PERC data.
- Identify a cyan ring structure in 37 GHz color composite microwave imagery (Kieper 2012), which may signal an imminent RI phase.
- Identify observed, sharp increase in objective intensity estimates, which may signal an imminent RI / ERI event.
- Identify areas of increasing vertical wind shear and cooler sea surface temperatures that tend to weaken a tropical cyclone.

- Identify synoptic-scale influences on outflow patterns around the tropical cyclone.

- If the outflow channel is directed poleward, the average maximum rate of intensification is 15-20 knots every six hours. If the outflow channel is directed equatorward, then the average maximum rate of intensification is 25-28 knots every six hours.

- Tropical cyclones with dual channel outflow intensify at a maximum rate of 35 knots every six hours. Dual channel outflow is a key factor in many cases of rapid intensification. The

TUTT must also be considered as a major contributor to tropical cyclone intensity change in the North-West Pacific. Both the placement and proximity of the TUTT to the tropical cyclone will determine the effect - positive or negative - that the TUTT will have on the intensity change of the tropical cyclone.

- Identify favorable sea surface temperature areas (between 26 and 29°C). Rapid intensification is more likely if sea surface temperature is 28.5°C or greater.
- Identify favorable areas of high ocean heat content, which is especially important for slow moving TCs.
- Identify and track the subtropical ridge access since rapid intensification often occurs as the tropical cyclone approaches the subtropical ridge axis, where the translation speed of the tropical cyclone decreases, vertical shear is usually very low, outflow is exceptionally favorable, and the underlying sea surface temperatures are sufficiently warm and ocean heat content is sufficiently high.
- Rapid intensification may occur wherever and whenever conditions are conducive. However, a few areas are noted for having such conducive conditions on a regular basis, including the Philippine Sea, Mozambique Channel, and Gulf of Carpentaria.

g) The Central Pacific Hurricane Center (CPHC)

A large percentage of Central Pacific TCs enter the basin from the east after reaching their peak intensity in the eastern Pacific, and are typically “spinning down” on their way to becoming a remnant low or dissipating. This is largely due to strong environmental vertical wind shear typically found in the basin, with this shear effectively entraining dry mid- and upper-level air into the cyclone’s circulation, leading to the demise of most TCs. The warmest ocean temperatures in the basin are typically south of the main TC storm track, and limited ocean heat content usually plays a role in limiting the intensity of Central Pacific TCs. With a minimal amount of land mass in the basin, interaction with land and topography rarely plays a role in forecasting intensity change. A pair of recent TCs (Iselle 2014 and Darby 2016) have made landfall on the Big Island of Hawaii, and in these limited cases, forecasters had to consider interaction with the extreme topography of the Big Island when developing the intensity forecast.

Statistical-dynamical model guidance is referenced during every forecast cycle. Known as SHIPS/LGEM, this guidance is based on climatology, persistence, and statistical relationships to current and forecast environmental conditions. Presented in tabular form, these data give the forecaster guidance on what factors may be most critical in the intensity change of a TC. The SHIPS guidance also includes statistical information on the probability of rapid intensification over the first 48 hours of the forecast.

Regional (HWRF/HMON) and global (GFS, IFS, COAMPS-TC, UK) dynamical model guidance is operationally referenced for anticipating intensity change. Although advances in global model capabilities have led to increased accuracy in TC track forecasts, they remain of limited utility in intensity forecasts due to several reasons. These limitations include insufficient model resolution to capture inner-core dynamics critical to intensity change, poorly understood inner-core dynamics, and challenges related to the model’s representation of environmental shear.

Consensus and ensemble guidance are utilized as well, with ICON/IVCN guidance representing a blend of the SHIPS/LGEM/HWRF/COAMPS-TC guidance. Ensemble guidance in the form of the Florida State Super Ensemble (FSSE) is available to CPHC forecasters, with this corrected-consensus utilizing dynamical models and the previous official forecast. These forecast techniques have been some of the best performers in anticipating intensity change.

In the operational setting, persistence is used quite a bit, especially when anticipating short-term changes in intensity. Forecasters also look for obvious environmental signals, i.e. cooler waters/increasing upper-level winds/decreased environmental moisture, and evaluate model guidance to determine if these are properly analyzed. Intensity forecasts at RSMC Honolulu tend to be conservative; as extreme intensity changes are rarely observed in the basin, they are almost never forecast.

h) The Fiji Meteorological Service

For forecast intensity and track, global model guidance are imported from the JTWC website to TC Module. Guidance like GFS, UKMO, JTWC, GFDL, JMA are available from the JTWC collaboration site. IFS was entered manually from Tropical Tidbits website but is now available through JTWC website. For the intensity forecast, model guidance is used together with the DVORAK rules for intensification and weakening. Midget systems which intensify rapidly are the most difficult to forecast.

i) The US National Hurricane Center (NHC)

No major change in the operational procedure for intensity forecast compared to the last IWTC report. Data from the initial state analysis are used as input into statistical-dynamical models, such as SHIPS and Logistic Growth model (LGEM; DeMaria 2009), and dynamical models such as the GFDL and HWRF hurricane models. Combination of various statistical-dynamical guidance and dynamical guidance are then performed to derive simple consensus, like the IVCN (an equally weighted variable-member consensus) or more sophisticated consensus like the HCCA (see above). Recently, that guidance along with HWRF, have become the most reliable for the North Atlantic as shown in figure 3.3.3.5 below.

The NHC forecasters also consider RII and DTOPS for RI, and are proving to be quite useful in operations.

