OPERATIONAL PERSPECTIVES ON TROPICAL CYCLONE INTENSITY CHANGE PART 2: FORECASTS BY OPERATIONAL AGENCIES

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ABSTRACT

This review summarizes experiences at operational centers to forecast tropical cyclone (TC) intensity change as presented to the International Workshop on Tropical Cyclones (IWTC-9) in Hawaii in 2018. Some operational forecast centers have been able to leverage advances in intensity guidance to increase forecast skill, albeit incrementally, while others have struggled to make any significant improvements. Rapid intensity changes continue to present major challenges to operational centers and individual difficult cases illustrate the forecasting challenges.

It is noteworthy that the realization of a recommendation from IWTC-8 in 2014, to adapt guidance initially developed for the North Atlantic and North-East Pacific to other basins, has led to improved forecast skill of

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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.

Keywords: tropical cyclone, intensity, change, rapid intensification

1. Introduction

Part 1 of the review into operational perspectives on tropical cyclone (TC) intensity change addressed improvements in intensity guidance following on from the International Workshop on Tropical Cyclones (IWTC) sessions (Courtney et al. 2019).

This review presents an updated picture of operational intensity forecasting and expands upon the IWTC-Landfalling Processes IV report on recent advances in research and forecasting of TC track, intensity and structure at landfall (Leroux et al. 2018b). Rapid intensification (RI) is a particular focus given the potentially catastrophic consequences when RI occurs just prior to landfall. Section 2 provides the recent progress of intensity forecasting by selected operational agencies along with current practices and guidance employed. Section 5 presents a list of difficult cases while section 6 summarizes and provides recommendations for the research and operational communities for the next 4 years.

Although it was not manageable to include all operational agencies that issue TC forecasts, a significant number of them contributed to this review, including notably all RSMCs. Thus, the following descriptions regarding intensity forecast performances and current operational procedures, are expected to be representative of the state of the art.

2. Intensity forecasting skill

Over the last 4 years and for the first time, reports of intensity forecast skill from operational agencies are split into two categories: four agencies report an improvement in intensity forecast skill, while others reported a generally stationary trend. Figure 1 show the scores of some operational agencies reporting those improvements. Although the progress has not been steady over recent years, improve-

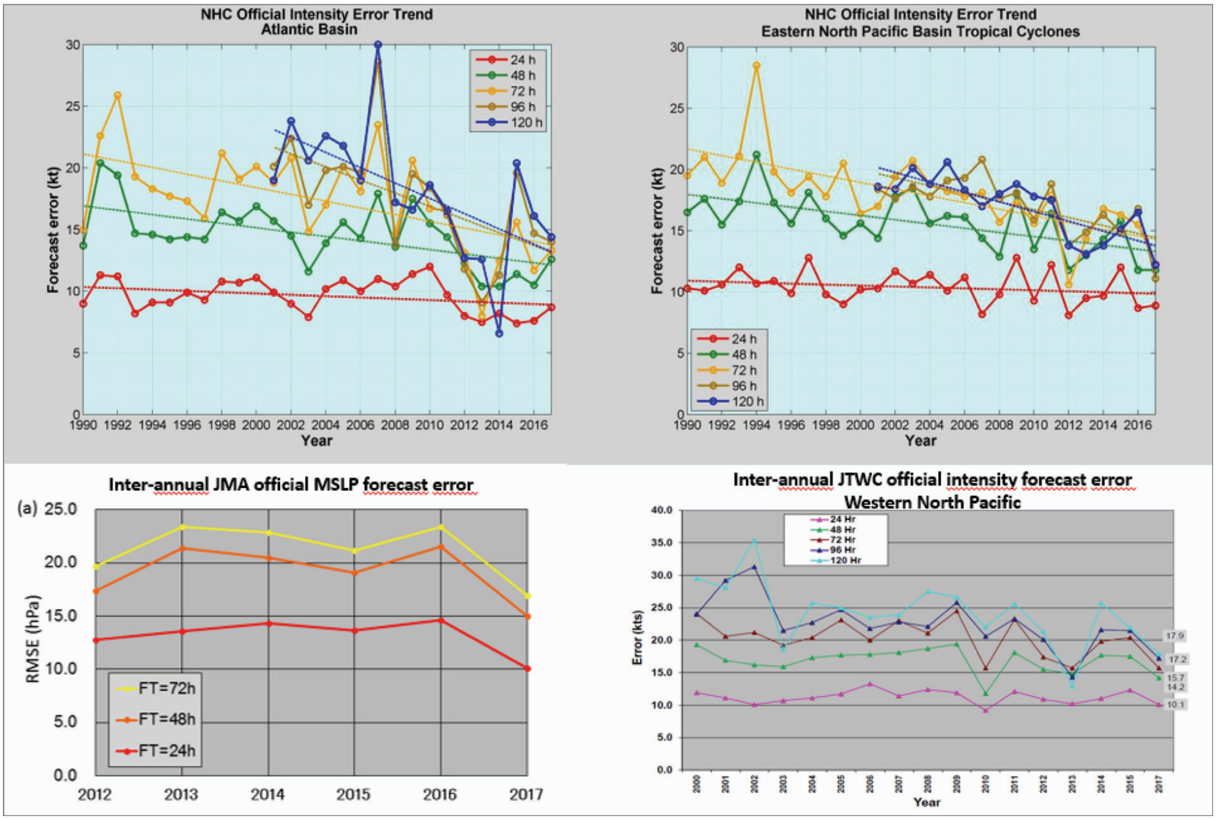


Fig. 1. Intensity verification at NHC for the North Atlantic and North-East Pacific, JMA and JTWC for the North-West Pacific. Note: JMA use central pressure as the intensity metric.

ments are remarkable at the NHC, especially for forecasts beyond 48 hours for the North Atlantic basin and to a lesser extend the North-East Pacific. For the North Atlantic, the 2011-2013 official intensity forecast skill that was around 10-15 per cent for 12 to 36-hour lead-times and near 0 per cent for longer lead times (WMO, 2014), have increased on average to between 25-45 per cent at all lead-times for the period 2014-2017. The NHC reports that until recently, the statistical/dynamical models DSHIPS and LGEM (DeMaria 2009) 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 (Tallapragada et. al. 2016), 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.

