Topic 2.7

ADVANCES IN INTENSITY GUIDANCE

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Abstract: A great deal of effort has been spent on tropical cyclone intensity forecasting in the last four years, with most of that effort focused on improving NWP models. The dramatic drop in track guidance forecast errors seen in the last decade has not been replicated with intensity guidance; however, there is evidence that the recent efforts are paying dividends with improvements in guidance, especially the NWP model guidance that is now competitive with the statistical-dynamical guidance. As recommended in the previous report, guidance available in the North Atlantic and eastern North Pacific has been developed for other basins and made available to RSMCs. This should continue.

Though improvements have been made, the road ahead is probably going to get a bit more challenging. Researchers are advancing the science of inner core dynamics and other influences on intensity change, but there are challenges implementing these advances into the guidance. On a more positive note, progress is being made in tropical cyclone observation guidance and track forecasting so the results of that progress should also translate into improvements in intensity forecasts.

2.7.0 Introduction

Using mean absolute forecast errors (MAE) as a metric for measuring skill in tropical cyclone track forecasting has been markedly improving for about 15 years, but improvements in intensity forecasting at the operational centres have shown little improvement (Cangialosi and Franklin 2012; Falvey 2012). However, the mean errors in the guidance available to forecasters is gradually decreasing at the rate of 1-2% per year at 24-72 h (Figure 1), which is about half the rate of improvement in track over the same 20 year period (DeMaria et al. 2014). If these trends continue, the official forecasts could also start to improve along with the guidance. In fact, Aberson (2008) finds evidence that the official forecasts are improving in other measures of forecast skill.

To assess current capabilities, we describe the forecasting practices and guidance employed at selected operational forecast centres, and then we discuss promising research efforts to improve said guidance, and finally we provide examples of remaining issues and recommendations to address those issues.

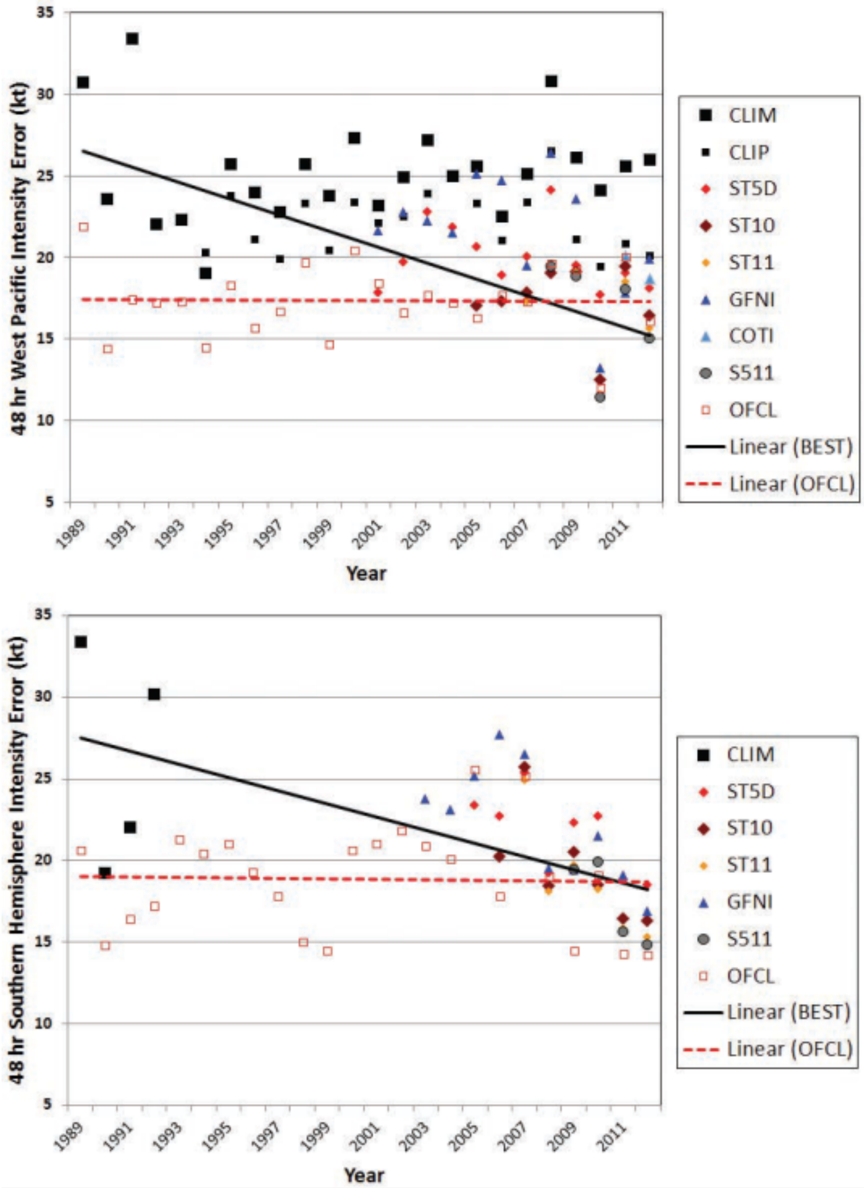

Figure 1. Time series of annual 48-h intensity errors (i.e., MAE) associated with intensity forecast guidance and simple intensity consensus methods in (top) the western North Pacific, and (bottom) the Southern Hemisphere. Linear trend lines for the best model in each year and the official forecasts are also shown.

2.7.1 Forecasting practices at operational centres

Some of the operational centres have contributed short summaries on their current operational capabilities and procedures. Although there are similarities in the processes, there are subtle differences related to operational needs, capabilities and staffing. The bigger centres have large staffs and abundant resources, so they tend to spend more time analyzing and forecasting. The smaller centres have less resources, erratic power and connectivity and possibly seasonal staffing. These centres would have fewer observations, less guidance, and possibly less time for intensity forecasting. The largest centre with the most resources is the National Hurricane Center (NHC), so we will summarize its process first. The others will be summarized in no particular order.

2.7.1.1 The National and Central Pacific Hurricane Centers (NHC and CPHC)

Intensity forecasting begins with the analysis of the current intensity. The amount and quality of data available for this analysis varies widely in NHC/CPHC's AOR. At times, especially far from land, the available data consist only of subjective Dvorak estimates and ADT. At other times a wider variety of platforms including scatterometer, AMSU intensity estimates, aircraft flight-level, dropsonde, and stepped-frequency microwave radiometer (SFMR) data, in-situ surface observations, and land-based radar are available for use in intensity analysis. These data are analyzed and used by the forecaster to determine the best initial intensity and structural analysis of the cyclone at the initial time of the forecast.

Data from this analysis are used as input into statistical-dynamical models, such as Statistical Hurricane Intensity Prediction Scheme (SHIPS; DeMaria et al. 2005) and Logistic Growth model (LGEM; DeMaria 2009), and dynamical models such as the GFDL and HWRF hurricane models. These four models comprise the primary operational hurricane intensity guidance available to NHC/CPHC forecasters. An average of these four models, IVCN, represents the intensity consensus that is heavily used in operations. The Florida State Superensemble (FSSE) is a weighted consensus technique for intensity forecasting that is also available at NHC. It has an extra advantage that it uses the 6-h old official intensity forecast (one of the best performing aids available to forecasters).

Recent verification of intensity guidance at NHC shows that over the period from 2011-2013, most of the individual intensity models had little skill in the Atlantic basin beyond 24 hours (Figure 2). The IVCN and FSSE had more skill than any individual model, but even these aids showed no skill after 72 hours.