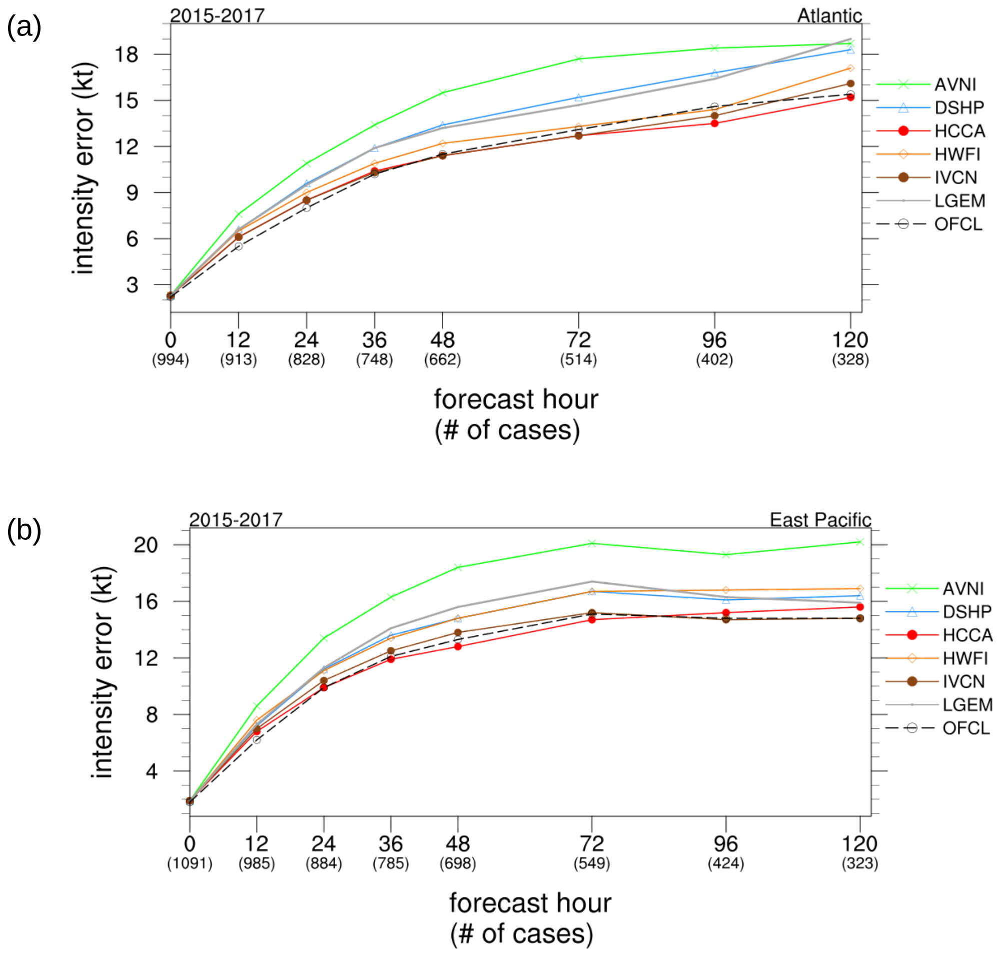


Figure 3.3.3.5: Intensity error for (a) Atlantic and (b) North-East Pacific forecasts from 2015 to 2017 for GFS (AVNI), DSHP, HCCA, HWRF, IVCN, LGEM, and OFCL (NHC forecasts).

3.3.3.3 Dealing with rapid intensity changes

The main challenge in terms of intensity forecasting remains the prediction of rapid intensity changes (i.e. Rapid Intensification (RI) and Rapid Weakening (RW)). According to the recent IWTC-LP IV report on recent advances in research and forecasting of tropical cyclone track, intensity and structure at landfall (Leroux et al., 2018), recent climatological studies of intensity changes have quantified the possible range of TC intensification and decay in different tropical regions outside of the NATL, that was documented since 2003 (Kaplan and DeMaria). Leroux et al. (2018) established thresholds of RI and RW appropriate for the SWIO using a 17-year climatology based on best-track data. The standard 30kt/day threshold was found to also apply in the SWIO for RI, while for RW a decrease of 27kt/day, although this threshold may not be appropriate for all systems (tropical depressions or storms or cyclones). According to Shimada et al. (2017), RI can be defined as at least -30 hPa over a 24h period for WNP TCs from RSMC Tokyo best track data.

The JTWC report that in the NWPac for the period 1970-2016, there were a total of 1387 TCs, of which 37.6% underwent RI and 11.7% underwent Extreme Rapid Intensification (ERI i.e. increase of Vmax greater or equal to 50 kt). Leroux et al. (2018), report that over the SWIO, and for the 1999-2016 period, 43% of all tropical systems and all very intense tropical cyclones (10-min wind greater or equal to 116 kt) underwent RI at least once during their lifetimes. Statistics indicate that operational intensity forecast errors are significantly greater at 24-h lead times for RI cases (19 kt versus 8 kt for non-RI events). Consequently, forecasters are generally not inclined to reflect a RI in their official forecast. However, some recent success has been reported in predicting RI (*Harvey* (2017) over the NATL and *Marcus* (2018) over the Australian region). In both cases, an agreement between various skillful RI guidance, lead to provide forecasters with confidence to predict RI.

Some agencies are using specific guidance that target the likelihood of RI (please refer to section 2 for further details), including statistical, dynamical-statistical and dynamical guidance. Selected operational agencies of the working group have reported insights they have gained in order to deal with similar cases in the future. Here is a synthesis of their feedbacks:
For Atlantic forecasts where RI occurred (Figure 3.3.3.6a), the NHC official forecasts have the lowest error out to 24 h, while HWRF has the lowest error from 36 h – 120 h. While the statistical models, DSHP and LGEM, would have typically performed better than the dynamical models several years ago, the high-resolution forecasts of HWRF (HWFI) have become the best intensity guidance for systems that rapidly intensify. HCCA and IVCN perform slightly better than the purely statistical models, but lag behind the performance of HWRF. The least skillful model for RI prediction included in this sample is GFS (AVNI). Although the skill of global models is less than that of the high-resolution regional models for intensity prediction, and especially so for RI, global models have improved considerably in recent years.

