OPERATIONAL PERSPECTIVES ON TROPICAL CYCLONE INTENSITY CHANGE PART 1: RECENT ADVANCES IN INTENSITY GUIDANCE

JOSEPH B. COURTNEY
Bureau of Meteorology, Australia

SÉBASTIEN LANGLADE
Meteo-France, La Réunion, France

CHARLES R. SAMPSON
Naval Research Laboratory (NRL), USA

JOHN A. KNAFF
NOAA/Center for Satellite Applications and Research, USA

THOMAS BIRCHARD
Central Pacific Hurricane Centre (CPHC), USA

STEPHEN BARLOW
Joint Typhoon Warning Centre (JTWC), USA

S.D. KOTAL
India Meteorological Department (IMD), India

TARIK KRIAT
Meteo-France, La Réunion, France

WOOJEONG LEE
Korea Meteorological Administration (KMA), Korea

RICHARD PASCH
National Hurricane Centre (NHC), USA

UDAI SHIMADA
Japanese Meteorological Agency (JMA), Japan

ABSTRACT

This review summarizes techniques used by operational centers to forecast tropical cyclone intensity change as presented to the International Workshop on Tropical Cyclones (IWTC-9) in Hawaii in 2018. 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,

Corresponding author: Joseph B. Courtney, joe.courtney@bom.gov.au

DOI: 10.6057/2019TCRR03.02

objective guidance has shown some improvement.

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. Continued improvement and availability of intensity guidance along with associated forecaster training are expected to deliver forecasting improvements in the future.

Keywords: tropical cyclone, intensity, change, rapid intensification

1. Introduction

Tropical Cyclone (TC) intensity change has long been recognized as a major forecasting challenge. The forecasting community has been requesting from the research and modelling community improved Numerical Weather Prediction (NWP) and associated techniques. The 2014 International Workshop on Tropical Cyclones (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 cent per year at 24-72h and if this trend continues, the official forecasts could also start to improve along with the guidance*."

This review builds on the summary in LeRoux (2018) to summarise recent advances in intensity guidance. 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 soon to be available to the operational agencies. This is followed by recommendations for the research and operational communities for the next 4 years and an overall summary. The companion paper in Part 2 describes practices from operational centers including the applications of different NWP and techniques discussed in this review.

2. Recent advances in intensity guidance

This section highlights recent advances in intensity guidance, stratified into five model categories as described below.

2.1 Statistical models

Statistical models are used primarily as skill baselines for both operational and model forecasts. Several operational centers use updated versions of the Statistical Hurricane Intensity FORecast (SHIFOR; Jarvinen and Neumann, 1979) to benchmark their forecast skill. At the JTWC, they have been updated to forecast out to 5 days (Knaff et al. 2003, Knaff and Sampson, 2009) are run in real-time. NHC also runs a version of the Knaff et al. (2003) model that accounts for in-land decay and called decay-SHIFOR (see Rappaport et al. 2009). Recently, researchers have developed statistical baselines that forecast beyond 5 days.

Tsai and Elsberry (2015, 2018) have extended the scope of an analog approach for the North-West Pacific, which selects analogs to the target cyclone track and initial intensity. An updated seven-day combined, three-stage Weighted Analog Intensity Pacific (WAIP) intensity prediction and intensity spread guidance product (Tsai and Elsberry 2018) includes 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 per cent of the verifying intensities), which was one of the recommendations from IWTC-8. It is notable that WAIP/WAIA is produced on a desktop computer in a few minutes given only the official track forecast, the initial intensity, and the climatological dataset. Low-cost analog techniques can be developed for other TC basins as well. Both WAIP and WAIA models are still undergoing evaluation by JTWC and NHC for transition to operations.

Also available at JTWC are seven-day North-West Pacific track and intensity forecasts that are 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 for their entire area of operations.

2.2 Statistical-Dynamical models and probabilistic guidance

Statistical-dynamical guidance such as Statistical Hurricane Intensity Prediction Scheme (SHIPS; DeMaria et al. 2005) and LGEM (DeMaria 2009) have proven to be reliable objective intensity guidance.

A recent advance is the installation of Rapid Intensification Prediction Aid (RIPA) at JTWC (Knaff et al. 2018), as shown in figure 1, based on predictors from the environment (from the SHIPS developmental dataset), IR imagery and initial TC conditions (e.g. intensity trend). Two distinct algorithms produce probabilistic forecasts for seven intensification thresholds: 25-, 30-, 35-, and 40-kt changes in 24 h; 45- and 55-kt in 36 h; and 70-kt in 48 h. The method then averages forecast probabilities from the two distinct