Over the North-West Pacific, JMA has developed the RSMC Tokyo version of SHIPS, known as TIFS. This has been used in trial mode since 2016 and is scheduled to be fully operational in 2019 extending to 5 days. The trial use of TIFS has greatly improved the accuracy of RSMC Tokyo intensity forecasts. Root Mean Square Error (RMSE) of the RSMC Tokyo official intensity forecast (defined in terms of the central pressure Pmin) decreased greatly in 2017 (figure 1) and skill has increased since 2016 passing from below 10 per cent to 15-20 per cent for 24, 48 and 72-hour lead-times.

Since 2000 JTWC reports a gradual improvement in intensity forecasts at 48 and 72 hours, but 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.

Other agencies report intensity forecast scores that shows no or little significant improvement in the past several years, with the example of the India Meteorological Department (IMD or RSMC New-Delhi) and Meteo-France La Réunion in figure 2.

The evidence also highlights differences in verification approaches and inadequacies of using simple MAE as a skill metric. There is a need for a more extensive and consistent verification effort at all operational centers in line with WMO (2013) guidelines. In addition to MAE, future metrics should include mean error (bias), examination of error distributions, probability of detection and false alarm rates associated with large changes in intensity and errors caused by timing.

3. 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, forecast track and the inherent uncertainty. While the track and intensity are interdependent, the intensity forecast is strongly connected with the track forecast especially for the timing of landfall and becomes most apparent at longer lead times. 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, sea surface temperatures and ocean heat content, low level inflow and proximity to land factors), the analysed initial intensity and trend over the past 24 hours. Many agencies noted the importance to identify inner core structural changes seen on satellite imagery such as annular structure (using enhanced infrared imagery), eyewall replacement cycles (ERC), using microwave imagery and microwave based probability of ERC (M-PERC) guidance, and identify a cyan ring structure in 37 GHz color composite microwave imagery (Kieper and Jiang 2012), which may signal an imminent RI phase.

A combination of synoptic assessment and persistence is usually weighted most heavily for the short term (to +24 h), after which subjective evaluation of the changes to the large-scale environment as indicated by NWP is combined with the range of objective NWP intensity guidance.

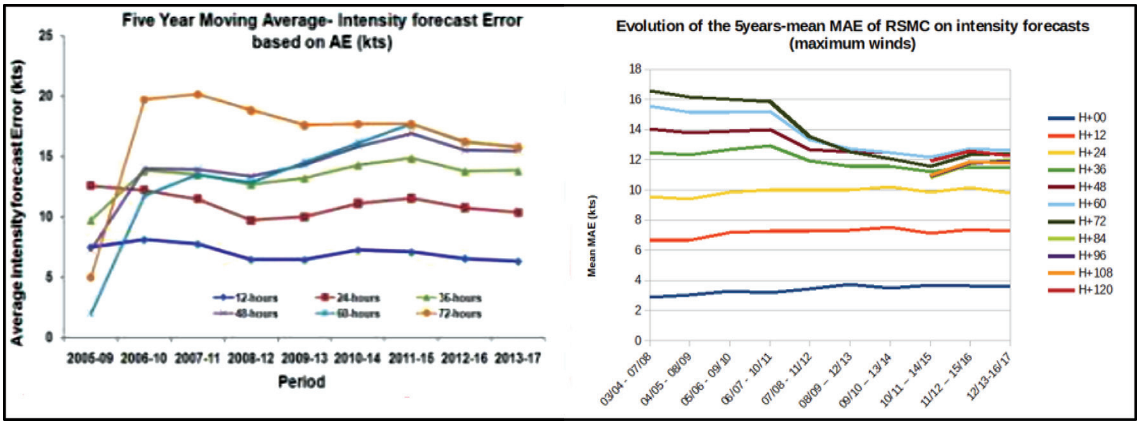


FIG. 2. Intensity verification at IMD Arabian Sea and Bay of Bengal (left), and Meteo France South-West Indian Ocean (right).

Consistency between dynamical models, as well as run-to-run consistency are important considerations with bias given to the better performing and higher resolution models. Consideration is also given to forecast continuity to avoid large changes from one forecast cycle to the next. Key differences between agencies lie in the preferred use models, reflecting a bias to regionally developed and available models and techniques. A summary of specific procedures at each agency is provided below.

a) RSMC Tokyo, JMA

RSMC Tokyo forecasters use TIFS, SHIFOR, JMA-GSM, JMA-MSM (JMA mesoscale regional model), HWRF, and cyclone phase space (Hart 2003) based on JMA-GSM. 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 may be adjusted upward or downward on the basis of the difference between the model and the analysed intensity. For the weakening or landfall stage, forecast intensity is modified so as to gradually approach JMA-GSM forecast intensity.

b) The Korea Meteorological Administration (KMA)

KMA use the STIPS based on statistical-dynamic model and dynamical model results of HWRF and TRUM (KMA Typhoon Regional Unified Model) (Kim et al. 2018) in addition to an assessment of oceanic and atmospheric influences affecting intensity. The decision whether a decaying TC transforms into an extratropical cyclone or not is mainly based on cyclone phase space diagram (Hart 2003), and the KMA operational extratropical cyclone transition manual (KMA, 2007).

c) The Bureau of Meteorology (BoM)

An initial intensity forecast estimate is typically considered in a Dvorak T-no. framework. For example, D for 0-24 h, D+ 24-48 h, D-/S 48-72 h, W+ 72-96 h etc., where D represents an increase of 1.0 T-no. per day. The Bureau follows research by US Naval Research Laboratory by using the latest version of SHIPS, 'ICNW' along with the Rapid Intensification Prediction Aid (RIPA, Knaff et al. 2018), augmented by other models not included in this guidance such as IFS and UKMO. Consistency between dynamical models, as well as run-to-run consistency 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 RI. BoM also consider trends in the EC-EPS and UKMO ensemble intensity output. While model trends have traditionally been given greater consideration than the absolute values, it is recognized that this is changing as model resolution increases.