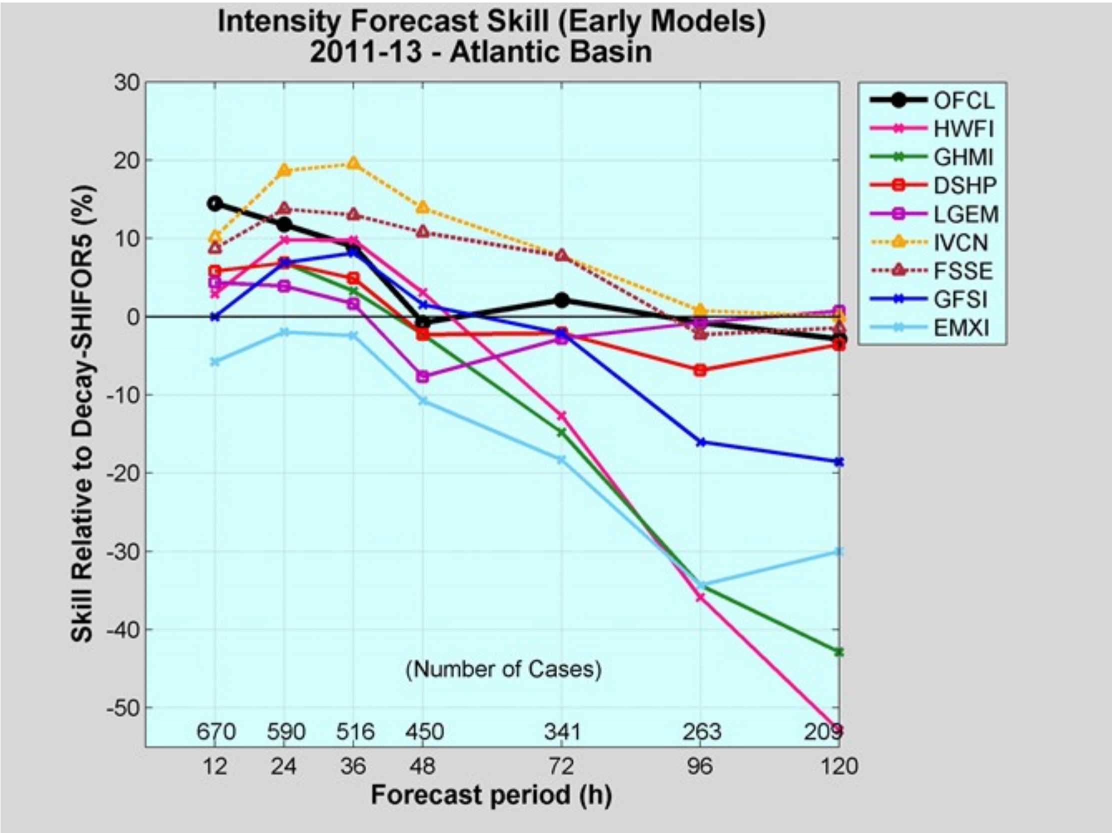

Figure 2. 2011-2013 Intensity model skill for the Atlantic basin. Aids shown include the NHC official forecast (OFCL), the HWRF (HWFI), GFDL (GHMI), SHIPS (DSHP), LGEM, the IVCN consensus, the Florida State Superensemble (FSSE), the GFS (GFSI) and the ECMWF (EMXI). Note that skill is calculated relative to the climatological/persistence Decay-SHIFOR5 model.

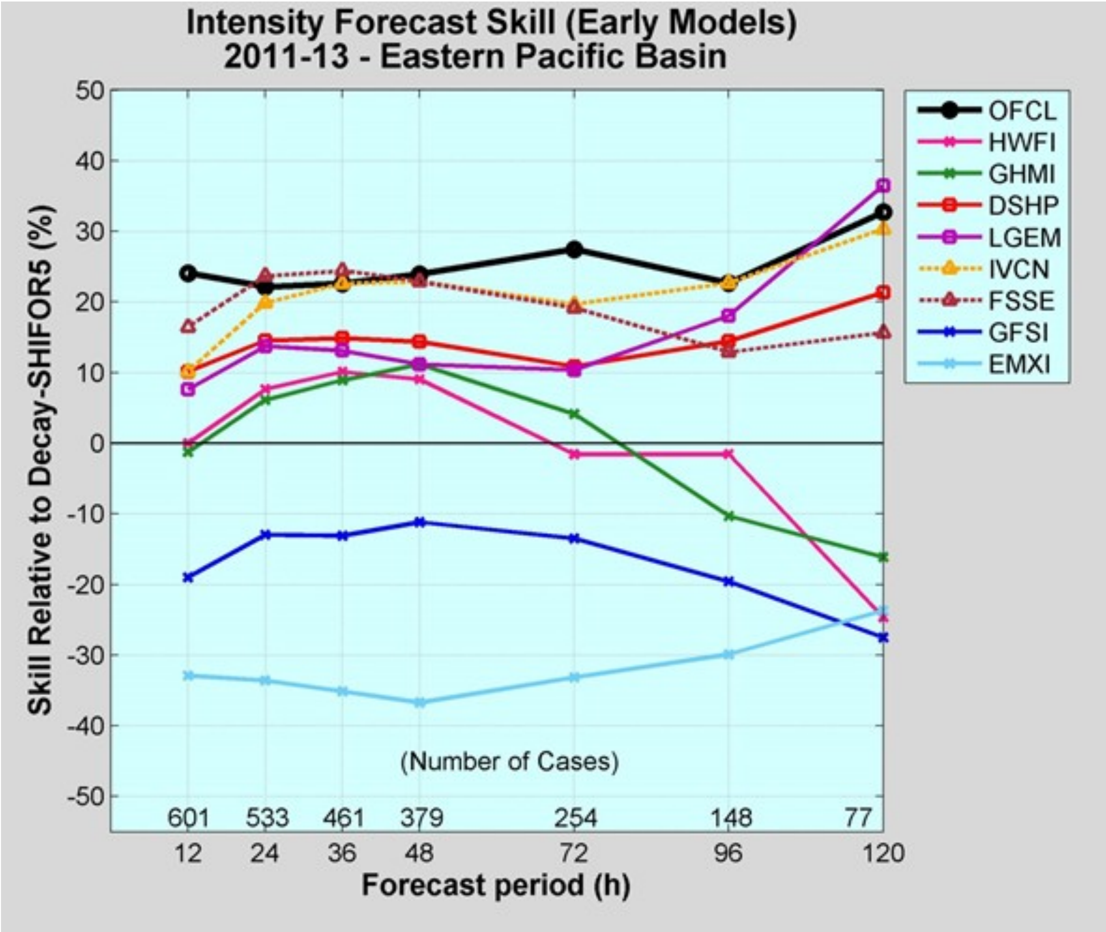

Figure 3. As in Figure 2, except for the eastern North Pacific basin

In the eastern North Pacific basin from 2011-2013, the statistical-dynamical SHIPS and LGEM models showed skill through 5 days (Figure 3). The GFDL and HWRF models had skill through 48 hours, but little or negative skill at days 3 through 5. The IVCN consensus was generally the most skillful intensity aid through 5 days, although the FSSE also showed skill through the forecast period.

Significant upgrades were made to the operational HWRF model in 2013. After this implementation was made, intensity skill of the HWRF model increased markedly (Figure 4). Additionally, 2013 marked the first time that Doppler radar velocity data from the NOAA P-3 aircraft was assimilated operationally into the HWRF model.

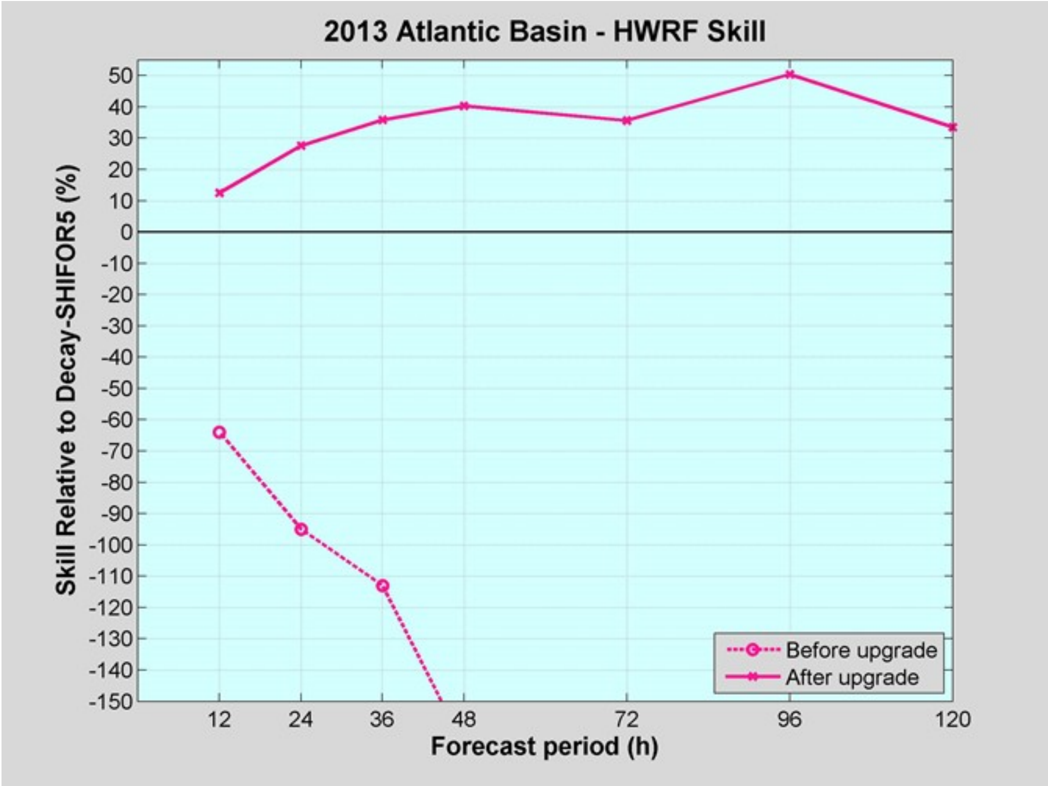

Figure 4. Intensity skill for the HWRF model in the Atlantic basin before and after the 2013 model upgrade. Note that skill is calculated relative to the climatological/persistence Decay-SHIFOR5 model.