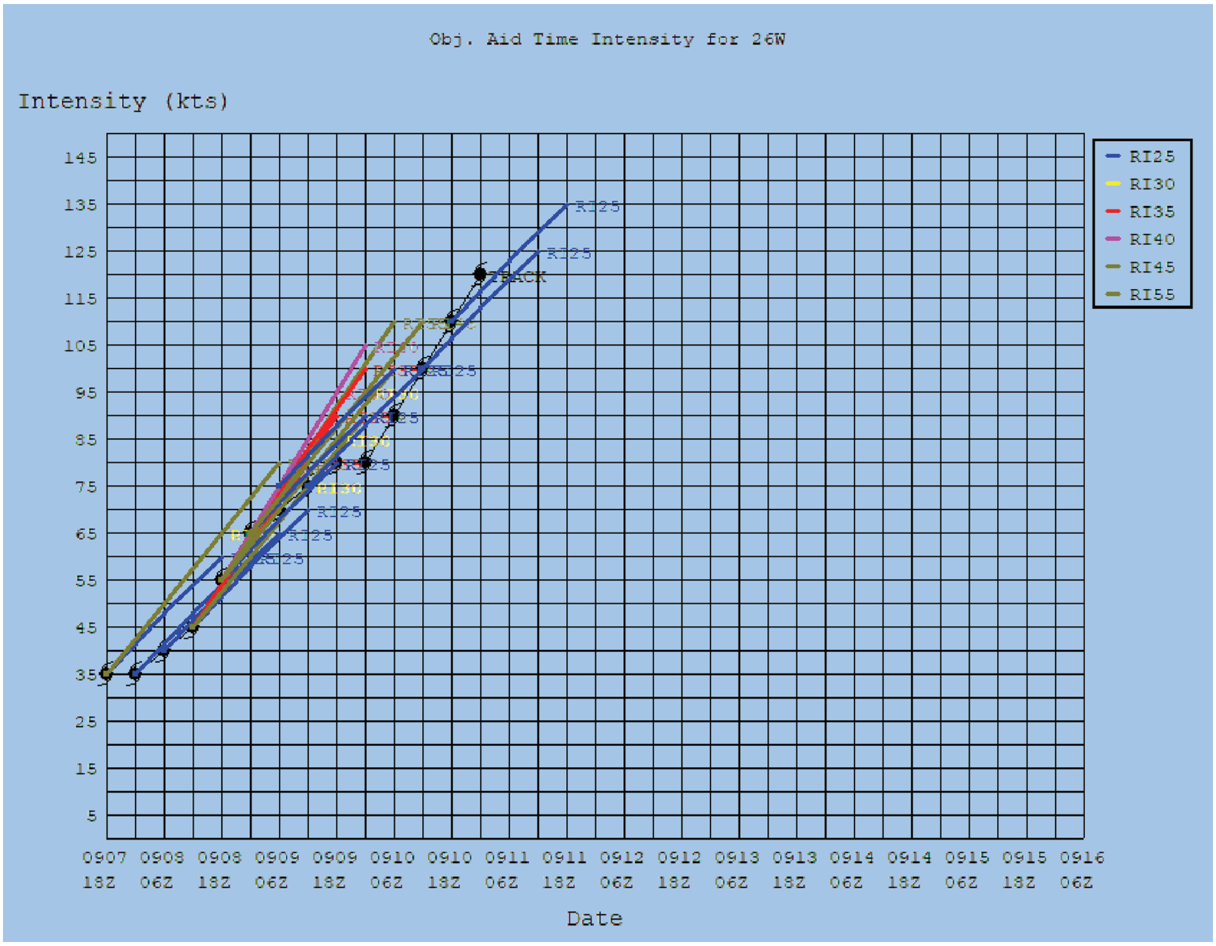

Fig. 1. An example of the RI aid at JTWC for typhoon Mangkut (2018).

algorithms to create mean probabilities at each of the seven intensification thresholds. Finally, the mean probabilities are used to trigger deterministic forecasts (equal to the intensification thresholds) when the mean probability for that threshold reaches 40 per cent. The deterministic forecasts are used directly by the forecaster and as additional members for an intensity forecast consensus (ICNW). Developers addressed forecaster concerns about overprediction of very weak cases and landfalling TCs by limiting the deterministic forecast to TCs with initial intensity exceeding 34 knots and removing forecast intensities for TC centers within 60 n mi of land, respectively. These rudimentary changes appear to have removed most of the false alarm forecasts.

At the NHC, researchers are addressing the likelihood of RI with the Deterministic TO Probabilistic Statistical model (DTOPS; Onderlinde and DeMaria 2018). DTOPS uses guidance from the Integrated Forecast System at the European Centre for Medium-Range Weather Forecast (IFS), US Global Forecast System (GFS), Hurricane Weather Research Forecast model (HWRF), LGEM, and SHIPS. The intensity change forecast by these models, along with several other geographic (e.g., storm latitude) or multi-model parameters, were compiled for cases from 2011 to 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 regression prediction scheme. The largest improvements (when compared to SHIPS-RII (Statistical Hurricane Intensity Prediction System-Rapid Intensification Index)) occurred in the Atlantic basin where substantial Brier Skill Score 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. The operational experience of applying forecasting guidance in operations is discussed further in Part 2.

The occurrence of Secondary Eyewalls and Eyewall Replacement Cycles (ERCs) present an additional challenge to TC forecasters. This inner-core phenomenon is associated with short-term intensity fluctuations that can sometimes be quite significant (> 15 knots). Until very recently, the skill to anticipate and quantify those intensity variations was rather limited. The Cooperative Institute for Meteorological Satellite Studies at the University of Wisconsin (CIMSS) has developed the M-PERC guidance (Microwave-based Probability of Eyewall Replacement Cycle) based on previous observational studies with aircraft data (Sitkowski et al. 2011 and 2012; Kossin et al. 2012). M-PERC uses an azimuthal ring score from ARCHER (Automated Rotational Center Hurricane Eye Retrieval, Wimmers and Velden 2010) derived from 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 2).