Forecasts of RI and rapid weakening (RW) are typically confined to landfall scenarios (weakening) and for the first 24-48 hours as it is difficult to pick the timing of such changes.

Forecasters appreciate tools that make it easy to visualize and interpret 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). Web displays such as the CIRA multi-model display (figure 4) are also well used as it includes displays of wind shear, SST and RH, but doesn't have the full range of guidance.

d) RSMC New-Delhi (IMD)

IMD uses guidance from various global and regional deterministic models including IMD-GFS, NCMRWF(India)-GFS, IFS, UKMO, JMA, ARP (Meteo France global model), 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, EC-EPS etc. In addition, intensity outputs from the CPS based on the SCIP dynamical-statistical model are used routinely at IMD (Kotal et al. 2014).

e) RSMC La Réunion (Meteo-France)

Among the usual models, IFS and GFS deterministic data are the most popular but EC-EPS, GEFS, UKMO, ARP and aids received from JTWC (NVGM, HWRF, GFDN, CONW) are also frequently considered. With the progressive increase in resolution of numerical models, some raw parameters like maximum winds, and central pressure are also examined more closely by the forecasters. These outputs are very valuable for the post-tropical phase and to a lesser extent during cyclogenesis.

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 the 2017/2018 season – probably owing to the inclusion of the ocean coupling – whereas some RI events were correctly forecast. These promising results, along with expected improvement of the model in the coming years, should lead to increased use of this model for short-term intensity forecasts.

f) The Joint Typhoon Warning Center (JTWC)

Forecasters generally hedge close to or above HWRF

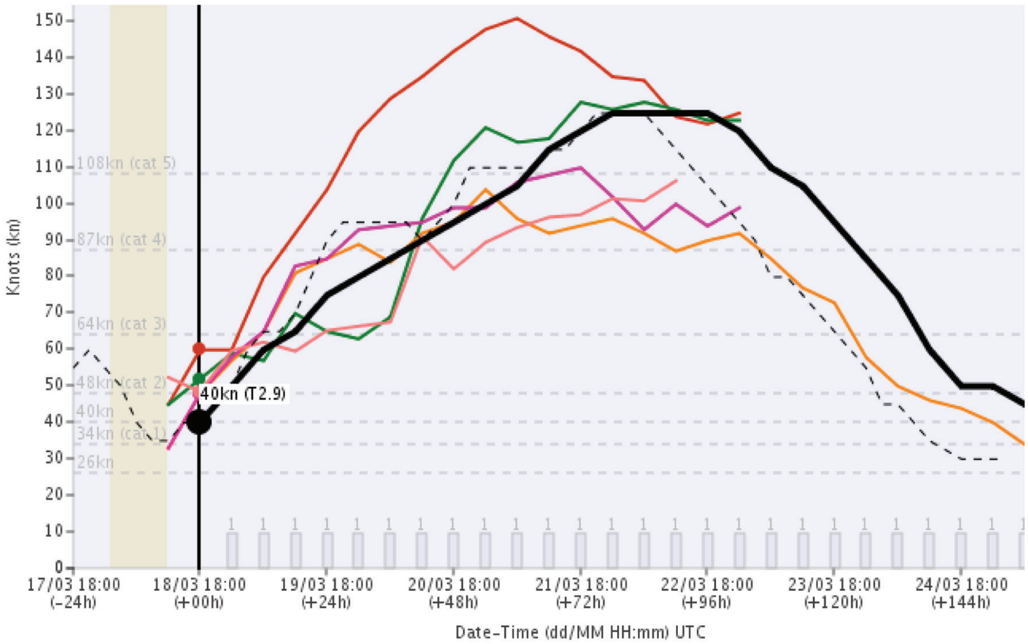


FIG. 3. BoM's intensity tool for Marcus (2018) showing the official forecast (black) against different guidance (coloured) and the previously issued forecast (dashed line). This tool improves the forecast generation process and onscreen editing and includes the standard inland decay rate.

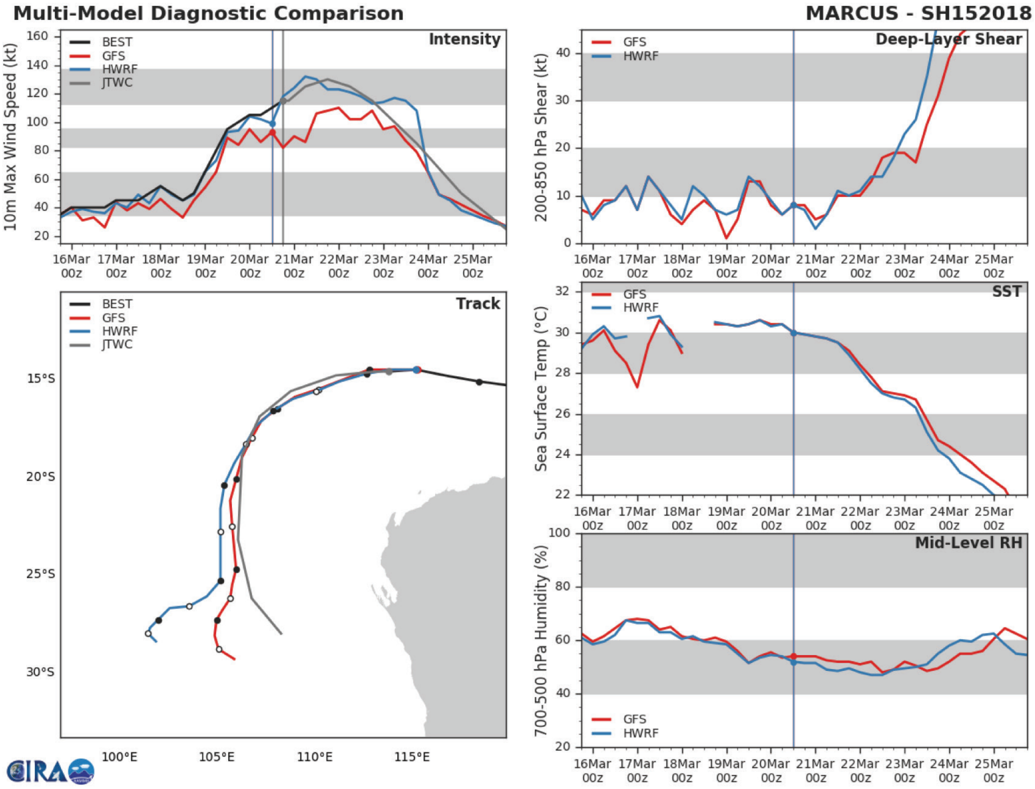


FIG. 4. CIRA's multi-model display showing intensity guidance with track, shear, SST and RH information provides clear and useful presentation of critical inputs.