The intensity error of RI forecasts for the North-East Pacific (Figure 3.3.3.6b) exhibit slightly different characteristics than those for the Atlantic. The best performing model from 24 h to 120 h is HCCA, which outperforms the NHC official forecasts by quite a wide margin at medium- and long-range forecast hours. The two worst performing models are AVNI and HWFI. Relative to the purely dynamical models, the statistical/dynamical models, DSHP and LGEM, perform better for RI forecasts in the eastern North Pacific compared to the Atlantic. This suggests that statistical/dynamical models (and corrected consensus techniques) still have an advantage in the eastern North Pacific over dynamical models.

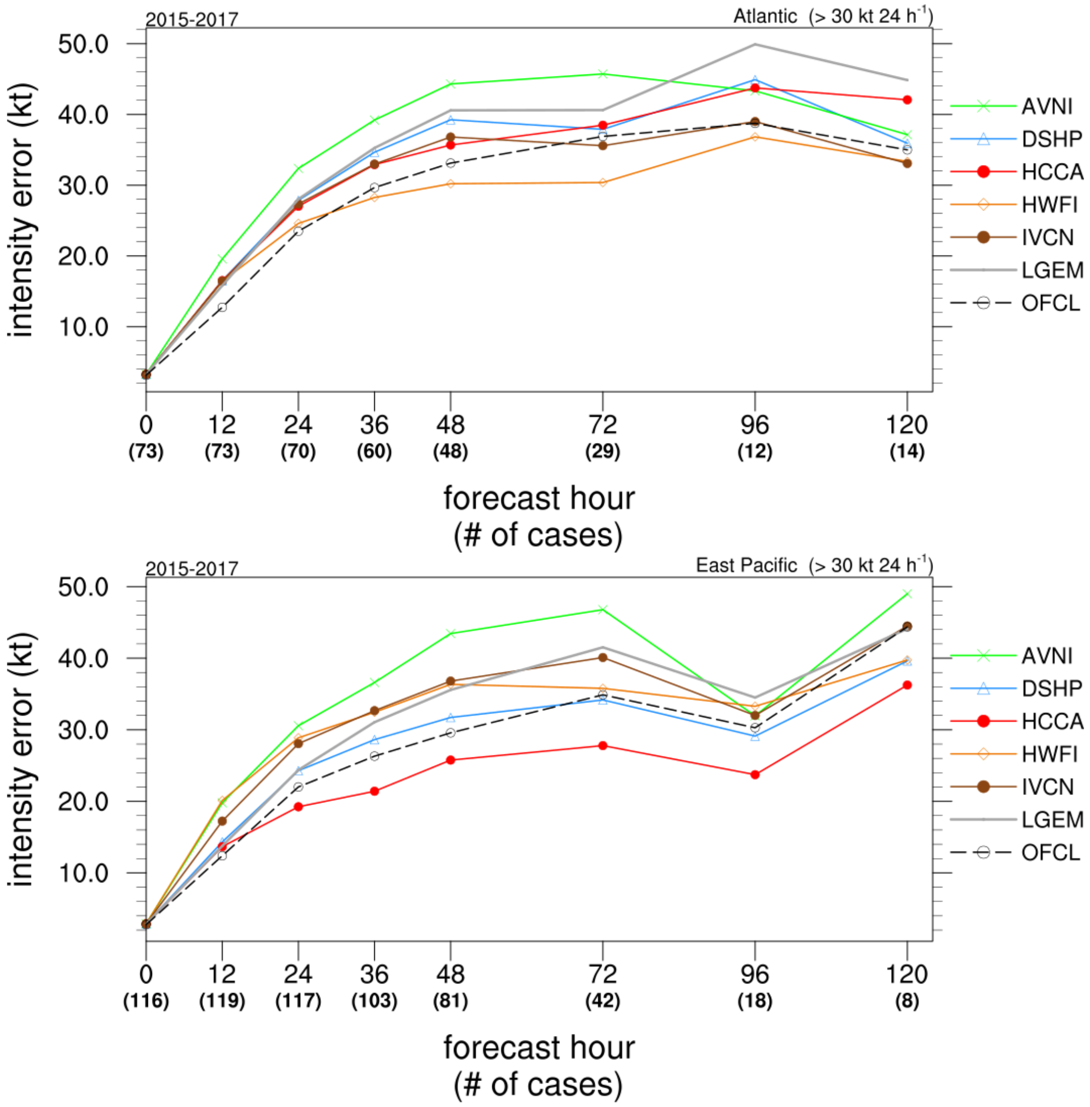
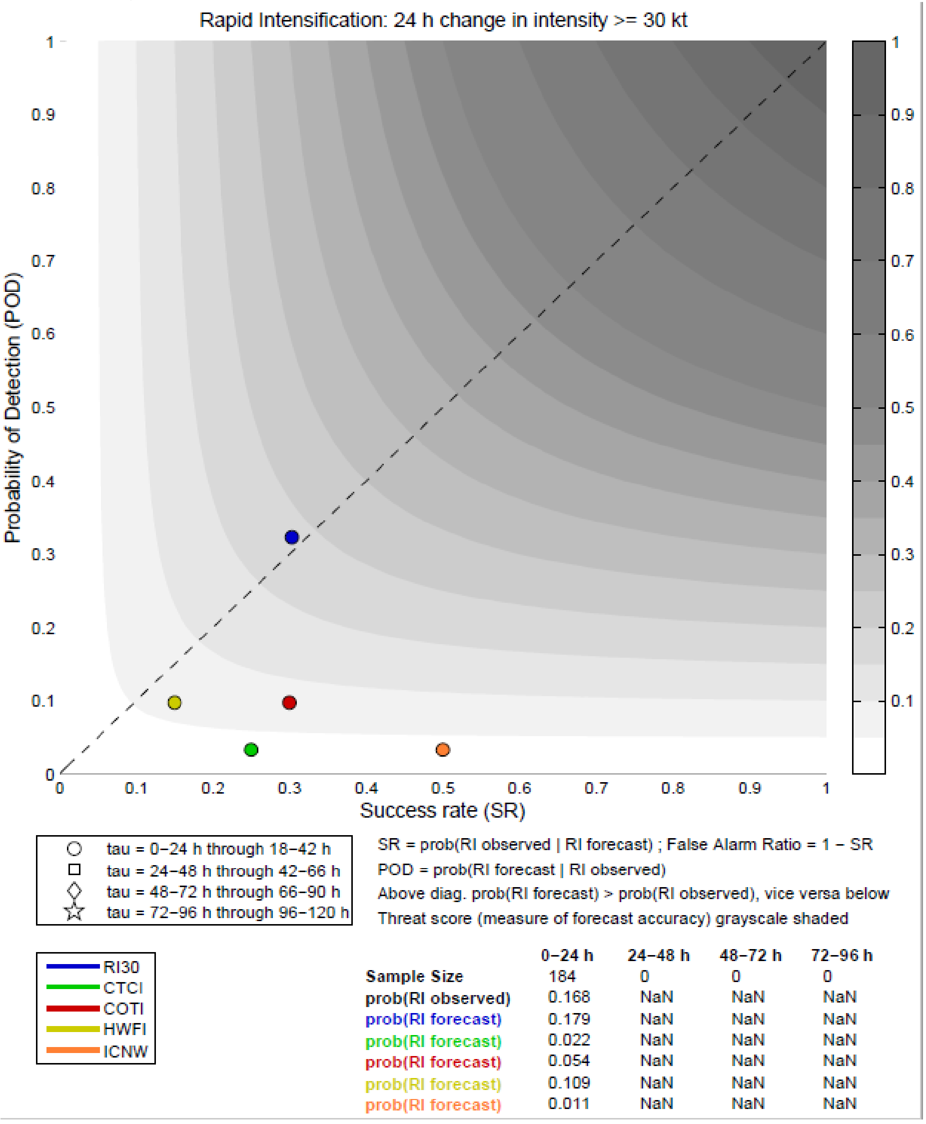