This new probabilistic guidance appears promising as it

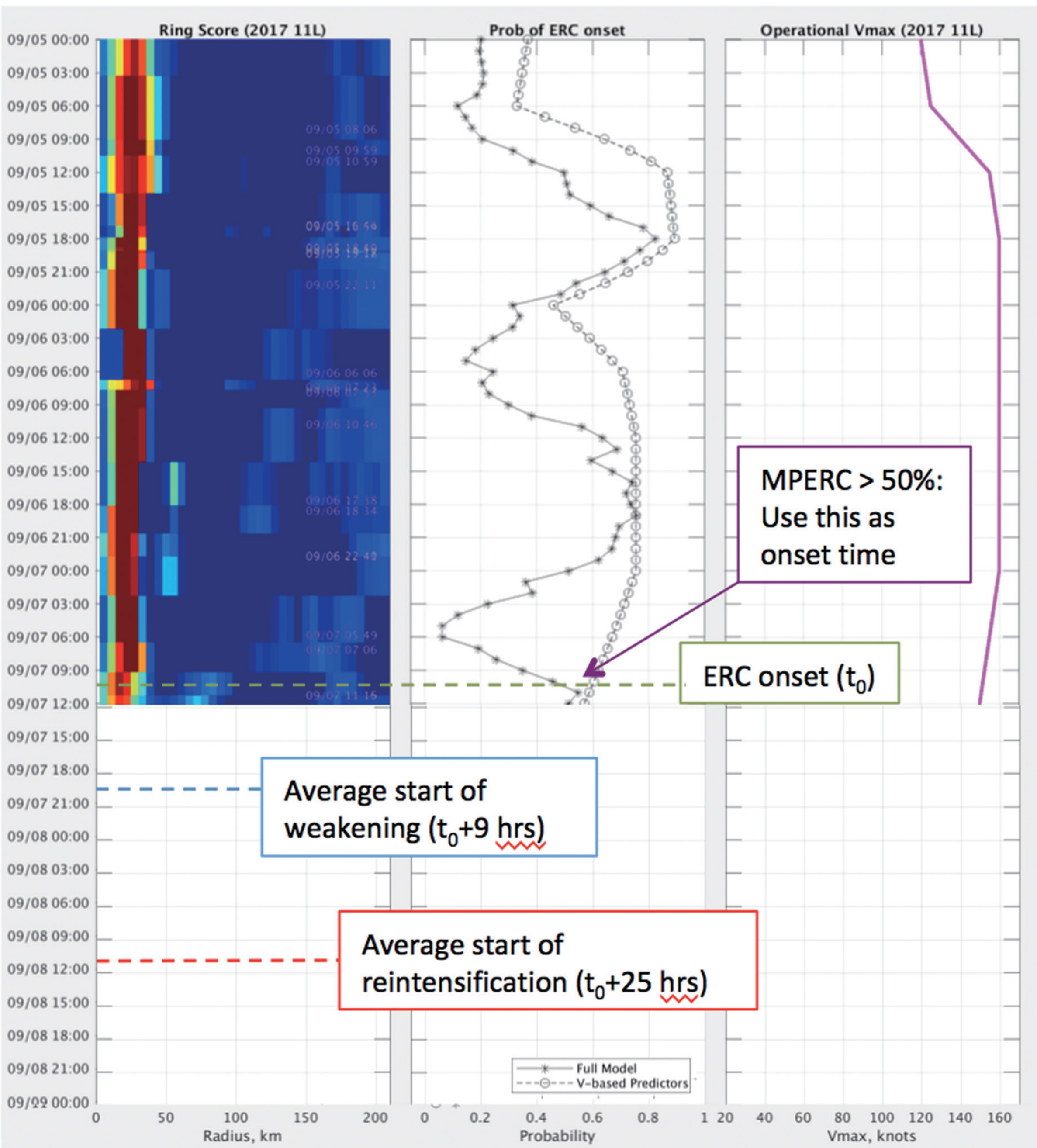

FIG. 2. The M-PERC guidance.

is available to operational TC forecasters in real-time on the CIMSS web site. Further improvements of this guidance are also likely within the next few years.

Following recommendations from IWTC-7 and IWTC-8, guidance methods available in the North Atlantic and North-East Pacific have continued to be implemented in other centers. Korea Meteorological Administration (KMA) developed a version of STIPS using ocean-coupled potential predictors (Kim et al. 2018) combined 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 such as the JMA-GSM (Japan Meteorological Agency-Global Spectral Model), 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. SHIPS and the Logistic Growth Model (LGEM) methods have also been developed for JTWC's basins and have been in use since 2015 (Andrea Schumacher, personal communication 2019).

The Meteorological Research Institute (MRI) at JMA, developed the RSMC (Regional Specialized Meteorological Center) Tokyo version of SHIPS in 2016 with great support from developers in the US (Yamaguchi et al. 2018). This version, the Typhoon Intensity Forecast Scheme or (TIFS) for the North-West Pacific basin. Figure 3 shows root mean square errors (RMSEs) and biases of TIFS forecasts for predicts central pressure (Pmin) and maximum 10-min sustained wind speed (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). TIFS has helped improve the accuracy of RSMC Tokyo intensity forecasts but the scheme has a tendency to overestimate TC intensity in the genesis stage, the response is slow with extremely rapid changes and it is not suited to handling of re-intensification after TC transformation to extratropical low status (Ono et. al. 2019).