guidance, recognized as the most reliable intensity change model; and may also hedge above COTC / ICNW when the range of guidance is consistent. Forecasters subjectively leverage Dvorak's (Velden 2006) climatological intensification model which shows the intensification rate may exceed 1.5 T-numbers per day in a very favorable environment, while in an unfavorable environment, it may be well below one T-number per day. Forecasters follow guidelines for particular synoptic-scale influences especially for upper-level patterns. For example, when the upper-level outflow channel is directed equatorward the rate of intensification is greater than when it is directed poleward. Scenarios of more than one outflow channel are a key factor in many RI cases. The Tropical Upper Tropospheric Trough (TUTT) is considered a major contributor to intensity change in the North-West Pacific. Both the placement and proximity of the TUTT to the TC will determine the effect - positive or negative - that the TUTT will have on the intensity change of the TC. Forecasters note that while RI may occur wherever and whenever conditions are conducive 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 US Central Pacific Hurricane Center (CPHC) and National Hurricane Center (NHC)

A large percentage of Central Pacific TCs enter the basin from the east after reaching their peak intensity in the North-East Pacific and are in a weakening phase, largely due to strong environmental vertical wind shear and limited ocean heat content.

The SHIPS/LGEM guidance including the probability of RI over the first 48 hours of the forecast is used. Regional (HWRF/HMON) and global (GFS, IFS, COAMPS-TC, UKMO) dynamical model guidance is operationally referenced as well as the ICON/IVCN consensus guidance representing a blend of the SHIPS/LGEM/HWRF/COAMPS-TC guidance. The Florida State Super Ensemble is a corrected-consensus utilizing dynamical models and the previous official forecast. These forecast techniques have been some of the best performers in anticipating intensity change.

The NHC also use a more sophisticated consensus like the HCCA, which along with HWRF, is considered to be the most reliable for the North Atlantic as shown in figure 5 below.

Intensity forecasts at CPHC tend to be conservative, as extreme intensity changes are rarely observed in the basin, and they are almost never forecast.

h) The Fiji Meteorological Service (FMS)

FMS import the range of model guidance (IFS, GFS, UKMO, JTWC, GFDL, JMA-GSM) from JTWC website into the TC Module software package. The model guidance is used together with the Dvorak rules to determine intensity changes. Small systems which intensify rapidly are recognized as the most difficult to forecast.

4. Rapid intensity changes

The main challenge in terms of intensity forecasting remains the prediction of rapid intensity changes. RI has been generally defined as a change of 30 kt per day as a result of Kaplan and DeMaria (2003) analysis of the 95th percentile of all 24-h intensity changes in the Atlantic. Leroux et al. (2018a) established thresholds of RI and RW appropriate for the South-West Indian Ocean calculated at the 95th percentile rate of change using a 17-year climatology based on best-track data. The standard 30 kt/day threshold was found to also apply in the South-West Indian Ocean for RI, while for RW a decrease was 27 kt/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 also be defined as at least 30 hPa decrease over a 24-h period for North-West Pacific TCs from RSMC Tokyo best track data.

The JTWC reports that in the North-West Pacific for the period 1970-2016, there were a total of 1387 TCs, of which 37.6 per cent underwent RI and 11.7 per cent underwent extreme RI (50 kt increase in 24 h). Leroux et al. (2018a), report that over the South-West Indian Ocean, and for the 1999-2016 period, 43 per cent of all tropical systems and all very intense TCs (intensity 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 North Atlantic, *Marcus* (2018) over the South-East Indian Ocean and *Walaka* (2018) in the Central North Pacific. In all three cases, an agreement between various skillful RI guidance, provided forecasters with confidence to predict RI.

Some agencies are using specific guidance that target the likelihood of RI, including statistical, dynamical-statistical and dynamical guidance as summarized in Courtney et al. (2019). Selected operational agencies of the working group have reported insights they have gained in order to deal with similar cases in the future.

NHC forecasters consider the RI index and DTOPS for RI, which are proving to be quite useful in operations. For Atlantic forecasts where RI occurred (figure 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, DSHIPS and LGEM, would have typically performed better than the dynamical models several years ago, the high-resolution forecasts of HWRF (HWFI) has become the best intensity guidance for systems that undergo RI. HCCA and IVCN perform slightly better than the purely statistical models, but lag behind the performance of