Figure 3.3.3.6: Intensity error (kt) for (a) Atlantic and (b) North-East Pacific forecasts from 2015 to 2017 that experienced at least a 30 kt increase in intensity over 24 h for GFS (AVNI), DSHP, HCCA, HWRF, IVCN, LGEM, and OFCL (NHC forecasts). Only the 24 h periods from each forecast that encompass the RI events are included in the verification.

JTWC report the following insights from using the Rapid Intensification Forecast Aid from Knaff et al. (2018) over the WNP:

I. Early presence of RI intensity aids may signal an RI event in the near future.
II. Sharp increasing trend / high values of RI probabilities above the 40% threshold may indicate greater potential for RI / ERI.
III. If used in conjunction with mesoscale models / other evidence, RI intensity aids may bolster confidence in imminent RI / ERI event.
IV. Consistent presence of RI intensity aids may indicate greater likelihood of RI event occurring. However, inconsistent behavior may indicate reduced likelihood of RI event.

The application of the RII is supported by verification statistics (figure 3.3.3.7 from Sampson and Moskaitis) demonstrating the improved probability of detection compared to HWRF, COAMPS, and ICNW.



SR = prob(RI observed | RI forecast) ; False Alarm Ratio = 1 − SR
POD = prob(RI forecast | RI observed)
Above diag. prob(RI forecast) > prob(RI observed), vice versa below
Threat score (measure of forecast accuracy) grayscale shaded

	0−24 h	24−48 h	48−72 h	72−96 h
Sample Size	184	0	0	0
prob(RI observed)	0.168	NaN	NaN	NaN
prob(RI forecast)	0.179	NaN	NaN	NaN
prob(RI forecast)	0.022	NaN	NaN	NaN
prob(RI forecast)	0.054	NaN	NaN	NaN
prob(RI forecast)	0.109	NaN	NaN	NaN
prob(RI forecast)	0.011	NaN	NaN	NaN

Figure 3.3.3.7: Verification of RI in terms of POD and SR for North-West Pacfic in 2017 demonstrating the skill of the RII over COAMPS, HWRF and ICNW guidance. Credit: Sampson and Moskaitis.

At RSMC Tokyo (JMA), TIFS is not good at predicting RI. To capture precursors to RI in real time, the formation of an eyewall ring is monitored from microwave satellite imagery and upper-level outflow is monitored from infrared satellite imagery. When eyewall formation and strong outflow are confirmed, forecast intensification rate is subjectively increased. For rapidly weakening TCs, TIFS forecast is used in combination with JMA/GSM forecast and the timing of extratropical transition.

Kotal et al. (2017) from RSMC New-Delhi, studied the evolution of thermodynamic structure during RI and RW periods of extremely severe cyclonic storm *Chapala* in October 2015 (figure 3.3.3.8). The inception of RI was associated with substantial increase of convective heating and its vertical extent in the inner core. Latent heat release produced a diabatically generated potential vorticity (PV) in vertical column. The amplification of PV in the vertical column over the inner-core region during RI reflects the amplification of the vortex as a whole. The RW coincided with the significant weakening in updraft of moisture flux consequently decrease of diabatic heating in the middle and upper troposphere and dissipation of upper and lower PV. From the operational point of view for forecasting RI in real time, it is a challenge to identify the threshold value of the inertial stability for the efficient conversion of diabatic heating and for convective bursts within the inner core. Further study is needed to identify the key characteristics of the inertial stability and the conditions that lead to the development of convective bursts necessary for RI.