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 may further improve the accuracy of TIFS while a method involving multiple TIFS models and an artificial intelligence algorithm are also being developed (Ono et. al. 2019).

Two 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 (Leroux, personal communication), using atmospheric and oceanic synoptic parameters (mostly from ERA-Interim data during the learning phase, but with data from IFS in operational application). The first model 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 model 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 and the second is designed specifically for identifying RI. They should become available for the forecasters for the 2019-2020 tropical cyclone season.

The India Meteorological Department (IMD) uses an integrated Cyclone Prediction System (CPS) based on statistical-dynamical guidance as described at IWTC-8. The

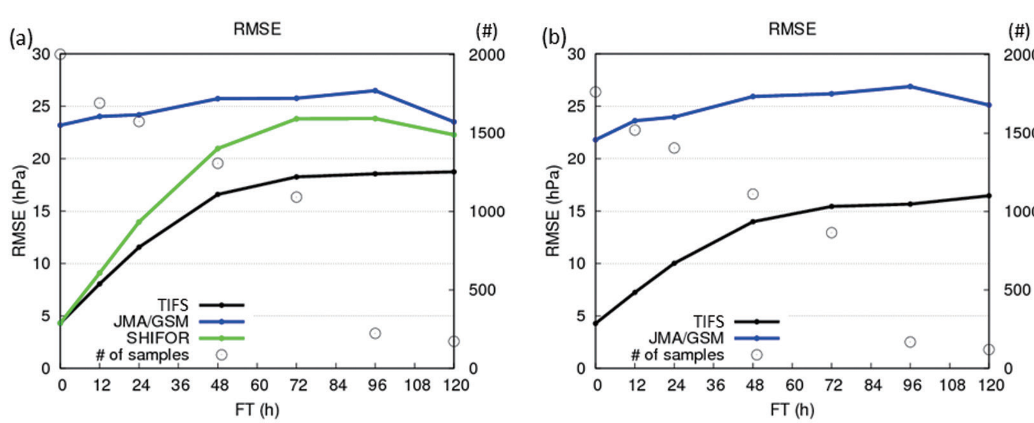

Fig. 3. Root mean square errors (RMSEs) of (a) Pmin (hPa) and (b) Vmax (kt) forecasts. TIFS, JMA/GSM, and SHIFOR (Pmin only) are black, blue, and green lines, respectively. Black open circles show the number of samples corresponding to y-axis on the right. RMSEs are based on RSMC Tokyo's best track data. Forecast samples are from 2013 to 2015 for the North-West Pacific basin. This figure is from Yamaguchi et al. (2018).

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.

2.3 Dynamical models

Numerical Weather Prediction (NWP) at both global and regional scales has demonstrated continued improvement in TC intensity forecast with further developments planned.

a) Recent or planned improvement with some selected global models

Global models have improved considerably in recent years. It was not long ago that global model intensity forecasts were unskillful and essentially ignored by operational forecasters. Recently however, the global models have begun to provide useful guidance on 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 initial treatment of TCs in the global European Center for Medium-range Weather Forecasts (ECMWF) IFS (Vitard et al. 2018). A major upgrade that includes ocean and sea-ice models coupled in the high-resolution forecast was implemented in the operational version in June 2018 (CY45r1). 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 upgrade shows a small statistically significant improvement in the intensity error at medium-range (figure 4).

In 2014 and 2015, the United Kingdom Met Office made two changes to their global model (UKMO) that had a significant impact on TC predictions (Heming and Vellinga, 2018). Global Atmosphere 6 (GA6), implemented in July 2014, includes changes to the global model dynamical core, physics and horizontal resolution and improved satellite data usage. In February 2015, the Met Office introduced a new technique for initialization of TCs using TC warning centre's central pressure estimates. In 2017, the global model 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 (i.e., storms are too large/broad). Near real-time trials of an atmosphere-ocean coupled version have shown some promising results. Over-deepening, which occurs in slow moving TCs, TCs that move over their previous track, and TCs in the subtropics, is markedly reduced in the coupled model. The UKMO has scheduled for operational implementation of the couple model in 2020. Experiments to cap the drag coefficient in the model at higher wind speeds have also shown positive results by increasing forecast 10-m winds for strong TCs without reducing the central pressure further. If trials results continue to be positive, operational implementation of the drag coefficient cap could take place in 2019.

In the U.S.A., NOAA's ambition to reduce forecast guidance errors (by 50 per cent from 2017) through the Hurricane Forecast Improvement Program (HFIP) has focused