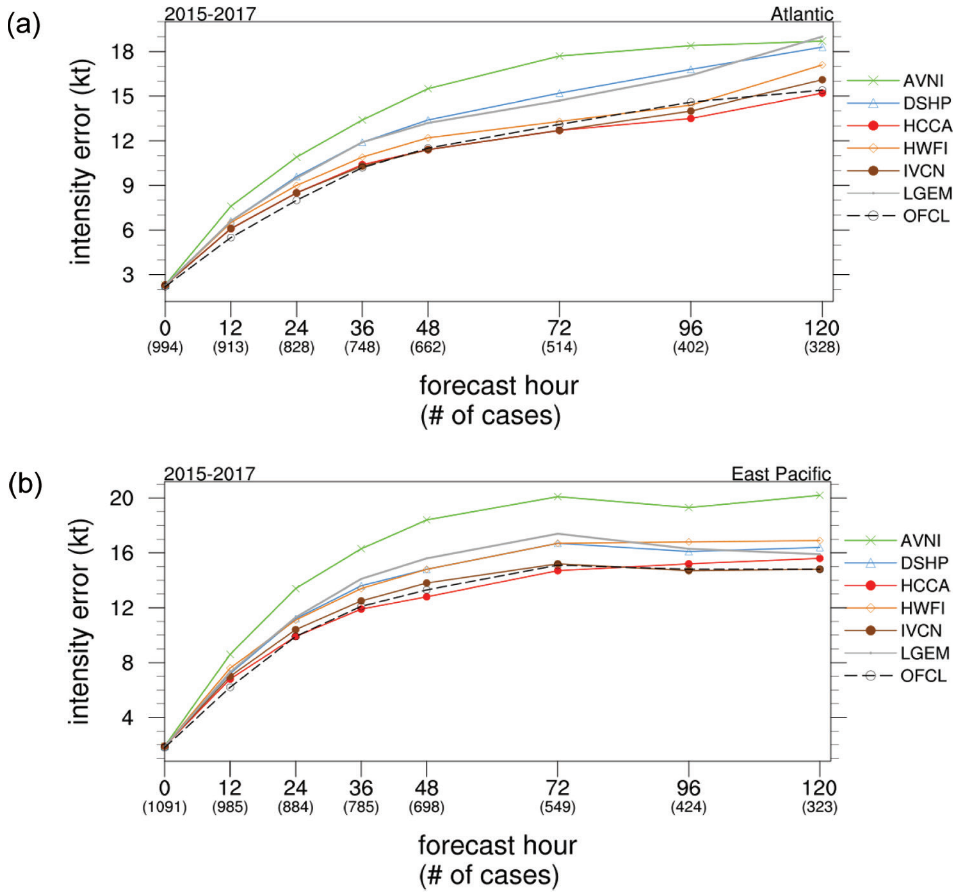


FIG. 5. Intensity error for (a) Atlantic and (b) North-East Pacific forecasts from 2015 to 2017 for GFS (AVNI), DSHIPS (DSHP), HCCA, HWRF, IVCN, LGEM, and OFCL (NHC forecasts).

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 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, DSHIPS and LGEM, perform better for RI forecasts in the North-East Pacific compared to the North Atlantic. This suggests that statistical/dynamical models (and corrected consensus techniques) still have an advantage in the North-East Pacific over dynamical models alone.

JTWC reports the following insights from using the Rapid Intensification Prediction Aid (RIPA, Knaff et al. 2018) over the North-West Pacific:

i. Early presence of RI intensity aids may signal an RI event in the near future.
ii. Sharp increasing trend or high values of RI probabilities above the 40 per cent threshold may indicate greater potential for RI.
iii. If used in conjunction with mesoscale models and other evidence, RI intensity aids may bolster confidence in imminent RI or Extreme Rapid Intensification (ERI i.e. increase of V_m greater or equal to 50 kt).
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 RIPA is supported by verification statistics (figure 7) demonstrating the improved probability of detection compared to HWRF, COAMPS-TC, and ICNW.