Global and regional model fields are used to diagnose environmental factors such as vertical wind shear and moisture related to intensity forecasting. Global model trends in the structure of the cyclone in fields from the GFS and ECMWF models, particularly in the lower-tropospheric vorticity and sea-level pressure fields, can provide subjective indications of intensity trends, especially for cyclones undergoing extratropical transition. In terms of explicit intensity guidance, from 2011-2013 the GFS model showed limited skill through 36 hours in the Atlantic (Figure 2), but little skill after that time. Neither the ECMWF nor GFS models were skillful for intensity forecasts in the eastern North Pacific (Figure 3). Other considerations for intensity forecasting include SST/upper ocean heat content, potential land interaction, and interaction with other meteorological features, including extratropical transition. Note that an accurate assessment of all of these factors is heavily dependent on the quality of the track forecast.

The SHIPS model also includes the Rapid Intensification Index (RII, Kaplan et al. 2010) that uses storm and environmental factors to assess the probability of rapid intensity change (25, 30, 35, and 40 kt) in the first 24 hours of the forecast period. This probabilistic information is helpful in identifying situations where rapid intensification may occur and where the intensity forecast may need to be near or above the highest intensity guidance.

During the past few years, experimental intensity guidance from the Hurricane Forecast Improvement Project (HFIP) has been available to NHC/CPHC forecasters. These models are run on a set of retrospective cases, and if they perform well enough explicitly or as part of a consensus, they are included as part of HFIP Stream 1.5 for a given hurricane season. These models include statistical-dynamical model ensembles and a variety of dynamical models, including a 20-member GFDL hurricane model ensemble.

When making the official forecast, NHC/CPHC forecasters use model guidance and their subjective analysis of the environment to prepare the intensity forecast. Consideration is also given to continuity to avoid large changes from one forecast cycle to the next. NHC/CPHC forecasters primarily display forecast guidance in the NHC version of the Automated Tropical Cyclone Forecast System (ATCF; Sampson and Schrader 2000, Figure 5). Global and regional dynamical model fields are also routinely viewed within the N-AWIPS system.

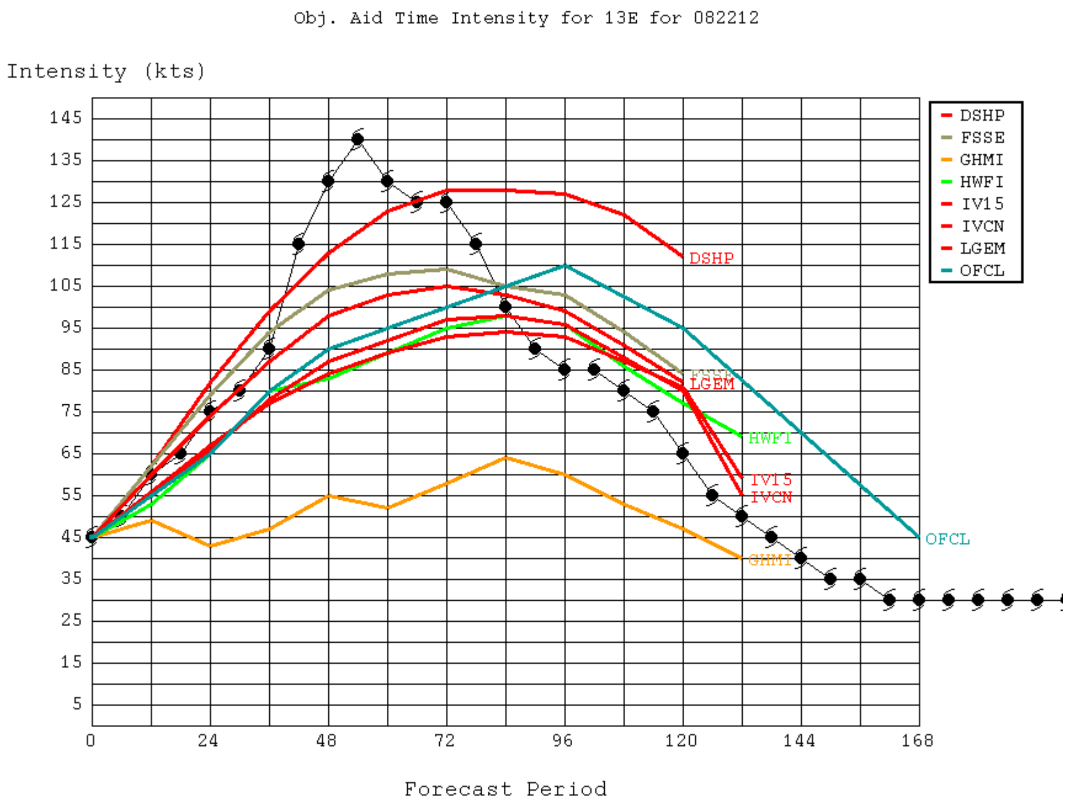

Figure 5. Time series of intensity guidance from various NHC/CPHC intensity models (coloured lines) including the official NHC forecast (OFCL) for Tropical Storm Marie for the 1200 UTC 22 August 2014 forecast cycle. The observed best-track intensity of Marie is shown by the black line with hurricane symbols.

2.7.1.2 RSMC La Reunion

While motion forecast has clearly improved over the past decade, intensity forecast remains a big challenge for forecasters and numerical guidance. Despite advances of numerical forecast of intensity and structure, operational simulations remain unsatisfactory.

Intensity forecasting methods at La Reunion are mostly still based on human expertise and analysis of environmental conditions changes that are usually well predicted by NWP.

To make a medium-range forecast (up to 120-h lead time), the duty forecaster scrutinizes parameters that are favourable or unfavourable for development.

Global environmental atmospheric parameters looked at:

- Vertical Windshear is often assessed as a proxy by considering the upper level winds between 300 and 150 hPa, depending on intensity (the more intense the TC, the higher the upper level winds are considered).
- Low/Mid-levels Humidity between 850 and 500 hPa.
- Upper level divergence and how efficient the upper level outflow is (number and strength of outflow channels).
- For early stages and cyclogenesis, check if low levels inflow – on both poleward and equatorward sides – are suitable for further intensification.
- Potential vorticity interaction with upper level troughs, even though this interaction is often hard to interpret.
- Global environmental oceanic parameters.
- Along-track analyzed Oceanic Heat content.
- Along-track analyzed Sea Surface Temperatures (and depth of the 26°C).
- Hybrid (Oceanic and Atmospheric parameters).
- Vmax, Maximum Potential Intensity.

This environmental global approach is completed by using the deterministic numerical forecasts issued by the various available models:

- Vmax and MSLP guidance are used via their trends (intensification or weakening) more than the associated numerical values. For systems undergoing extra-tropical transition, the NWP numerical MSLP and Vmax are often quite informative however.
- Ensemble qualitative approaches are now more and more used.
- STIPS is also helpful for forecaster despite the email dissemination format that is not adapted for easy automatic decoding.

Other elements considered, at least to adjust the intensity forecast:

- Is the forecast structure (large or small outer circulation) liable to enable/favour a rapid weakening/intensification rate. Consideration of specific features on sat imagery (especially microwave) can help anticipate rapid intensification at short range, incipient shearing or specific evolutions (such as an eyewall replacement cycle to come).
- How could be the oceanic response/feedback, depending on the TC motion’s speed forecast.
- What coastal interactions may occur, if a TC is forecast to track close to a shore without making landfall.
- In case of temporary landfall with a TC going back over sea a few hours later (case of a TC crossing the northern part of Madagascar for instance), is the mid-levels structure enough robust to permit a future re-intensification.
- Motion and Intensity forecasts have to be coherent one with each other (for instance: weakening through upper ventilation/shear implies lowering of levels ruling the steering flux).

Intensity forecast verifications are not routinely done, but the general feeling (confirmed by the verification) is that intensity guidance improvements are far more gradual than recent reductions in track forecasts.

2.7.1.3 RMSC Tokyo

Conventional atmospheric and oceanic environmental parameters such as atmospheric vertical shear and sea surface temperature have been monitored by RSMC Tokyo to forecast the development of ongoing tropical cyclones along with the results of climatic guidance and dynamical forecasts conducted by global atmosphere model every six hours. In addition, tropical cyclone heat potential (TCHP) has been monitored preliminary to utilize tropical cyclone intensity forecasting. TCHP is a measure of the ocean heat content integrated from the surface down to the depth of 26˚C isotherm (Leipper and Volgenau 1972). TCHP is daily computed based on Wada et al. (2012) from the oceanic dataset by the Meteorological Research Institute multivariate ocean variational estimation (MOVE) system (Usui et al. 2006) operationally used in the Japan Meteorological Agency.