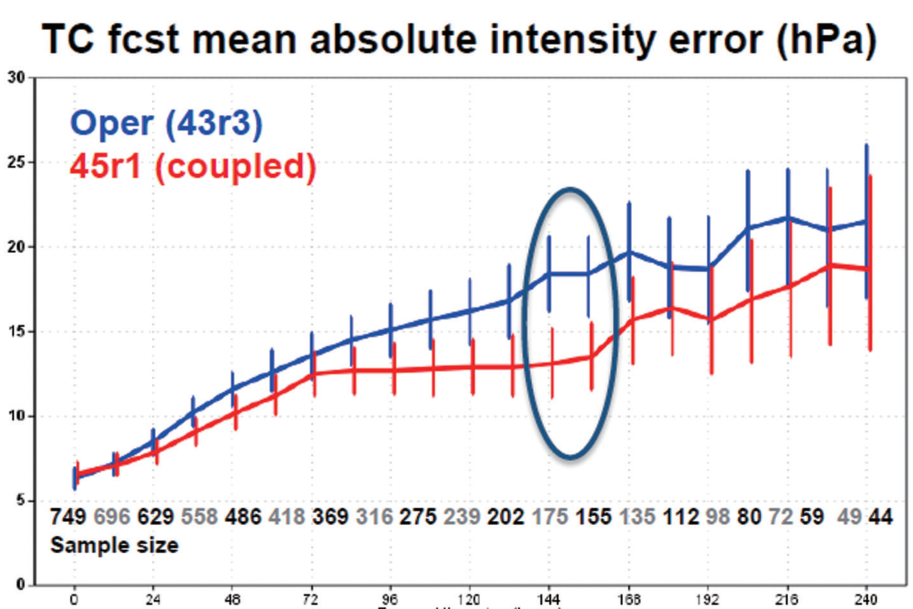

FIG. 4. Intensity verification of the IFS (ECMWF) 2018 operational model highlighting the skill improvement with ocean coupling (red) especially beyond 4 days. From: https://www.ecmwf.int/en/about/media-centre/news/2018/ifs-upgrade-improves-extended-range-weather-forecasts

particular attention on model guidance intensity improvements. The GFDL (Geophysical Fluid Dynamics Laboratory's Finite-Volume Cubed-Sphere (FV3), dynamical core, selected as the USA's Next-Generation Global Prediction System (NGGPS), has been transferred to NCEP (National Center for Environmental Prediction), to be operational at NCEP in 2019 as the replacement for GFS. An improved version of the model developed at GFDL (referred to as fvGFS) and has been run daily in real time since 2 July 2018. The 2018 version of fvGFS had the lowest mean absolute intensity errors of all available operational guidance at 3 to 5 days (figure 5), even beating the high-resolution regional hurricane models HWRF and COAMPS-TC (Coupled Ocean-Atmosphere Mesoscale Prediction System-Tropical Cyclone model).

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. 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 be a potential option for NOAA's (National Oceanic and Atmospheric Administration) next generation hurricane model – taking advantage of FV3's unique design for unified modelling efforts.

b) Recent or planned improvement with some selected regional models

Regional Hurricane modeling systems implemented at NOAA's NCEP operations are now used for forecasting guidance in all worldwide ocean basins (Mehra et al. 2018). The Hurricane Weather Research Forecasting atmospheric model (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 in the North Atlantic during 2017 at all lead times, and was the best performer for short lead times (< 48h) over the North-East 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, accounting for dropsondes drift and tail Doppler radar from the G-IV) and the physics (e.g. advanced planetary boundary layer and cumulus schemes). HWRF now also combines advanced vortex initialization and hybrid ensemble Kalman filter data assimilation to provide initially balanced model analysis (Tong et al., 2018). Improvements are also planned for the

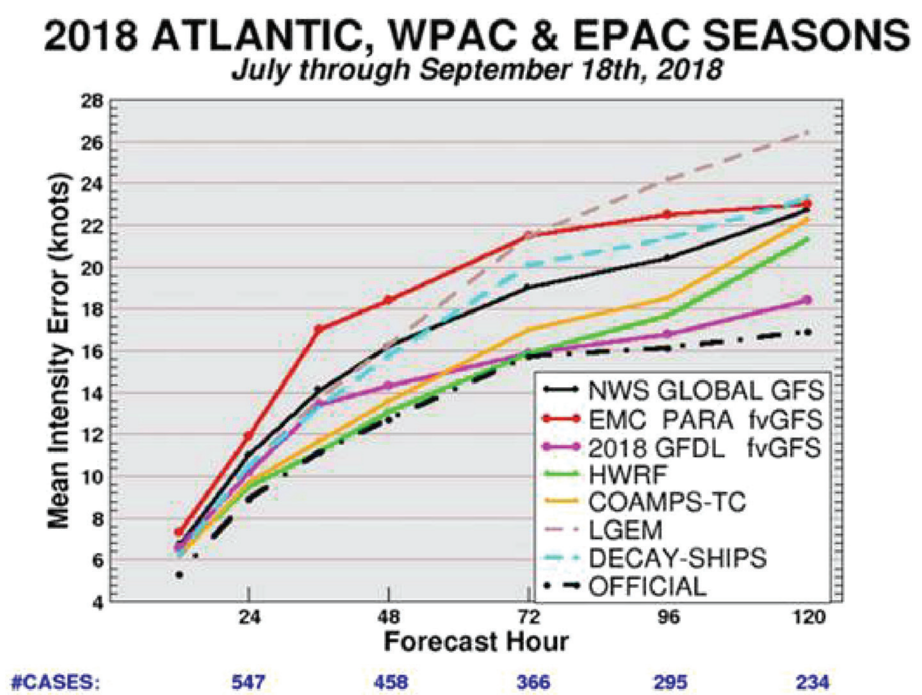

Fig. 5. Average intensity errors (knots) for a portion of the 2018 TC season (July 2-18 September), for the North Atlantic, North-East Pacific, North-West Pacific, and the combined 3 ocean basins, comparing the operational GFS (black) with other operational models including the EMC version of fvGFS (FV3-GFS, 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).

non-NHC basins with an increase in the vertical resolution and ocean coupling through the Hybrid Coordinate Ocean Model (HYCOM) for the southern hemisphere basins. Early verification over the North Atlantic suggests similar or slightly better performances than the 2017 version. The improved structure forecasts that now allows for better prediction of secondary eyewalls and eyewall replacement cycles in turn results in improved TC intensity and RI predictions.