At RSMC Tokyo, 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 imag-

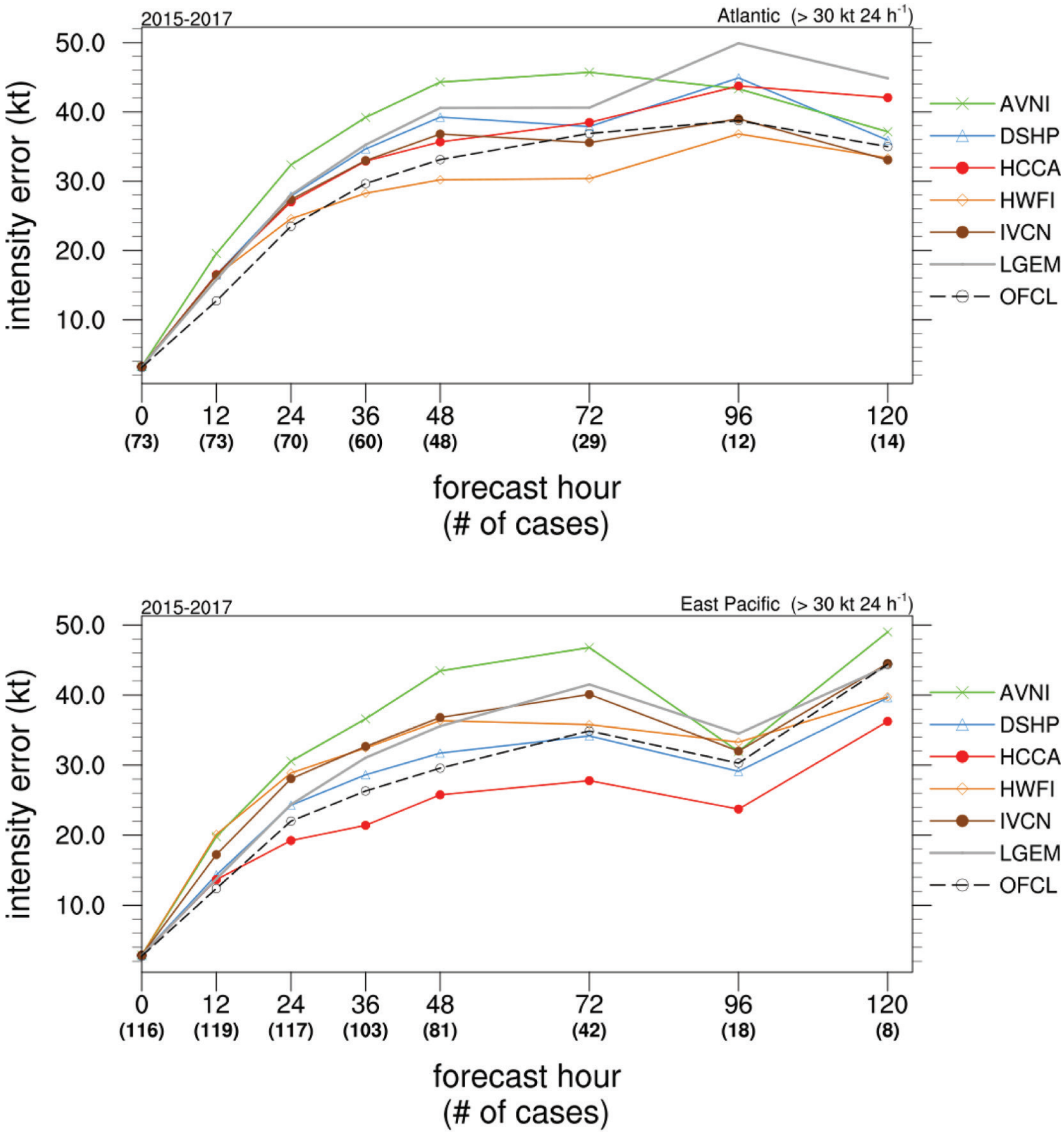
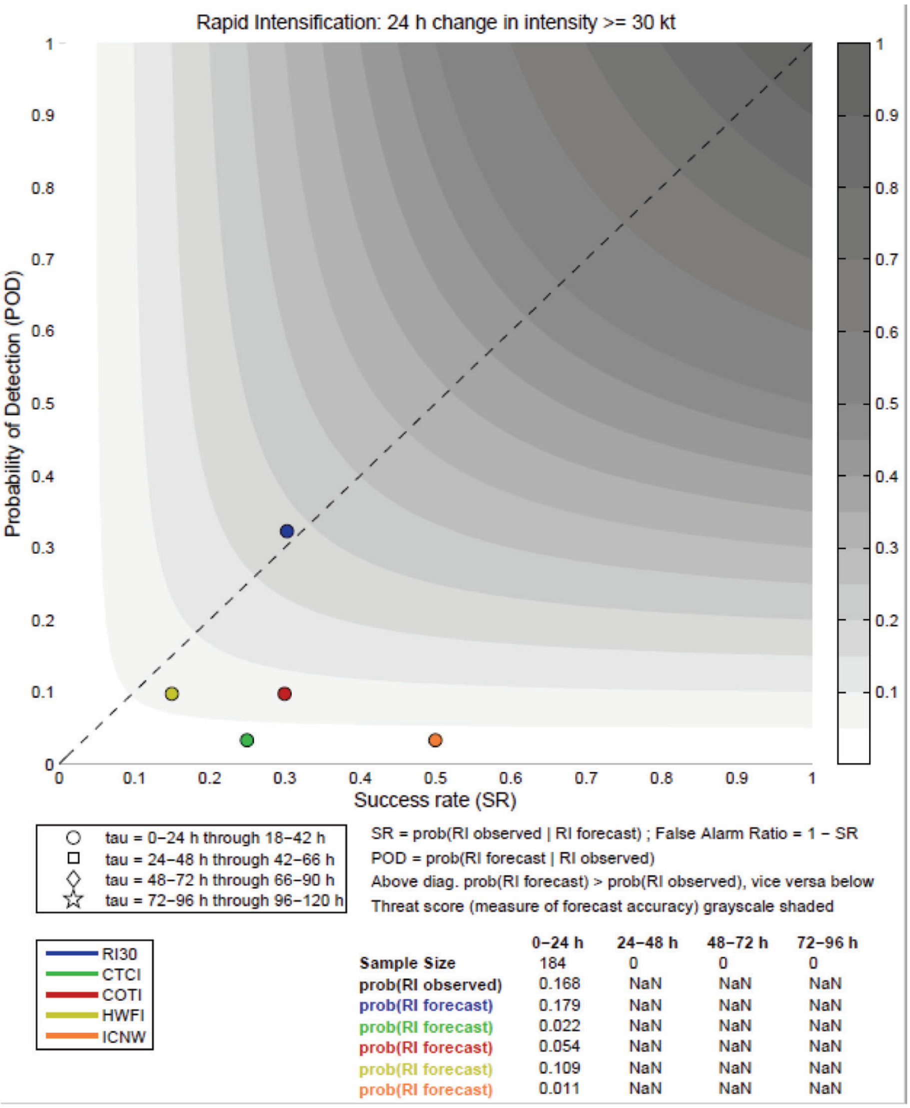


FIG. 6. Intensity error (kt) for (a) Atlantic and (b) North-East Pacific forecasts from 2015 to 2017 that experienced at least a 30 kt increase in intensity over 24 h for GFS (AVNI), DSHIPS (DSHP), HCCA, HWRF, IVCN, LGEM, and OFCL (NHC forecasts). Only the 24-h periods from each forecast that encompass the RI events are included in the verification.

ery 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 is used in combination with the JMA-GSM forecast and 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 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 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 forecast convective bursts within the inner core. Further study is needed to identify



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

FIG. 7. Verification of RI in terms of POD and SR for North-West Pacific in 2017 demonstrating the skill of the RIPA (RI30) over COAMPS-TC, HWRF and ICNW guidance. Credit: Jon Moskaitis.

the key characteristics of the inertial stability and the conditions that lead to the development of convective bursts necessary for RI.

At RSMC La Réunion, the most extreme events like the Very Intense TC *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 these 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).