2.7.1.4 RSMC, New Delhi

RSMC, New Delhi has issued intensity forecasts for deep depression stage (mean surface winds of 28-33 kts) and above since 2009 for 12-, 24-, 36-, 48-, 60- and 72-h forecast periods (Mohapatra et al. 2013 and Figure 6).

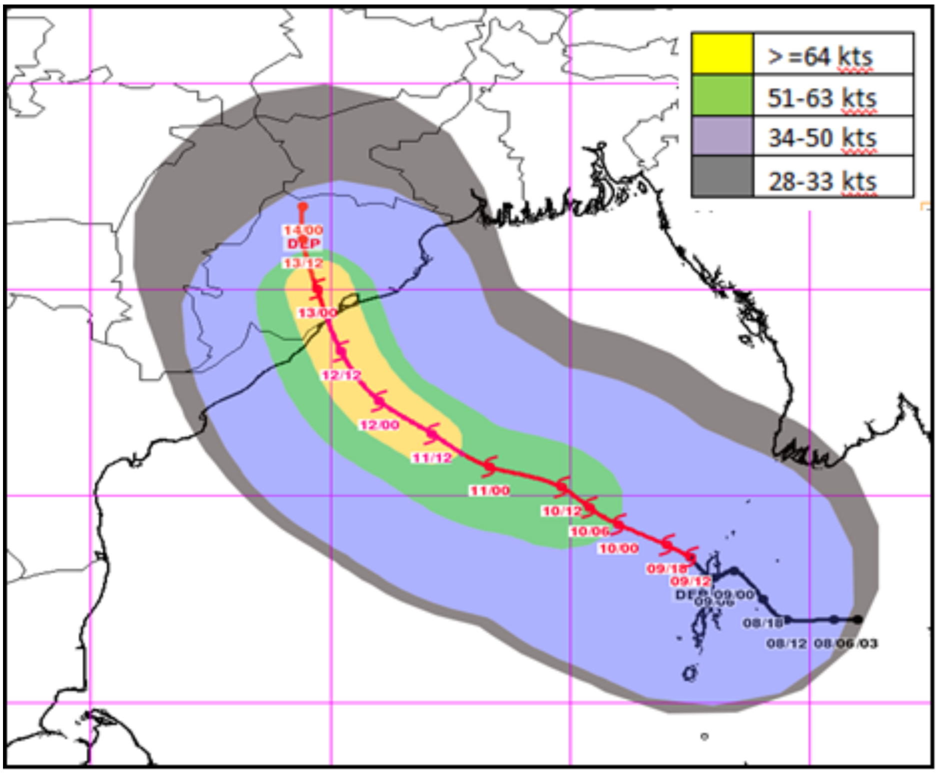

Figure 6. A typical graphical presentation of intensity and quadrant wind forecast issued at 1200 UTC of 09th October 13 for TC Phailin (08-14 October 2013)

As of 2013, RSMC, New Delhi issues TC intensity forecasts 4 times a day out to 120 h starting at synoptic times (00, 06, 12 and 18 UTC). The forecasts are issued about three hours after those synoptic times. The tools and methods used by IMD for TC intensity forecasting include satellite, radar and synoptic observation as well as guidance from various global and regional deterministic models (IMD-GFS, NCMRWF (India)-GFS, ECMWF, UKMO, JMA, ARP (Meteo France), IMD-WRF, WRF run at Indian Institute of Technology - Delhi, NCMRWF-WRF, NHWRF, NCEP-HWRF) and probabilistic predictions from ensemble prediction systems (NCMRWF-GEFS, ECMWF-EPS etc.) (Mohapatra et al. 2013). In addition there are statistical-dynamical models (i)

Statistical Cyclone Intensity Prediction (SCIP; Kotal et al. 2008) and (ii) Satellite based cyclone observations and real time predictions over the Indian Ocean (SCORPIO; (http://122.252.237.243/scorpio/) developed by the Indian Space Research Organization.

The SCIP scheme (Kotal et al. 2008) has been used as guidance for operational intensity prediction since 2009. SCIP model predictions are available to operations in a delayed mode (created with the most recent and available model output). A simultaneous comparison of the AAEs for 24-, and 48-h forecasts (Figure 7, top), indicate that IMD's operational forecast errors are similar to that of the SCIP model. However, a comparison in a 12-h delayed mode (Figure 7, bottom) indicates lower errors in the operational forecasts. This demonstrates the value added by the forecasters' evaluations of all available information.

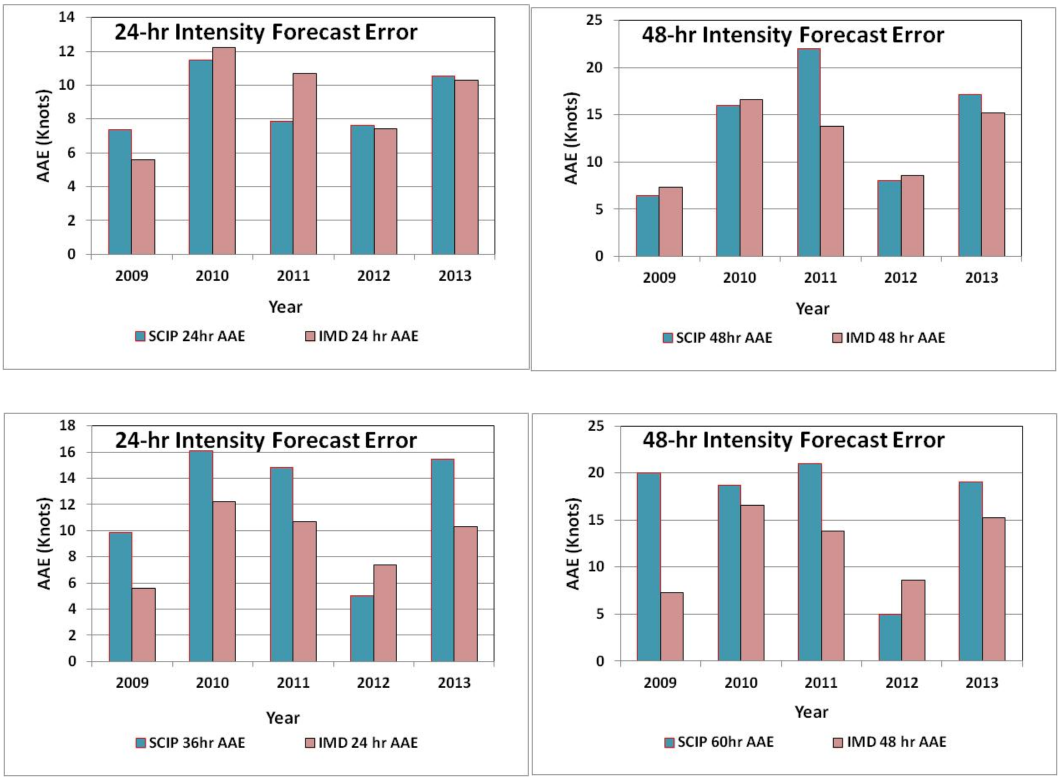

Figure 7. Performance of SCIP intensity prediction and IMD's operational forecasts during 2009-2013 for (top) 12-h delayed SCIP forecasts and (bottom) real-time forecasts

The IMD forecast MAE during 2009–2013 is about 10, 14 and 18 knots for 24, 48 and 72 h, respectively (Mohapatra et al. 2013). The skill (with respect to persistence) is 44%, 60% and 60% for 24-, 48- and 72-h forecasts and has improved at 9% per year at 24 h. For 2005-2013, mean absolute errors have decreased 1 knot per year, though the trend is not significant. IMD also finds that the intensity forecast errors are typically greater for more intense TCs and intensity prediction is more difficult over Arabian Sea than over Bay of Bengal. The later finding is thought to be due to poorer data availability in the Arabian Sea; leading to poor initial conditions in NWP models. Similar findings were found in the NWP model-based studies of Osuri et al. (2012).

To help anticipate rapidly intensifying TCs, a statistical-dynamical rapid intensification index (RII, decrease of 30 hPa in 24 hrs) has been developed by Kotal and Roy Bhowmik (2013) based on the period 2003-2013. During this period there were 10 cyclones that underwent rapid intensification. The IMD RII has been operational since 2013. An example of the forecast probability of Rapid intensification for cyclone PHAILIN over Bay of Bengal during 08-14 October 2013 is given in Table 1. The table shows that the RII was mostly able to predict the OCCURENCE as well as NON-OCCURENCE of Rapid Intensification of cyclone PHAILIN. Other forecast times during Phalin showed varying degrees of success with RII forecasts. Hence, work continues to improve IMD RI guidance.