The Environmental Modelling Center (EMC) 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 North-East Pacific. HMON implements a long-term strategy at 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 6). Development of HMON is consistent with, and a step closer to developing Next-Generation Global Prediction System (NGGPS)/FV3-dynamic-core-based, global-to-local-scale coupled models in a unified modeling framework.

NCEP's plans include the Hurricane Analysis and Forecast System (HAFS) an FV3 based multiscale model and data assimilation package for fixed and moving nest domains (Mehra, 2019).

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 horizontal resolution) initialised by the IFS analysis now runs 4 times per day out to 42 h in each French territory's domains (figure 7). In 2017 (Faure et al. 2018), a 1D ocean coupling and reduction of the spin-up time was implemented. 1D ocean-coupling allows the model to represent cooling in TC wake even with no observations.

AROME short-range forecasts of intensity and structure provide value already, and track forecast scores remain reasonable. 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 ERC of TC Fantala in April 2016. In the North Atlantic, AROME forecasts have been verified against available observations (including radar, recon, and RSMC analyses) during hurricanes Irma and Maria in September 2017 as those systems were

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

FIG. 6. 2018 HWRF and HMON configurations.

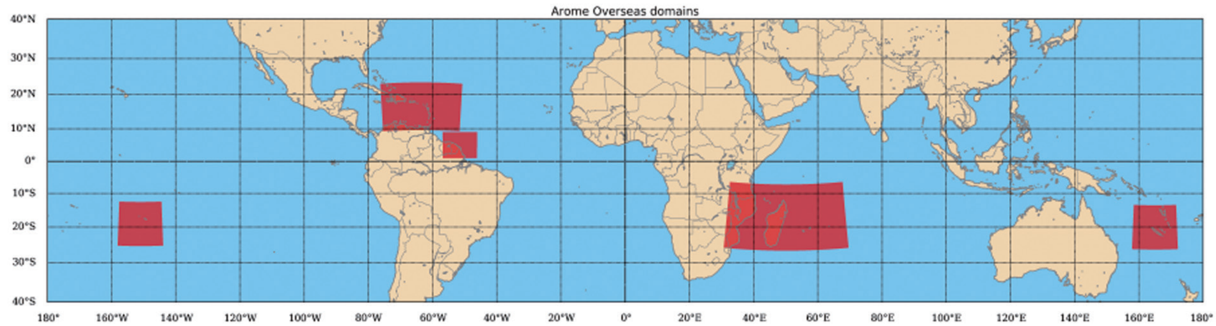

FIG. 7. Meteo-France non-hydrostatic AROME regional model domains associated with French overseas territories (red swaths).

crossing the lesser Antilles (Dupont et al. 2018). The model demonstrated its excellent ability to forecast realistic TC structures, tracks and intensities.

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

The India Meteorological Department (IMD) have adapted HWRF 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 used extensively for track forecasting but use in intensity forecasting is less widespread. Recently, however, intensity consensus methods are gaining popularity as the availability and skill of intensity guidance at operational centers increases.

JTWC has used an equally weighted consensus for many years, and the consensus generally outperforms individual members. Increase in skill in existing models and addition of more skillful model has led to a gradual decrease in mean absolute forecast errors through the years at 72 h (figure 8). Although this shows improvement, it is only a single metric. By other metrics like the probability of detecting rapid intensification, consensus methods may lag behind individual members. As equally weighted consensus methods have limitations predicting extremes like rapid intensification, other attempts are being made to work with deterministic and ensemble models to address these forecast issues.

In the HFIP framework, a Corrected Consensus Approach (HCCA) for TC 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 (DSHIPS), LGEM, GFS, UKMO, IFS, COAMPS-TC, HWRF, the GFS Ensemble Forecast System (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 continues to be a skillful model in both basins (North Atlantic and Northeast Pacific).

Recent work at RSMC La Réunion has designed a technique to generate weighted ensemble predictions around the

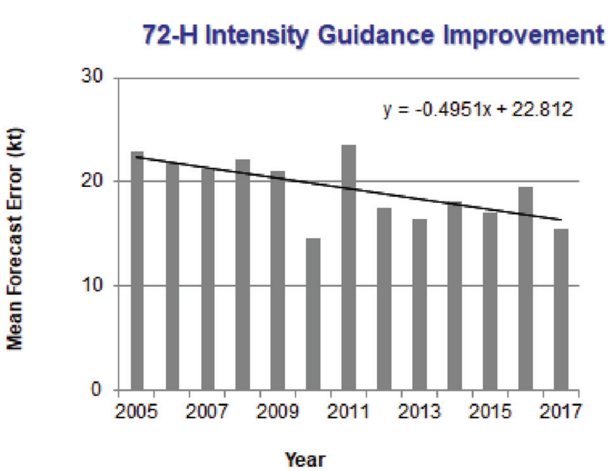

FIG. 8. The 72-h intensity skill trend in the JTWC consensus for NWPac, 2005-17 showing approximate improvement of 5 kt in mean absolute forecast error in 10 years.

official track and intensity forecast (Quetelard et al. 2018) by combining 5-years statistical errors of RSMC forecasts and ECMWF ensemble forecast (EC-EPS) spread, allowing a situation-dependent quantification of official intensity forecast as recommended during IWTC-8.