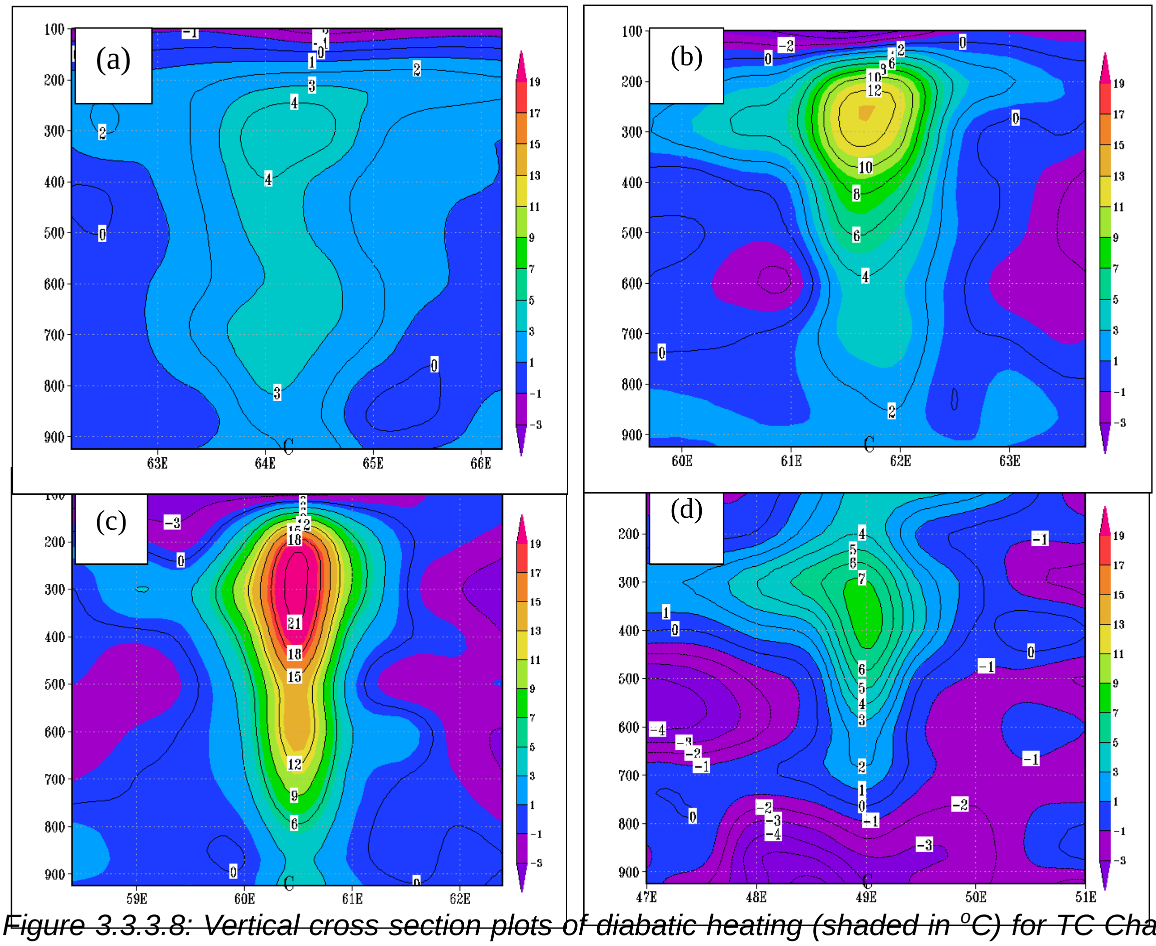


Figure 3.3.3.8: Vertical cross section plots of diabatic heating (shaded in ^{o}C) for TC Chapala (2015) for 24-h periods: (a) non-RI phase: 00 UTC 28-29 Oct., (b) RI phase-I: 00 UTC 29-30 Oct., (c) RI phase-II:12 UTC 29-30 Oct., (d) RW phase: 00 UTC 2 Nov. to 3 Nov.

At RSMC La Réunion, the most extreme events like the Very Intense Tropical Cyclone *Hellen* in March 2014 (around 150 hPa absolute variation in 48h, pending publication from Colomb & Kriat) are studied intensively, with the support of researchers from CNRM (National Centre for Meteorological Research) and LACY (Laboratory of Atmosphere and Tropical Cyclones at Réunion Island University). Those cases are also extensively used to improve the quality of the non-hydrostatic Arome-IO model. During experimental tests, this model has been able to closely predict those extreme intensity variations of *TC Hellen*. Based on these simulations and on a few radiosondes, dry air and vertical wind shear at mid-levels (400 hPa) were found to be the main cause of *Hellen*'s rapid weakening by 90 kt in 24 h. Downdrafts originating at mid-levels flushed the inflow layer with low-entropy air. This process contributed to depress near core θ_e values, which upset the updrafts in the eyewall. The upper half of the warm core was consistently ventilated by the vertical wind shear, which also contributed to the storm rapid weakening (from hydrostatic considerations).

While forecasters are increasingly conscious of identifying cases suitable for rapid intensification, there have been cases of RI that fall outside the standard scenario of developing in 'favourable environments' especially cases in moderate rather than low wind shear. *Ernie* (2017) shown in figure 3.3.3.9 and *Marcia* (2015) are two recent cases over the BoM area of responsibility, of development in moderate shear which may align with research from Ryglicki et al. (2018) in which the convectively induced upper level outflow effectively reduces the shear. In both cases the wind shear decreased during the process of RI. An as yet unrealised opportunity is to harness the collective research on intensification under moderate shear (e.g. 2018 AMS Hurricane conference session: Doyle et al. and others) to present as training for operational forecasters.