Table 1. Probability of Rapid intensification for cyclone PHAILIN over Bay of Bengal during 8-14 October 2013

Forecast based on	Probability of RI predicted	Chances of occurrence predicted	Intensity changes (kt) in 24h	Occurrence
00 UTC/08.10.2013	9.4 %	VERY LOW	5	NO
00 UTC/09.10.2013	9.4 %	VERY LOW	15	NO
12 UTC/09.10.2013	9.4 %	VERY LOW	***40***	***YES***
00 UTC/10.10.2013	72.7 %	HIGH	65	YES
12 UTC/10.10.2013	72.7 %	HIGH	40	YES
00 UTC/11.10.2013	72.7 %	HIGH	5	NO
12 UTC/11.10.2013	32.0 %	MODERATE	0	NO

Rapidly weakening TCs is also recognized as a forecast problem since it very often leads to over-warning. During the period 2003-2013, 7 cyclones underwent rapid weakening (decrease in intensity by 30 knots or more in 24 hours). Such situations are typically managed by providing frequent update and immediate revision of forecasts with the sign of weakening envisioned through synoptic analyze; however, there is a need for more guidance on rapid weakening.

There are also cases when landfalling cyclones maintain their intensity after landfall. This often occurs when a TC moves over flat terrain, especially over deltas such as the Ganges during post –monsoon season (October-December). These slowly weakening systems typically occur when soil moisture and atmospheric moisture are high due to recent rainfall associated with monsoon. To provide guidance for these slowly weakening systems, IMD uses a statistical DECAY model (Roy Bhowmik et al. 2005). This model is a simple statistical model. It performs reasonably well, but does not account explicitly for all the hydro-dynamic processes related to decay after landfall.

2.7.1.5 Tropical Cyclone Warning Centers (TCWCs) Perth, Darwin and Brisbane

The intensity forecast process follows the determination of the analysis fix and forecast track and its inherent uncertainty. It is predicated on an understanding of the current large-scale environment and the analyzed intensity and trend over the past 24 hours or so. The intensity process then requires examination and comparison of the expected changes to the large-scale environment as indicated by different NWP. This includes upper level flow, vertical wind shear, low- to mid-level moisture, ocean heat content, low-level inflow and proximity to land factors.

An ongoing issue for forecasters is the display of the most representative wind shear on a vortex and the associated interpretation of how this could affect the future intensity. This is particularly the case for the Australian region where wind shear is a dominant influencing factor. This can result in an initial intensity forecast estimate. 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-number per day in a Dvorak T-number framework.

This initial subjective assessment is followed by a check of the objective NWP intensity forecasts and statistical, statistical-dynamic models. BoM has used Statistical Typhoon Intensity Prediction Scheme (STIPS; Knaff and Sampson 2009) output for several years and the output is particularly valued as it quantifies the environmental parameters from NWP. It utility is limited by the models used in the consensus (it not including some models such as ECMWF) and by forecasts being insensitive to rapid changes in environmental influences, especially at long lead times.

In the 2013/14 season Bureau of Meteorology began receiving experimental NRL products [Statistical Hurricane Intensity Prediction Scheme (SHIPS), Logistic Growth Equation Model (LGEM, based on both NAVGEM and GFS models), and RII (Rapid Intensification Index] and intensity output from HWRF and COAMPS-TC. There was only limited use of this new information as forecasters require verification evidence and training on how best to use this guidance.

Consistency between dynamical models is an important consideration with bias given to the better performing and higher resolution models. Because NWP have historically underestimated the intensity, trends rather than absolute values of model intensity are given greater consideration. 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.

An ongoing issue facing forecasters is assimilating the increasing amount of information to make a decision. To help alleviate this issue, BoM is developing a tool within its forecast software, *TC Module*, to improve the display of the available guidance and make it easier to determine the intensity at each forecast time step (Figure 8).

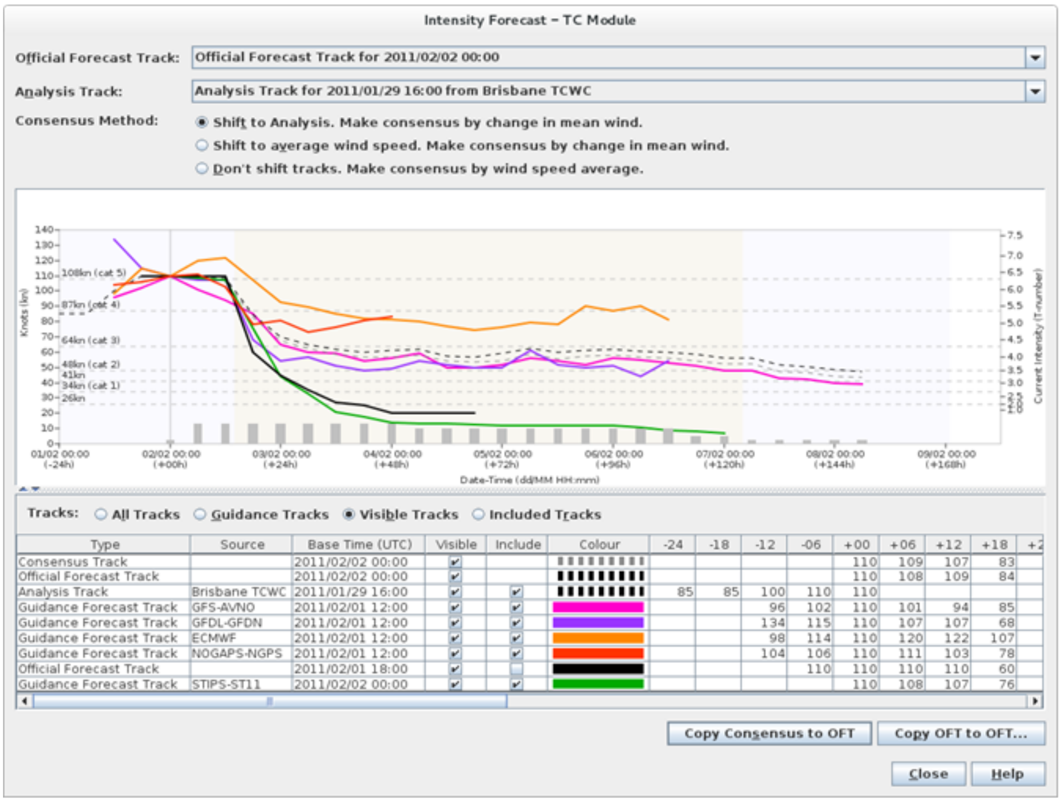

Figure 8. Example of operational intensity forecast interface, this one from the BoM TC Module

2.7.1.6 Joint Typhoon Warning Center (JTWC)

Guidance for TC intensity change, particularly for the onset, duration, and magnitude of rapid intensification and weakening, remains JTWC's top operational need. The JTWC production timeline allows approximately one hour for analysis, one hour for forecast synthesis, and one hour for warning generation and dissemination. Mandated timeliness of TC warnings and advisories provides little time to dedicate to any individual analysis and forecast. This is particularly true when multiple warned systems and invests are active in the area of responsibility (AOR). This lack of time in the forecast process underscores the need for 1) the transition and integration of efficient and straight-forward guidance in to operational tools (e.g., *ATCF*) and 2) proper training on guidance interpretation, evaluation, and skillful application to the art of forecasting.

The JTWC intensity forecast begins with an analysis of a TC's current state (position, intensity, structure) and synoptic-scale environment. This analysis not only forms the basis of any forecast, but these data are ingested to varying degrees into many of the models which make up the intensity consensus via the "TC vitals" inputs. A poor analysis can have a dramatic impact on the model guidance, negatively affecting the eventual forecast.

An intensity forecast is intrinsically tied to the TC's track and the local- to synoptic-scale conditions it will encounter over the course of that track. Therefore, consistency between track and intensity forecast philosophies is essential. After the forecast track has been established, the Typhoon Duty Officer (TDO) must take into consideration a number of intensity factors and general guidelines, including:

- Strength and directionality (i.e., single-channel, dual-channel, radial) of the upper-level outflow.

- Strength of vertical wind shear (VWS) Proximity and position of tropical upper-tropospheric trough (TUTT) or TUTT cells.
- Interaction potential with mid-latitude troughs.
- Oceanic heat content (OHC) conditions.
- Sea surface temperature variations.
- Relative proximity to other TCs.
- Low- to mid-tropospheric moisture. Rapid Intensification (RI) potential.
- Eyewall replacement cycle (ERC).
- Annular Tropical Cyclone Structure.
- Land interaction.
- Consistency with previous warning(s)
- Temporal Model Continuity.

Several key intensity elements for the short-range forecast can be diagnosed in the analysis, while longer range considerations must be gleaned from dynamical and statistical-dynamical model guidance. As a general rule, the initial intensity change assessment calls for intensification of one Dvorak T-no per day. The final forecast combines the initial assessment with the TDO's subjectively weighted inputs and guidance from NWP. Each of these aids is displayed in ATCF for examination and inter-comparison, with or without intensity probabilities (GPCE; Goerss and Sampson 2014) that outlines the 67th percentile of the intensity guidance consensus. Although global model intensity skill generally lags mesoscale model performance, examination of the model fields and/or intensity trends extracted from global models provide useful information on the synoptic-scale processes that may be impacting the forecast. Global model intensities that are inconsistent with the analysis or track philosophy may be excluded from consideration. Differences in global model forecasts also provide insight on mesoscale models - those initialized with specific global models.