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

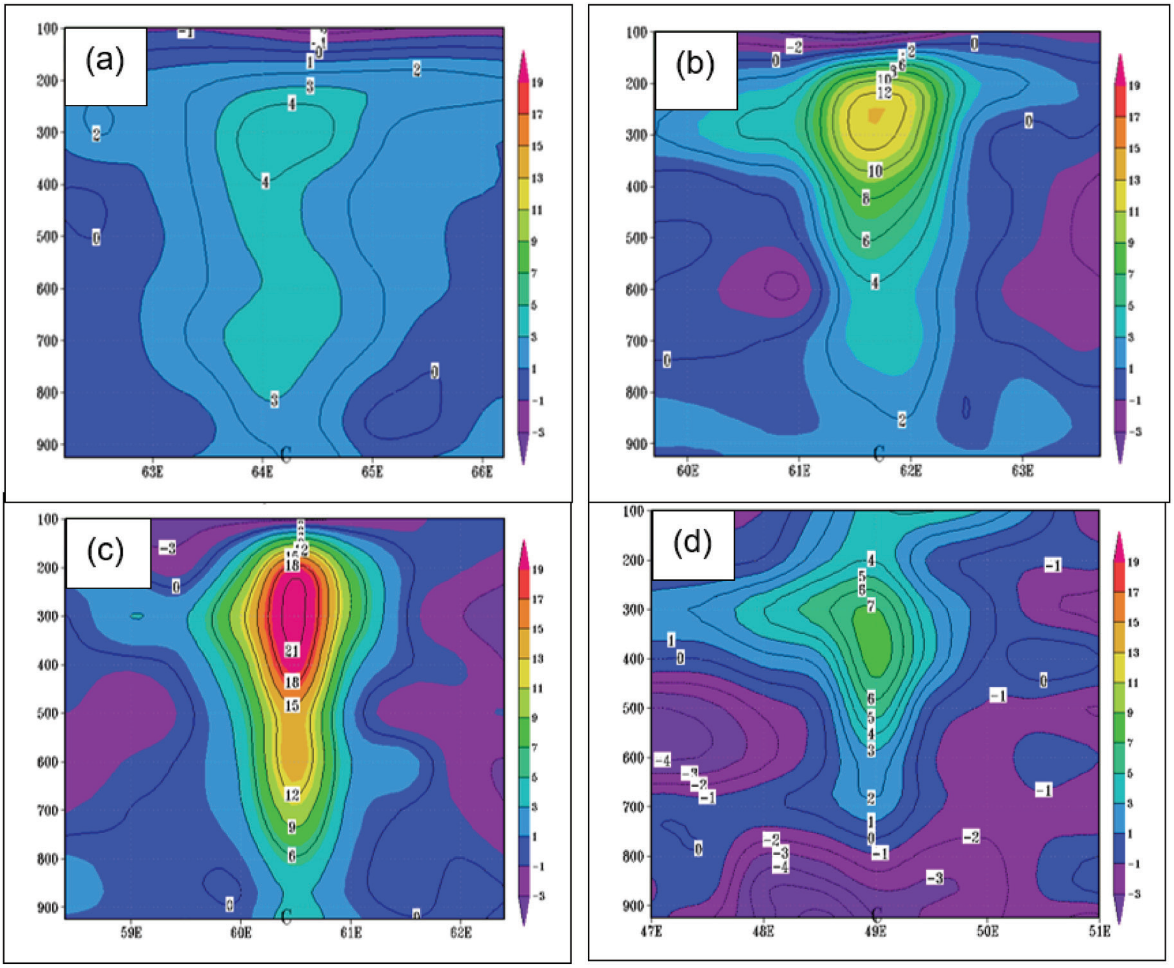


FIG. 8. Vertical cross section plots of diabatic heating (shaded in ºC) for TC Chapala (2015) for 24-h periods: (a) non-RI phase: 00 UTC 28-29 Oct., (b) RI phase-I: 00 UTC 29-30 Oct., (c) RI phase-II:12 UTC 29-30 Oct., (d) RW phase: 00 UTC 2 Nov. to 3 Nov.

time period and displayed concentric eyewalls and 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 to the west, south of the main Hawaiian Islands, with low environmental wind shear and SSTs between 27°C and 28°C. 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.

While forecasters are increasingly vigilant to assess situations favouring RI, 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 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, wind shear decreased during the process of RI. There is currently an unrealised opportunity to harness the collective research on intensification under moderate shear (e.g. 2018 AMS Hurricane conference session: Doyle et al. 2018, and others) to present as training

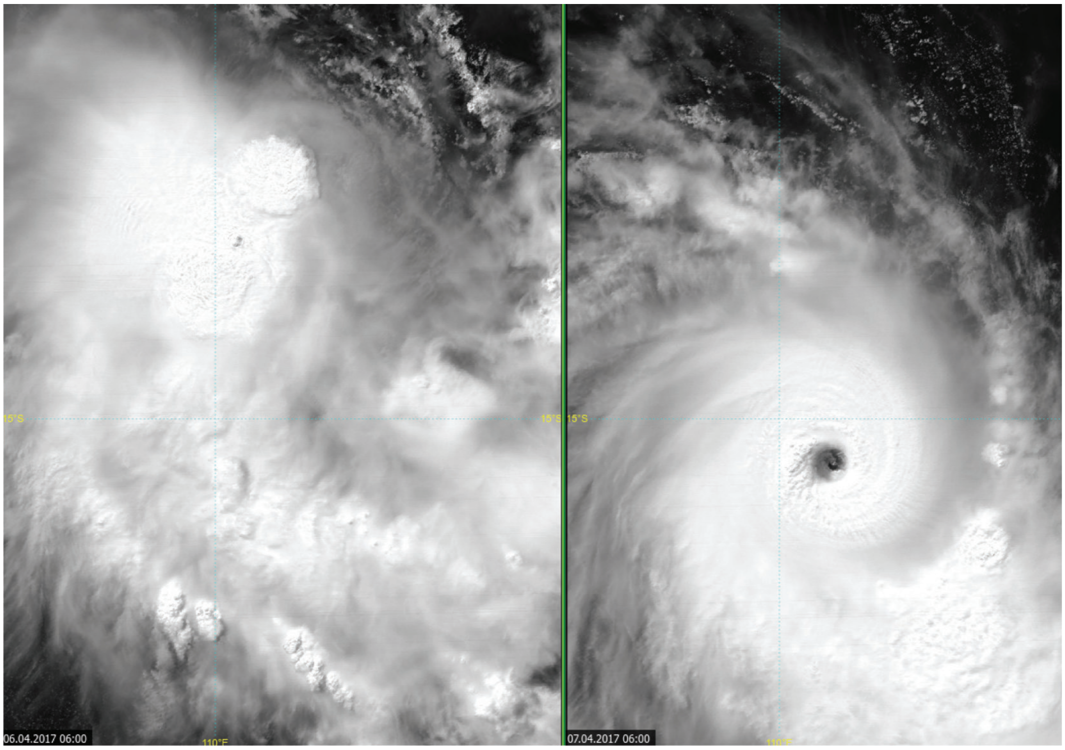


Fig. 9. Vis images of Ernie, 24 h apart at 06 UTC, 6 April (left) and 7 April (right) 2017.The DT change was from 2.5 to 7.0.

for operational forecasters.