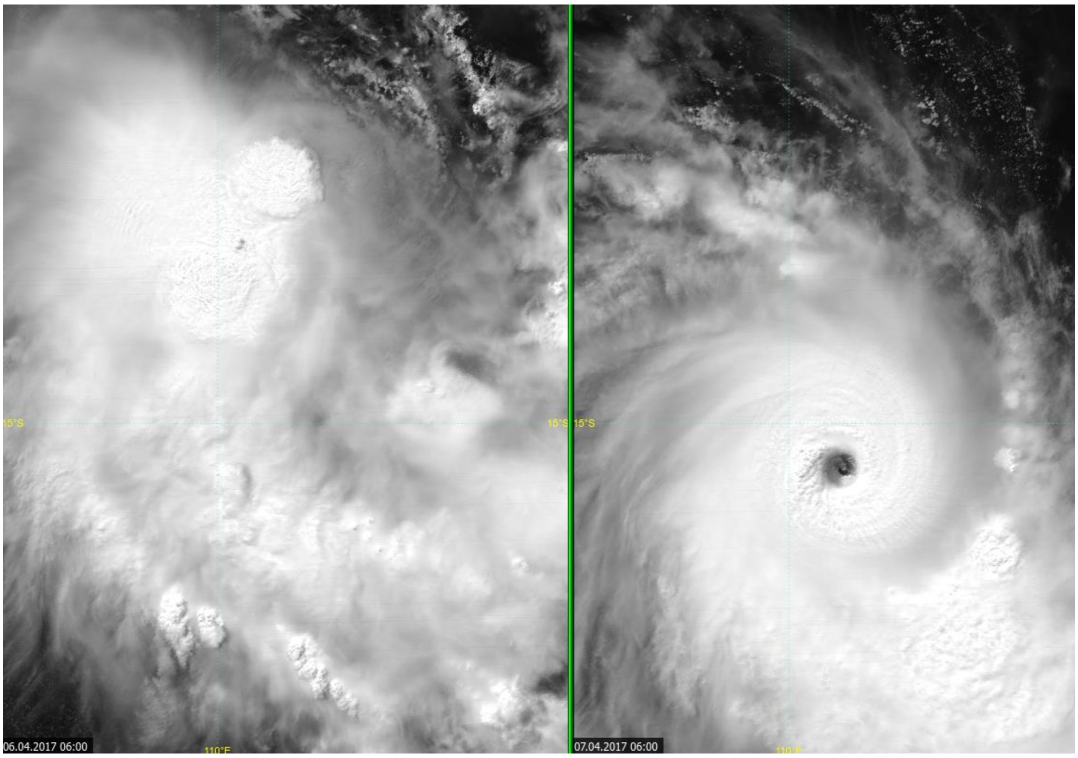


Figure 3.3.3.9: Vis images of Ernie, 24h apart at 06UTC, 6 April (left) and 7 April (right) 2017.The DT change was from 2.5 to 7.0.

Some challenges in intensity forecasting at RSMC Honolulu include the recent Hurricane Hector (EP10 - August 2018), despite a fairly accurate track forecast. Hector remained an intense cyclone over the basin for an extended time period, and displayed concentric eyewalls and eyewall replacement cycles (ERCs) not typically observed in the Central Pacific. One such ERC preceded a period of strengthening, and was well analyzed and anticipated by the recently developed objectively-based M-PERC. One of the lessons from Hector is that forecasters may be better than model guidance in anticipating short-term intensity changes, especially under certain conditions. Environmental factors appeared conducive for Hector to continue as a strong hurricane as it moved west to the south of the main Hawaiian Islands, with low environmental wind shear and SSTs between 27°C and 28°C expected. Despite what appeared to be an environment conducive for the maintenance of a strong TC, the majority of the intensity guidance indicated that Hector would gradually weaken from a peak intensity near 135 kt. The re-strengthening observed as the ERC ended was not well anticipated by the official forecast, nor the bulk of the guidance. Had the forecasters had more confidence in the timing and completion of the ERC, the official forecast more than likely would've better anticipated Hector's second peak in intensity.

3.3.4 List of recent difficult cases

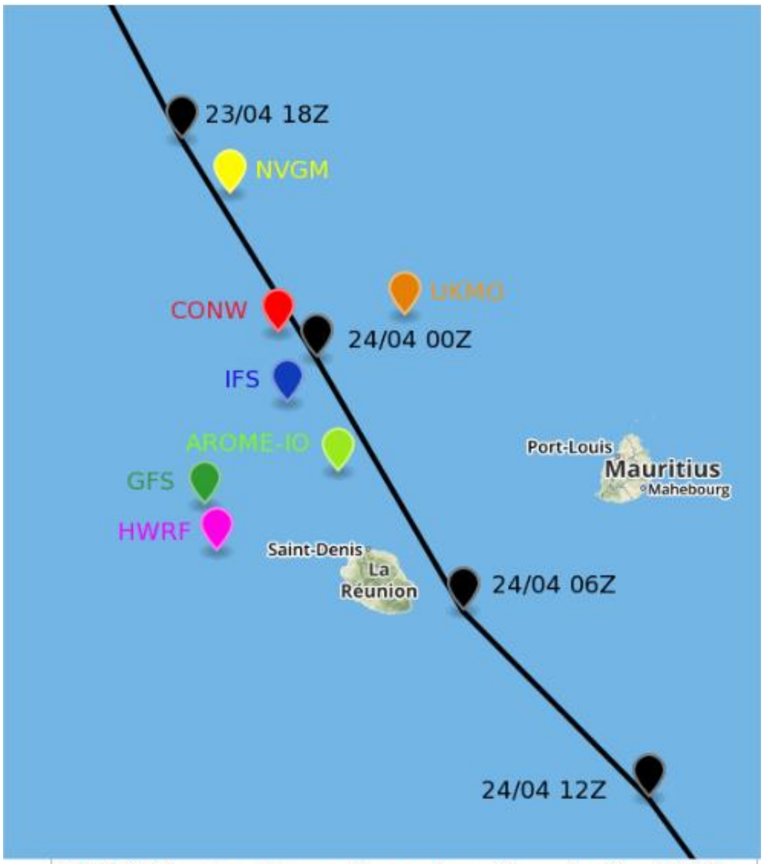
Recommendation number 2 from IWTC-VIII that was addressed to both Operational centers and Research Community stated that *operational TC centers identify their most difficult forecast cases as well as extreme events and make them available to the TC community. The TC research community is encouraged to use this list to focus on model performance and explore the predictability of these events*. A selection of difficult cases (2015-2018) are presented in Table 3.3.4.1. This should be viewed as a starting point for ongoing sharing by agencies to the TC community.