The number of mesoscale models available to JTWC has steadily climbed over the last five years, with routine evaluation of GFDN, COAMPS-TC, and HWRF conducted for each forecast. HWRF has been available since 2012 and support was expanded to include the Indian Ocean in 2013 and Southern Hemisphere in 2014.

JTWC's primary WESTPAC forecast intensity guidance, S5YY, is generated by ATCF at every synoptic time. The 2014 version of S5YY consists of the following members:

- LGEN/DSHN – SHIPS/LGEM using NAVGEM track and wind and thermal field inputs
- LGEA/DSHA – SHIPS/LGEM using GFS track and wind fields, and NAVGEM thermal fields
- CHII – Interpolated CHIPS model
- GFNI – Interpolated GFDN model forecast intensity
- COTI– Interpolated operational COAMPS-TC
- HWFI – Interpolated WESTPAC HWRF model

Not surprisingly, many of the SHIPS factors are listed in the intensity considerations above. SHIPS output is available for review in ATCF, providing the TDO detailed information on how the model weighed each of the inputs. In the future, the SHIPS algorithm may be applied to additional global and mesoscale models, opening the door for the potential of a SHIPS ensemble. JTWC recently received the following guidance on the interpretation of SHIPS/LGEM (Mark DeMaria, personal communication):

1. LGEM is likely to have a low bias with the initial intensity is less than approximately 30 knots

2. A large negative contribution to the intensity (≥ -5 knots) associated with the upper level temperature is an indicator of a potential low bias in both LGEM and SHIPS.

The best performing guidance in the Indian Ocean and Southern Hemisphere basins is currently the S5XX, a combination of a STIPS ensemble with GFDN, COAMPS-TC, and CHIPS (Emanuel et al. 2004) inputs. Recent improvements to S5YY are under evaluation as a likely replacement to the S5XX.

RI, defined as a 30 knot or greater increase in 24 hours, is one of the most challenging aspects of the intensity forecast in the WESTPAC, where a large percentage of tropical cyclones experience such intensification during their lifespans. Since 1961, 44% of WESTPAC tropical storms experienced at least one RI event, while fully two-thirds of all typhoons did the same. A major addition to ATCF in 2013 was the SHIPS-RI module, which has been extended to IO and SHEM basins for 2014. SHIPS-RI output is figured into the intensity forecast calculus, however, a verification of the optimal threshold indicator and overall performance is ongoing. Additionally, COAMPS TC, HWRF, and GFDL are being evaluated for their efficacy to forecast RI.

Focused investment on dynamical and statistical-dynamical models and consensus methodologies has contributed to a pronounced increase in 2-3 day forecast intensity skill of the NRL-MRY consensus over the last five years (Figure 9). Combined with increased forecaster awareness of intensity forecast considerations and change indicators, JTWC forecast intensity errors, which remained nearly unchanged for almost two decades, have seen a slight downward trend over the past five years at the longer forecast periods (Figure 10). The increasing quantity and quality of intensity guidance should pave the way for continued improvement and a transition to probabilistic forecasting.

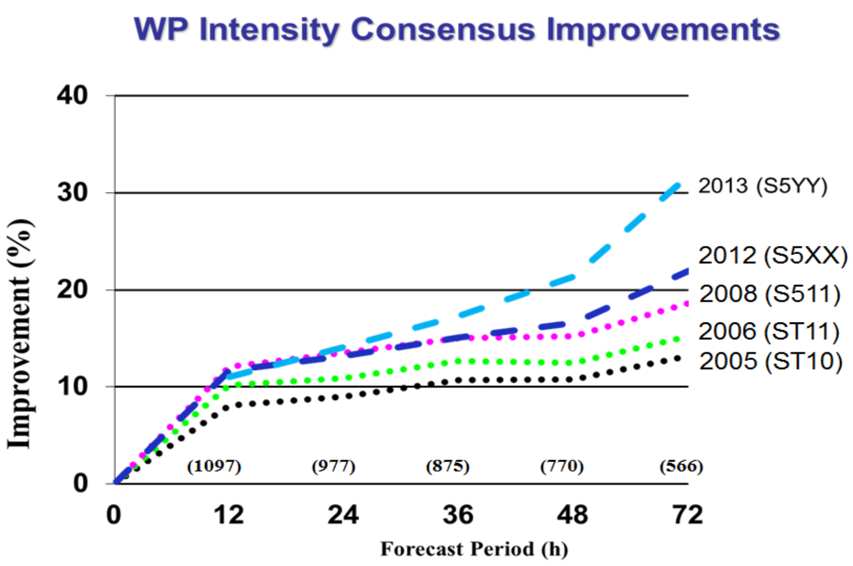

Figure 9. Intensity consensus skill over the past decade at JTWC

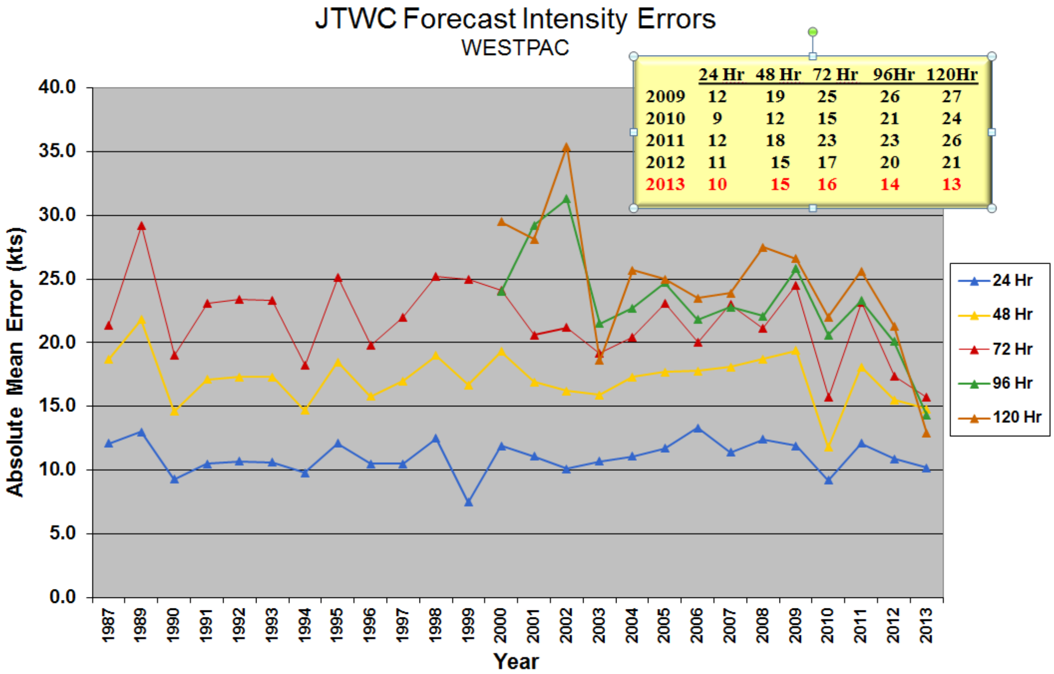

Figure 10. JTWC Mean Forecast Intensity Errors, 1987-2013

2.7.2 Intensity forecast guidance summaries

As indicated in the operational centre summaries, the deterministic intensity guidance employed in operations generally fits into categories of statistical models, statistical-dynamical models, NWP models, and consensus/ensemble means. More recently some probabilistic applications are gaining popularity. The following highlight the different types of guidance available to forecasters.

2.7.2.1 Statistical Models

Although they still have some use in operational forecasting, statistical models are primarily used as skill baselines for both operational and model forecasts. The Statistical Hurricane Intensity Forecast model (SHIFOR; Jarvinen and Neumann 1979) was the first of these, and it uses climatology and persistence variables to forecast intensity changes out to 72 h. Subsequently a 5-day version of this model was implemented in the early 2000s, as described in Knaff et al. (2003), for all basins. Other centres have their own versions of statistic models or even use persistence (Kotal et al. 2008) for baselines.

Analog models may also provide guidance and baselines for measuring skill at the longer ranges. One such recent model is WANI (Tsai and Elsberry, 2014), which is developed from best tracks, and relies on an average of the 10 closest analogs to a given cyclone and its forecast track.