5. Recent difficult cases

Recommendation number 2 from IWTC-8 (WMO, 2014) that was addressed to both operational centers and the 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 1. A website listing difficult and extreme TC cases has been created on the WMO TC forecaster website (WMO, 2019) for ongoing sharing by agencies to the TC community.

6. Summary, conclusions and recommendations

Forecasting intensity skill has shown improvements 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 RI timing and magnitude.

Overall forecasters report greater confidence in the application of improved intensity guidance, summarized in Part 1 of this review, which has extended to anticipating rapid intensity changes. Despite the above improvements, large intensity forecast errors are still occurring. A list of selected cases that occurred during the past 4 years is presented (as a recommendation of IWTC-8) which should be continued and shared, so the research community can explore the predictability of such events.

Furthermore, there are two recommendations:

1) The research community should continue to address cases of large errors documented by the operational centers on a register that is kept up to date (Research and Operational recommendation).

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

Acknowledgements

Preparation of this report for IWTC-9 greatly benefited from discussions at the workshop. The mix of formal and informal discussions makes the IWTC a great initiative in the sharing of ideas and activities. The co-authorship order

Table 1. Difficult intensity cases (2015-2018).

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-day forecasts during the development stage of Pam strongly underestimated the rate of intensification. A climatological development was expected from 35 kt to 70 kt, but Pam actually intensified from a 35 kt to 135 kt.		
Chapala	28 Oct. – 04 Nov. 2015	Arabian Sea	RI (00 UTC 29 Oct. to 00 UTC 30 Oct)	+55	+22
			RI (12 UTC 29 Oct. to 12 UTC 30 Oct)	+60	+21
			RW (00 UTC 2 Nov. to 00 UTC 3 Nov.)	-35	-22
Choi-Wan	1 – 7 Oct. 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 Nov. 2015	Arabian Sea	RI (00 UTC 7 Nov. to 00 UTC 8 Nov.)	+40	+10
			RI (12 UTC 7 Nov. to 12 UTC 8 Nov.)	+30	+8
			RW (00 UTC 9 Nov. to 00 UTC 10 Nov.)	-35	-20
Pali	08 – 15 Jan. 2016	Central North Pacific (unusual location and low lat. TC)	Missed intensification: between 12 UTC 10 Jan. and 18 UTC 12 Jan;, little or no intensification anticipated but Pali intensified from 35 to 85 kt.		
			RW (00 UTC 13 Jan. to 00 UTC 14 Jan.)	-35	-5
Ernie	5 – 10 April 2017	South-East Indian Ocean	RI (12 UTC 6 April to 12 UTC 7 April)	+75	+10
Talim	8 – 17 Sept. 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 Sept. – 2 Oct. 2017	North Atlantic	RI (06 UTC 18 Sept. to 06 UTC 19 Sept.)	+55 (65/18 h)	+25
Ockhi	29 Nov. – 6 Dec. 2017	Arabian Sea	RI (00 UTC 1 Dec. to 00 UTC 2 Dec.)	+30	+12
Kelvin	15 – 19 Feb. 2018	South-East Indian Ocean	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 moved overland developing an eye.		
Keni	8 – 11 April 2018	South Pacific	RI: At the initial stage (8 April), the system was expected to rapidly intensify from a tropical depression to 50 kt in 24 h. The intensification rate was expected to level-off after that. Actually, Keni almost did the first 24 h expected intensification to 45 kt but continued developing to 85 kt during the next 24 h.		
Fakir	20 – 26 April 2018	SW Indian Ocean	RI (06 UTC 23 April to 06 UTC 24 April). Delay in expected rapid weakening due to along-track error.	+30	+10
Hector	27 July – 13 Aug. 2018	Central North Pacific	Missed post-ERC intensification (06 UTC 9 Aug. to 18 UTC 10 Aug.)	+25	0

after the first two authors is determined by the surnames and not by the degree of author contribution The views, opinions, and findings contained in this report are those of the authors and should not be construed as an official National Oceanic and Atmospheric Administration or U.S. Government position, policy, or decision.

Acronyms used in the report:

AROME – Applications de la Recherche à l'Opérationnel à Méso-Echelle
BoM – Australian Bureau of Meteorology
CIRA – Cooperative Institute for Research in the Atmosphere (Colorado State University)
COAMPS-TC – Coupled Ocean/Atmosphere Mesoscale Prediction System – TCs
CPS – Cyclone Prediction System
D-SHIPS – SHIPS model adjusted for decay over land
DTOPS – Deterministic to Probabilistic Statistical Model
EC-EPS – IFS ensemble prediction system
ECMWF – European Center for Medium Range Weather Forecasts
ERC – Eyewall replacement cycle
GFDL – Geophysical Fluid Dynamics Laboratory
GFS – Global Forecast System
HCCA – Hurricane Forecast Improvement Program (HFIP) Corrected Consensus Approach
HWRF – Hurricane Weather Research and Forecasting
ICNW – Intensity consensus used at JTWC
IFS – Integrated Forecast System (ECMWF)
IMD – India Meteorological Department
IWTC – International Workshop on Tropical Cyclones
JMA – Japan Meteorological Agency
JMA-GSM – JMA global spectral model
JMA-MSM – JMA mesoscale regional mode,
KMA – Korea Meteorological Administration
LGEM – Logistic Growth Equation Model
M-PERC Microwave-based Probability of Eyewall Replacement Cycle
NHC – National Hurricane Center
NWP – Numerical Weather Prediction
RI – Rapid intensification
RIPA – Rapid intensification prediction aid
RSMC – Regional Specialized Meteorological Center
SCIP – Statistical Cyclone Intensity Prediction
SHIFOR – Statistical Hurricane Intensity Forecast model
SHIPS – Statistical Hurricane Intensity Prediction System
STIPS – Statistical Typhoon Intensity Forecast System
SST – Sea surface temperature
TC – Tropical cyclone
TIFS – Typhoon Intensity Forecasting Scheme (JMA)
TRUM – Typhoon Regional Unified Model
TUTT – Tropical Upper Tropospheric Trough
UKMO – United Kingdom Meteorological Office
WMO – World Meteorological Organization

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