Table 3.3.4.1 Difficult intensity cases (2015-2018) For further information, please refer to the official agencies represented in this working group.

Tropical Cyclone	**Period**	**Ocean basin**	**Characteristics (RI, RW, ERC ...)**	**Observed intensity change (kt)**	**Official intensity change forecast (kt)**
PAM	6-22 March 2015	South Pacific	RI: Several 3-days forecast during the development stage of Pam strongly underestimated the rate of intensification. As a climatological development was expected from CAT 1 (AUS) / 35 kt to CAT 3 (AUS) / 70 kt, PAM actually intensified from a CAT 1 (AUS) to a Cat 5 TC (AUS) / 135 kt		
CHAPALA	28 October – 04 November 2015	Arabian Sea	RI (00 UTC of 29 Oct to 00 UTC of 30 Oct)	+55	+22
			RI (12 UTC of 29 Oct to 12 UTC of 30 Oct)	+60	+21
			RW (00 UTC of 2 Nov to 00 UTC of 3 Nov)	-35	-22
CHOI-WAN	1 – 7 October 2015	NW Pacific	Monsoon gyres and/or monsoon depressions with very slow rate of intensification despite favorable environmental conditions. The forecasts overestimated the actual intensity. Similar cases with Omais (2016) and Maliksi (2018)		
MEGH	05-10 November	Arabian Sea	RI (00 UTC of 7 Nov to 00 UTC	+40	+10

	2015		of 8 Nov)		
			RI (12 UTC of 7 Nov to 12 UTC of 8 Nov)	+30	+8
			RW (00 UTC of 9 Nov to 00 UTC of 10 Nov	-35	-20
PALI	08 – 15 January 2016	Central North Pacific (unusual location and low lat. TC)	Missed intensification: between 12 UTC of 10 Jan and 18 UTC of 12 Jan, little or no intensification anticipated but PALI's strength increased from 35 kt to 85 kt.		
			RW (00 UTC of 13 Jan to 00 UTC of 14 Jan)	-35	-5
ERNIE	5 – 10 April 2017	Australian region	RI (12 UTC of 6 Apr to 12 UTC of 7 Apr)	+75	+10
TALIM	8 –17 September 2017	NW Pacific	Suspended intensification due to unexpected strong vertical wind shear, dry air intrusion and/or the passage over cold waters. Forecast can overestimate quite significantly. Similar cases with typhoon LAN (2017).		
MARIA	16 September – 2 October 2017	North Atlantic	RI (06 UTC of 18 Sept to 06 UTC of 19 Sept)	+55 (+65/18hrs)	+25
OCKHI	29 November-06 December, 2017	Arabian Sea	RI (00 UTC of 1 Dec to 00 UTC of 2 Dec)	+30	+12
KELVIN	15 – 19 February 2018	Australian region (offshore developer)	Kelvin was expected to develop quickly in a favourable environment off the coast. When that failed to occur, forecasts eased off but the TC eventually developed rapidly in the 12h prior to landfall, and continued to show an improved satellite signature as it moves overland developing an eye.		
KENI	8 April – 11 April 2018	South Pacific	RI: At the initial stage (8th of April), the system was expected to rapidly intensify from a tropical depression to CAT 2 (AUS) / 50 kt in 24 hr. The intensification rate was expected to level-off after that. Actually, KENI almost did the first 24hr expected intensification (CAT 1 (AUS) / 45 kt) but continue on that trend to reach CAT 3 (AUS) / 85 kt during the next 24 hours.		
FAKIR	20 April – 26 April 2018	SW Indian Ocean	RI (06 UTC of 23 Apr to 06 UTC of 24 Apr)	+30	+10

			– Strong delay in timing and localization of the expected rapid weakening trend, due to unusually high short range along-track error.		
HECTOR	27 July – 13 August 2018	Central North Pacific	Missed post-ERC intensification (06 UTC of 9 Aug to 18 UTC of 10 Aug)	+25	0



23/04 00Z run guidance forecast positions for the 24/04 06Z (H+30) (colored spots), Bestrack (black spot/line)

Figure 3.3.4.2: Fakir's case in April 2018 in the South-Western Indian Ocean. The poor intensity forecast is associated with a remarkable short-range along track error due to a rarely seen forward motion at this latitude. The weakening trend was delayed and the system passed close to La Réunion just below its peak intensity.

3.3.5. Summary and conclusions

Since IWTC-8 in 2014, considerable work has continued worldwide to improve tropical cyclone intensity guidance and to understand the influences that sometimes lead to rapid intensity changes. The application of these enhancements has translated to a general improvement in intensity skill. Improved resolution, physics and data assimilation of dynamical models combined with their inclusion in statistical-dynamical consensus techniques has not only improved forecasting skill but has led to greater confidence in anticipating rapid intensity changes. However, it is difficult for forecasters to stay updated with the ongoing model upgrades and development of techniques, as well as the underlying scientific research and understanding.