2.7.2.2 Statistical-Dynamical Models

Statistical-dynamical models are not terribly complex, relying on relationships of parameters thought to be important in intensity change (e.g., current intensity and trend, shear, thermodynamic variables and SST) to changes in intensity. The first of these models, The Statistical Hurricane Intensity Prediction Scheme (SHIPS; DeMaria et al. 2005) first became available for the Atlantic basin in 1991 and has undergone considerable changes in the intervening years (e.g., explicit treatment of land, use of satellite retrievals and ocean heat content). Implementation of SHIPS-like models in other basins followed (STIPS; Knaff et al. 2005, Knaff and Sampson 2009), and more recently a more sophisticated prediction equation has been applied to the same predictors (LGEM;

DeMaria 2009). The latest versions of STIPS, SHIPS and LGEM are now all run as ensembles at the JTWC, and the live forecasts for are available on the JTWC collaboration site and to WMO RSMCs as text emails from NRL upon request. The IMD runs a statistical-dynamical model for the Indian Ocean (Kotal et al. 2008), which is discussed in more detail above.

2.7.2.3 Dynamical Models

By far the greatest effort and greatest improvements in tropical cyclone intensity forecast guidance in the past four years has been with the NWP models. As these models attain higher resolution and more sophistication, they have been able to achieve skill required to be of use in operations. Table 2 is a partial list of operational global models and Table 3 is a partial list of regional models used in intensity forecasting. Each of these models has shown incremental improvements with development, and some are now competitive with the statistical-dynamical models in terms of skill.

Not surprisingly the models showing the best ability to improve intensity forecasts are regional models that provide high resolution by using nested grids. Figure 11 shows the domain of the Meteo France AROME-IO model, which is an example of this strategy.

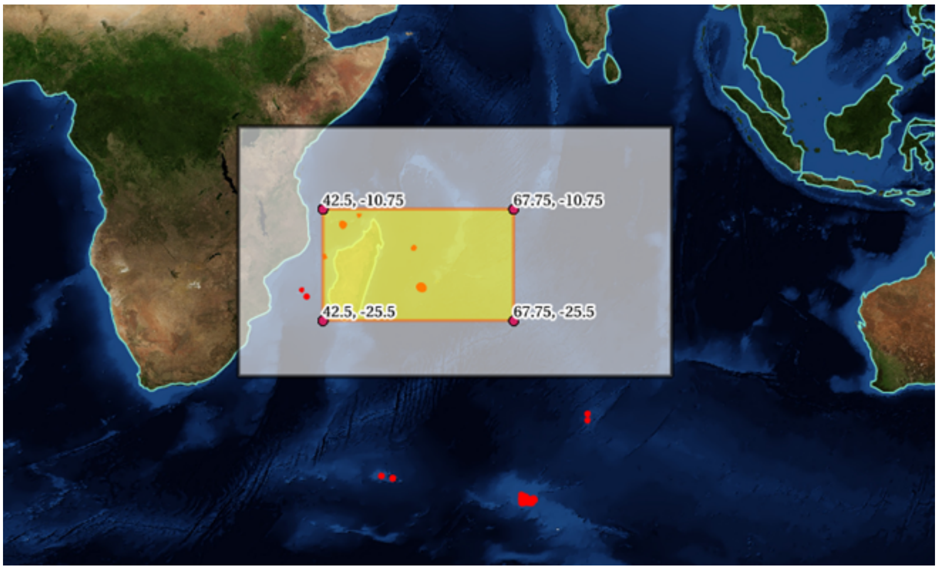

Figure 11. Current domain of Arome-OI (yellow) overlying ALADIN-Réunion operational domain (area of responsibility of RSMC La Réunion; white)

One of the recommendations of IWTC-7 was to increase the availability of TC intensity guidance by making methods developed in the eastern North Pacific and Atlantic available in other basins. This recommendation has resulted in the development of not only statistical-dynamical techniques (SHIPS, LGEM, and RII) in different basins, but by expansion of effort in the NWP community. Figure 12 shows the regions where HWRF and GFDL/GFDN models are currently operated in real-time.

To provide a sense of the improvements we include a short summary of one model (GFDL). This is not in any way a recommendation of the GFDL model over the others, but is only provided as an example of the improvements finding their way into the operational NWP models. More extensive descriptions, including citations, for several other high quality NWP models addressing the intensity problem can be found at http://www.emc.ncep.noaa.gov/HWRF/IWTC_VIII. This is not an endorsement of these models over others, but is intended to provide readers a sense of the level of effort on and intensity forecast improvements being attained.

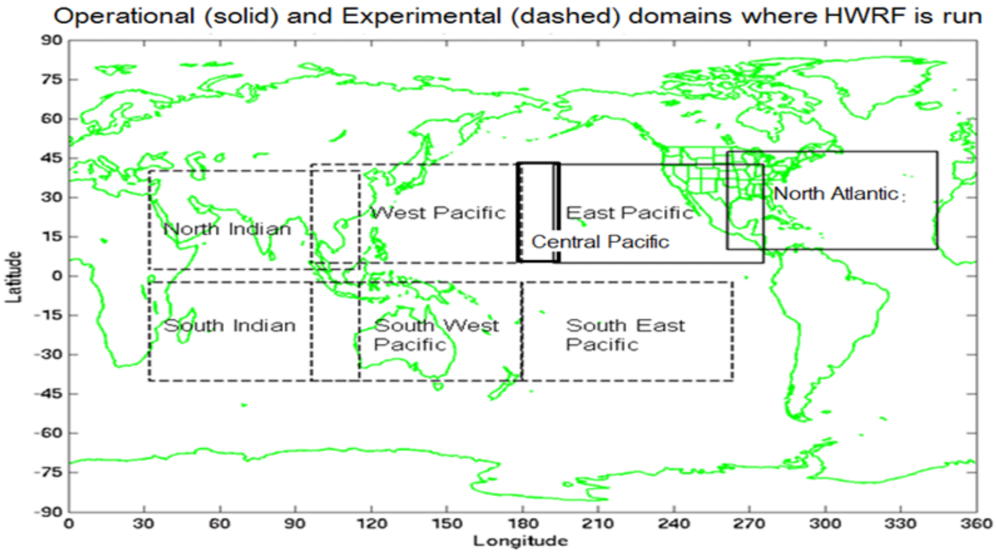

Figure 12. Tropical oceanic basins covered by the HWRF model. Solid lines represent operational HWRF/GFDL domains at NCEP. Dashed lines show areas where experimental HWRF forecasts are provided.

Table 2. Global operational models used for TC intensity forecasting. List is not necessarily comprehensive.

Global Models		
Model Name	**Information**	**Notes**
ARPEGE (France; Action de Recherche Petite Echelle Grande Echchelle)	http://www.cnrm-game.fr/spip.php?article121	
GFS (USA; Global Forecast System)	http://www.emc.ncep.noaa.gov/GFS/doc.php	
GDPS (Canada; Global Deteministic Prediction System)	http://weather.gc.ca/model_forecast/global_e.html	
Met Office (UK; Met Office)	http://research.metoffice.gov.uk/research/nwp/numerical/operational/	Also known as the unified model
NAVGEM (USA; NAVy Global Environmental Model)	http://www.nrlmry.navy.mil/metoc/nogaps/	Replaces NOGAPS
NGFS (India:GFS run at NCMRWF)	http://www.ncmrwf.gov.in/#	
ECMWF (Europe; European Center for Medium Range Weather Forecasts)	http://www.ecmwf.int/en/forecasts/documentation-and-support	
ACCESS (Australia; Australian Community Climate and Earth-System Simulator)	http://www.bom.gov.au/australia/charts/about/about_access.shtm	
GSM (Japan; Global Spectral Model) **CMA-GSM** (China; Global Spectral Model run at NMC/CMA)	http://www.jma.go.jp/jma/en/Activities/nwp.html Yu et al. (2013)	

Table 3. Regional/TC operational models. List is not necessarily comprehensive.

Regional Models		
Model Name	**Information**	**Notes**
GFDL (USA; Geophysical Fluid Dynamics Lab)	http://www.gfdl.noaa.gov/operational-hurricane-forecasting	Running in West Pacific
GFDN (USA; run off of NAVGEM by the US Navy)		Development behind GFDL
ALADIN (France/Consortium)	http://www.cnrm.meteo.fr/aladin/?lang=en	
AROME-IO (France; AROME-Indian Ocean)	http://www.cnrm.meteo.fr/spip.php?article120	AROME will replace ALADIN in 2015
HWRF (USA; Hurricane Weather and Research Forecast Model)	http://www.emc.ncep.noaa.gov/?branch=HWRF	Coupled, 3km inner mesh Also run in W. Pacific and SH
NHWRF (India; Hurricane Weather and Research Forecast Model run at NCMRWF)		
COAMPS-TC (USA)	http://www.nrlmry.navy.mil/coamps-web/web/tc?&spg=2&scl=3	Coupled, big improvements in 2014 thus far.
ACCESS-TC (Australia; TC centric)	http://www.bom.gov.au/australia/charts/about/about_access.shtml	Replaces TC-LAPS, 3 re-locatable domains
ACCESS-R (Australia; Regional)	http://www.bom.gov.au/australia/charts/about/about_access.shtml	
GRAPES-TCM (China; GLOBAL/REGIONAL ASSIMILATION AND PREDICTION SYSTEM –TC Model) **GRAPES-TCM** (China; GLOBAL/REGIONAL ASSIMILATION AND PREDICTION SYSTEM –Tropical Model)	http://www.ral.ucar.edu/hurricanes/repository/models/grapestcm.php Yu et al. (2013)	

2.7.2.3.1 GFDL Model Upgrades (Example of NWP Model Improvements)

The Geophysical Fluid Dynamics Laboratory (GFDL) hurricane model (Bender et al., 2007) has been used as an operational track and intensity forecast guidance tool by the U.S. National Weather Service (NWS) since 1995 for the Atlantic and eastern Pacific basins and by the U.S. Navy since 1996 for other global TC basins. The model is a moveable, triply-nested, regional grid point model that uses data from a parent global model for the initial and lateral boundary conditions. The vortex that is present in the global model's initial condition is removed and replaced by running a two-dimensional version of the forecast model to create a vortex that has characteristics consistent with current observations of the real storm. Since 2001, the model has been coupled to the Princeton Ocean Model in order to more accurately depict the two-way interactions between the atmosphere and the upper-ocean layers in the near-storm environment (Bender and Ginis, 2000).