The Australian Bureau of Meteorology has applied an intensity bias-correction to increase the EC-EPS 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, however, carries an additional overhead to recalibrate the difference with ongoing model upgrades.

Through NOAA's HFIP program, an HWRF ensemble has been successfully configured and trialled. Although this has yet to be used operationally, it holds promise to deliver useful probabilistic intensity output.

3. Summary, conclusions and recommendations

Since IWTC-8 in 2014, considerable work has continued worldwide to improve TC intensity guidance, and to understand the influences that sometimes lead to rapid intensity changes. 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.

Following a recommendation from previous IWTC, the sharing of intensity guidance initially designed for the North Atlantic and the North-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 (undergoing evaluation at NHC) are now combining IFS (ECMWF) with US guidance GFS, HWRF, LGEM, and SHIPS. For this purpose, continued support to applied research centers that provide useful and globally available intensity guidance is warranted.

It is apparent that the considerable research efforts into understanding intensity changes as outlined in the companion IWTC sub-topics on internal influences and external influences may not be reaching forecasters. This research, along with advances in intensity guidance including verification results, needs to be communicated to operational staff through appropriate notifications, workshops and training material.

There are three recommendations for WMO and research community:

Continue to bring forecasting intensity guidance (NWP models, statistical-dynamical models and statistical models) to operations and extend globally so that guidance is available to all operational centers. For example, extend HCCA globally (Research recommendation).

Statistical-dynamical guidance should take advantage of the skill of the range of dynamical models including IFS (ECMWF), UKMO, 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 limited guidance is included). Complete an independent assessment of techniques in each TC area (Research and WMO recommendation).

Evaluations and specifics of upgrades to intensity guidance should be communicated to operational centers. Provide training material (through multiple media) and workshops for forecasters to ensure the appropriate application of the guidance and the underlying science (Research and WMO 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 valuable initiative in the sharing of ideas and activities.

References

DeMaria, M., M. Mainelli, L.K. Shay, J.A. Knaff, and J. Kaplan, 2005: Further improvements to the Statistical Hurricane Intensity Prediction Scheme (SHIPS). *Wea. Forecasting*, **20**, 531–543.

DeMaria, M., 2009: A Simplified Dynamical System for Tropical Cyclone Intensity Prediction. *Mon. Wea. Rev*., **137**, 68-82.

Dupont, T., and G. Faure, 2018: Taking Advantage of the High Resolution AROME Model for Monitoring and Forecasting Major Hurricanes IRMA and MARIA at Meteo-France/French West Indies. 33rd Conference on Hurricanes and Tropical Meteorology, 16-20 April 2018, Ponte Vedra, FL.

Faure, G., P. Chambon and C. Lebeaupin Brossier, 2018: Météo-France New NWP Models in Tropical Regions. 33rd Conference on Hurricanes and Tropical Meteorology, 16-20 April 2018, Ponte Vedra, FL.

Heming, J. T., and M. Vellinga, 2018: The Impact of Recently Implemented and Planned Changes to the Met Office Global Model on Tropical Cyclone Performance. 33rd Conference on Hurricanes and Tropical Meteorology, 16-20 April 2018, Ponte Vedra, FL.

Jarvinen, B. R., and C. J. Neumann, 1979: Statistical forecasts of tropical cyclone intensity. NOAA Tech. Memo. NWS NHC-10, 22 pp. [Available from National Technical Information Service, U.S. Department of Commerce, 5285 Port Royal Rd., Springfield, VA 22151.]

Kaplan, J., and M. DeMaria, 2003: Large-scale characteristics of rapidly intensifying tropical cyclones in the North Atlantic basin. *Wea. Forecasting*, **18**, 1093–1108.

Kim S.-H., I.-J. Moon and P. S. Chu., 2018: Statistical-Dynamical Typhoon Intensity Predictions in the Western North Pacific Using Track Pattern Clustering and Ocean Coupling Predictors. *Wea. Forecasting*, **33**, pp. 347-365.

Knaff, J. A., M. DeMaria, C. R. Sampson, and J. M. Gross, 2003: Statistical, Five-Day Tropical Cyclone Intensity Forecasts Derived from Climatology and Persistence. *Wea. Forecasting,* **18(2)**, 80-92.

Knaff, J. A., and C. R. Sampson, 2009: Southern Hemisphere Tropical Cyclone Intensity Forecast Methods Used at the Joint Typhoon Warning Center, Part I: Control Forecasts Based on Climatology and Persistence. Australian Meteorological and Oceanographic Journal, **58(1)**, 1-7.

Knaff, J.A., C.R. Sampson, and K.D. Musgrave, 2018: An operational rapid intensification prediction aid for the western North Pacific. Wea. Forecasting, **33**, 799–811, DOI: /10.1175/WAF-D-18-0012.1

Kossin, J. P., and M. Sitkowski, 2012: Predicting hurricane intensity and structure changes associated with eyewall replacement cycles. *Wea. Forecasting*, **27**, 484-488.