Recently, the intensity skill has started to improve for some operational centers but this trend needs to be confirmed through verification and extended to all operational centers. Some centers were only able to report improvements on an anecdotal basis in the absence of specific verification evidence. Ideally verification includes the methodology suggested by WMO, 2013 which in addition to MAE and mean error (bias), includes distributions approach, PODs and FARs and verification of rapid intensification timing and magnitude.

Following a recommendation from previous IWTC, the sharing of intensity guidance initially designed for the North Atlantic or the East Pacific have benefited other operational centers. Some techniques have been tailored to local basins by some operational centers using available dynamical guidance. Emerging techniques such as DTOPS (being trialled at NHC) are now combining IFS (ECMWF) with US guidance GFS, HWRF, LGEM, and SHIPS. For this purpose, a continuing support should be maintained to operational agencies that provide useful and globally available intensity guidance like NRL, CIMSS and CIRA.

Despite the above improvements, large intensity forecast errors are still occurring. A list of selected cases over the past 4 years is presented in the report (as a recommendation of the previous IWTC) at the attention of the research community to explore the predictability of such events.

It is apparent that the considerable research efforts into understanding intensity changes as outlined in the companion sub-topics on internal influences (3.1) and external influences (3.2) may not be reaching forecasters. It is important that this research, along with advances in intensity guidance including verification results are adequately communicated to operational staff though appropriate notifications, workshops and training material.

3.3.6. Recommendations

1) Continue to bring forecasting intensity guidance (NWP models, statistical-dynamical models and statistical models) to operations and be extended globally for availability to all operational centers. For example extend HCCA globally. (Research recommendation)

2) Statistical-dynamical guidance should take advantage of the skill of the range of dynamical models including IFS (ECMWF), UK, GFS etc. and the higher resolution TC models (e.g. HCCA approach at NHC). Websites having intensity guidance should improve visualisation to all guidance not just subsets (for example the CIRA multi-

model diagnostic comparison is an excellent product but not all the reliable guidance are indicated). An independent assessment of techniques in each TC area should be done. (Research and WMO recommendation)

3) The results of upgrades to intensity guidance should be regularly communicated to operational centers. Training material (through multiple media) and workshops for forecasters should be available to ensure the appropriate application of the guidance and the underlying science (Research and WMO recommendation)

4) A continuing effort should be done by the research community to address cases of large errors documented by the operational centers. (Research and Operational recommendation)

5) All operational centers should regularly verify their intensity forecasts and adopt WMO guidelines on intensity verification. (Operational recommendation)

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Acronyms used in the report:

AMV - Atmospheric Motion Vectors

AROME - Meteo France non-hydrostatic fine scale spectral model

ARCHER – Automated Rotational Center Hurricane Retrieval

ARPEGE or ARP - Meteo France global model

BOM - Australian Bureau of Meteorology

CIMSS – Cooperative Institute for Satellite Studies at the University of Wisconsin

CIRA – Cooperative Institute for Research in the Atmosphere

CNRM - National Centre for Meteorological Research at Meteo-France

COAMPS-TC – Coupled Ocean-Atmosphere Mesoscale Prediction System-Tropical Cyclone model

CPS - Cyclone Prediction System used at IMD

DTOPS – Deterministic To Probabilistic Statistical model

ECMWF – European Center for Medium-range Weather Forecasts

EMC – Environmental Modelling Center at NCEP

ERC – Eyewall Replacement Cycle

ERI- Extreme Rapid Intensification

FSSE - Florida State Super Ensemble

FV3 - Finite-Volume Cubed-Sphere

GFDL- Geophysical Fluid Dynamics Laboratory

GFS – US Global Forecast System model

HCCA - HFIP Corrected Consensus Approach

HFIP - Hurricane Forecast Improvement Program

HMON - Hurricanes in a Multi-scale Ocean-coupled Non-hydrostatic

HWRF – Hurricane Weather Research Forecast model

ICNW - JTWC intensity consensus

IFS – Integrated Forecast Model – ECMWF global model

IMD – Indian Meteorological Department or RSMC New-Delhi

IVCN – Equally weighted variable-member consensus of intensity

JMA – Japanese Meteorological Agency or RSMC Tokyo

JMA-GSM - JMA Global Spectral Model

JMA/MSM - JMA mesoscale regional model

JTWC – Joint Typhoon Warning Center

KMA – Korean Meteorological Agency

LACy – Laboratory of Atmosphere and Tropical Cyclones (Meteo-France / CNRS / La Réunion Univ.)

LGEM – Logistic Growth Equation Model

MFR – Meteo France la Réunion or RSMC La Réunion

MOGM or UKMO or UK - Met Office Global Model

M-PERC - Microwave Probability of Eyewall Replacement Cycle

NCEP – National Center for Environmental Prediction (US)

NGGPS - Next-Generation Global Prediction System

NHC – The National Hurricane Center, Miami, FL

NOAA – National Oceanic and Atmospheric Administration (US)

NRL – Naval Research Laboratory

NWP – Numerical Weather Prediction

NWS - National Weather Service

ONR – Office of Naval Research

RI – Rapid Intensification

RIPA - Rapid Intensification Prediction Aid

RSMC – Regional Specialized Meteorological Center

RW – Rapid Weakening

SHIPS – Statistical Hurricane Intensity Prediction System

SHIPS-RII - Statistical Hurricane Intensity Prediction System-Rapid Intensification Index

SHIFOR - Statistical Hurricane Intensity FORecast (statistical baseline)

TC – Tropical cyclone

TCLP - Trajectory CLIPER

TCWC – Tropical Cyclone Warning Center

TIFS - Typhoon Intensity Forecast scheme based on SHIPS used at JMA

TRUM - KMA Typhoon Regional Unified Model

TUTT – Tropical Upper Tropospheric Trough

WAIA - Weighted Analog Intensity Atlantic

WAIP - Weighted Analog Intensity Pacific

WANI - Weighted ANalog Intensity

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