Leroux, M-D., Wood, K., R.L. Elsberry, E.O. Cayanan, E. Hendricks, M. Kucas, P. Otto, R. Rogers, C.R. Sampson, and Z. Yu, 2018: Recent Advances in Research and Forecasting of Tropical Cyclone Track, Intensity, and Structure at Landfall. *Tropical Cyclone Research and Review,* **7(2)**, 85-105.

Mehra A., V. Tallapragada, Z. Zhang, B. Liu, W. Wang, L. Zhu, H. S. Kim, D. Iredell, Q. Liu, B. Zhang, J. A. Sippel, B. Thomas, K. Wu, S. Abarca, and H. Winterbottom, 2018: Recent and Future Advances in Tropical Cyclone Modeling at NOAA's National Weather Service National Center for Environmental Prediction (NWS/NCEP). 33rd Conference on Hurricanes and Tropical Meteorology, 16-20 April 2018, Ponte Vedra, FL.

Mehra, A. 2019: Operational Hurricane Modeling at NCEP: Recent Advances and Plans, Joint Australian Meteorological and Oceanographic Society (AMOS) conference and International Conference on Tropical Meteorology and Oceanography (ICTMO), Darwin.

Tong M., J. A. Sippel, V. Tallapragada, E. Liu, C. Kieu, I.-H. Kwon, W. Wang, Q. Liu, Y. Ling, and B. Zhang, 2018: Impact of Assimilating Aircraft Reconnaissance Observations on Tropical Cyclone Initialization and Prediction Using Operational HWRF and GSI Ensemble–Variational Hybrid Data Assimilation. *Monthly Weather Review*, **146**, 4155-4177.

Onderlinde, M., and M. DeMaria, 2018: Deterministic to Probabilistic Statistical Rapid Intensification Index (DTOPS): A new method for forecasting RI probability. 33rd Conference on Hurricanes and Tropical Meteorology, 16-20 April 2018, Ponte Vedra, FL.

Ono, M., S. Notsuhara, J. Fukada, Y. Igarashi, and K. Bessho. 2019: Operational Use of the Typhoon Intensity Forecasting Scheme Based on SHIPS (TIFS) and Commencement of Five-day Tropical Cyclone Intensity Forecasts. *Technical Review No. 21*. RSMC Tokyo – Typhoon Center.

Quetelard, H. M., F. D. Bonnardot, G. D. Jumeaux, and M. Bessafi, 2018: Probabilistic forecasts of tropical cyclone track and intensity through ensemble techniques. In prep. for *Quart. J. Roy. Meteor. Soc.*

Rappaport, E.N., J.L. Franklin, L.A. Avila, S.R. Baig, J.L. Beven, E.S. Blake, C.A. Burr, J. Jiing, C.A. Juckins, R.D. Knabb, C.W. Landsea, M. Mainelli, M. Mayfield, C.J. McAdie, R.J. Pasch, C. Sisko, S.R. Stewart, and A.N. Tribble, 2009: Advances and Challenges at the National Hurricane Center. *Wea. Forecasting,* **24**, 395–419.

Simon, A., A.B. Penny, M. DeMaria, J.L. Franklin, R.J. Pasch, E.N. Rappaport, and D.A. Zelinsky, 2018: A description of the real-time HFIP Corrected Consensus Approach (HCCA) for tropical cyclone track and intensity guidance. *Wea. Forecasting*, **33**, 37-57.

Shimada, U., H. Owada, M. Yamaguchi, T. Iriguchi, M. Sawada, K. Aonashi, M. DeMaria, and K. Musgrave, 2018: Further improvements to the Statistical Hurricane Intensity Prediction Scheme using tropical cyclone rainfall and structural features. *Wea. Forecasting*, **33**, 1587–1603.

Sitkowski, M., J. P. Kossin, and C. M. Rozoff, 2011: Intensity and structure changes during hurricane eyewall replacement cycles. *Mon. Wea. Rev.*, **139**, 3829-3847.

Sitkowski, M., J. P. Kossin, C. M. Rozoff, and J. Knaff, 2012: Hurricane eyewall replacement cycles and the relict inner eyewall circulation. *Mon. Wea. Rev.*, **140**, 4035-4045.

Tsai, H.-C. and R.L. Elsberry, R.L. 2015: Seven-day intensity and intensity spread predictions for western North Pacific tropical cyclones. *Asia-Pacific J.Atmos. Sci*. **51**, 331–342.

Tsai, H.-C. and R.L. Elsberry, 2018: Seven-Day Intensity and Intensity Spread Predictions in Bifurcation Situations with Guidance-On-Guidance for Western North Pacific Tropical Cyclones. *Asia-Pacific J.Atmos.*

Vitard, F., and colleagues, 2018: ECMWF: Research developments and plans. Presentation for ECMWF member states.

Wimmers, A. J., and C. S. Velden, 2010: Objectively determining the rotational center of tropical cyclones in passive microwave satellite imagery. *J. Appl. Meteor. Climatol.*, **49**, 2013–2034.

Yamaguchi M., H. Owada, U. Shimada, M. Sawada, T. Iriguchi, K. D. Musgrave, and M. DeMaria, 2018: Tropical cyclone intensity prediction in the western North Pacific basin using SHIPS and JMA/GSM. *SOLA*, **14**, 138–143.