Numerous upgrades have been performed on the model in recent years that have led to improvements in track and intensity forecasting. Most recently, for the 2014 hurricane season, a set of major upgrades was introduced, including an increase in horizontal resolution of the innermost grid from 1/12^o to 1/18^o. In addition, significant effort was given to reformulating the momentum drag (C_d) and enthalpy exchange coefficients (C_h) to be more consistent with recent observational and theoretical studies (e.g., Figure 13).

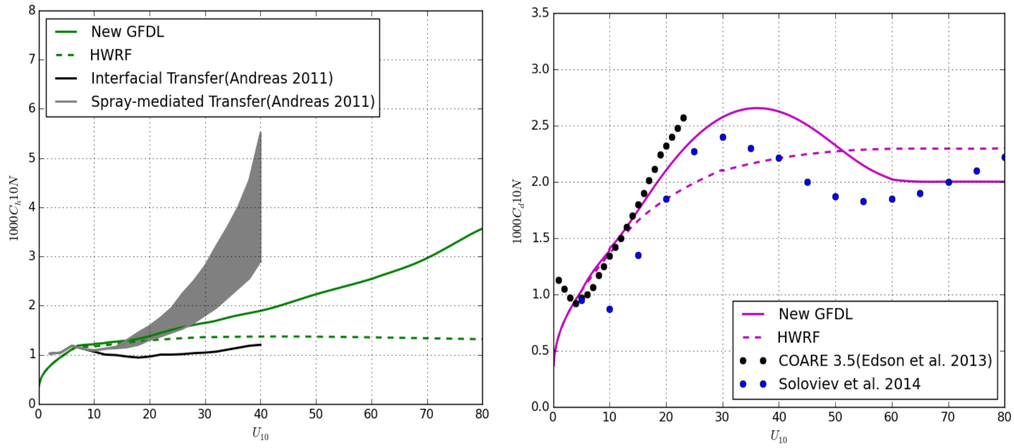

Figure 13. Values for the momentum drag coefficient (C_d, left) and enthalpy exchange coefficient (C_h, right) across a range of 10-m wind speeds for various models and observational and theoretical studies.

Additional key upgrades for 2014 include modifications to the micro-physics, improved targeting of the observed initial storm maximum wind speed and storm structure in the vortex initialization, and the removal of the synthetic vortex specification for storms with an observed intensity of 40 knots or weaker. The net effect of all of these upgrades has been a positive impact on track and especially intensity forecasts. Results shown in Figure 14 indicate that for a large sample of forecasts of storms from recent years, statistically significant improvements in intensity forecasts have been achieved when results from the 2014 model are compared with those from the previous operational version of the GFDL model.

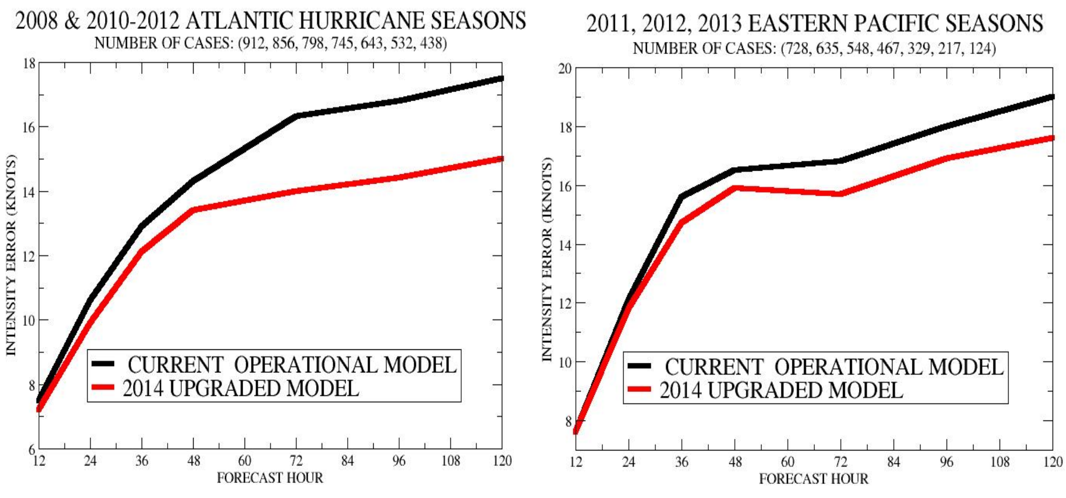

Figure 14. Mean absolute intensity forecast error for storms in the Atlantic (left) and eastern Pacific (right) basins, using both the 2014 upgraded GFDL model (red) and the version of the GFDL model that was current at the time of the operational forecasts. Storms included in the sample extend from 2008-2013, with 912 (728) forecasts in the sample at the initial time for the Atlantic (eastern Pacific).

2.7.2.4 Consensus and Ensemble Mean Forecasts

As the guidance becomes more skillful and plentiful, opportunities for forming consensus or ensemble means and distributions have been developed. One of the first published for use as both deterministic and probabilistic guidance (PEST; Weber, 2005), relied on many aids of varying skill. Others were developed with different methodologies and using more skillful guidance and many been pressed into operations with success. Some of the deterministic aids are equally weighted averages using several skillful models (e.g., see Sampson et al. 2008, Cangialosi and Franklin 2012), while others attempt to weight the guidance (SPICE; Musgrave and DeMaria 2014, FSSE; Krishnamurti et al. 2011). Some studies warn that constructing weights without prior knowledge of the performance characteristics of the individual models can result in no gain or even degradation in forecast skill (e.g., Kharin and Zwiers 2002, Weigel et al. 2010, Del Sole et al. 2013, Qi et al. 2014), so the topic remains active in the scientific community. Equally weighted consensus aids are popular at the operational centres because they are easy to construct and maintain and remain difficult to beat.

Many of the NWP models in Tables 2 and 3 also run ensembles with some success. Very recent results from the GFDL and HWRF groups indicate skill improvements on the order of 10s of percent, especially at the longer leads. This guidance will soon be evaluated in real-time since it has just recently become available to operations.

2.7.2.5 Probabilistic guidance

Prediction of intensity forecast uncertainty has become an active area of research as the deterministic guidance becomes more skillful and plentiful. Some techniques use analogs (WANI; Tsai and Elsberry 2014), others use consensus (PEST; Weber 2005, GPCE; Goerss and Sampson 2014) or ensemble information, and still others use an assortment of initial data, objective aid forecasts and environmental data (e.g., shear) input (Bhatia and Nolan 2014).

New techniques to forecast probabilities of rapid intensification (Kaplan et al. 2010, Rozoff and Kossin 2011) and NWP model improvements are making some headway in this difficult task. There is also some preliminary progress being made to forecast inner core processes. Efforts to make probabilistic real-time predictions of secondary eyewall formation (Kossin and Sitkowski 2009), eyewall replacement cycles (Kossin and Sitkowski 2012) and annular tropical cyclones (Knaff et al. 2008) have also been developed and are being integrated into SHIPS.

2.7.2.6 Conclusions and Recommendations

The primary metric for measuring improvements and skill in intensity forecasting is the mean forecast error (i.e., MAE). Mean forecast error has its merits (simplicity being the main one), and is routinely used in conjunction with biases to assess skill of guidance against a baseline such as SHIFOR-5, decay SHIFOR-5 and ST5D (Knaff et al. 2004). By these measures, improvements in statistical-dynamical guidance and NWP models have increased skill of consensus aids that include this guidance to the point where consensus is now competitive with official forecasts. But using only mean forecast errors to measure skill has drawbacks (see Aberson 2008 for alternative measures of skill), and forecast busts are still common enough (Figures 15 and 16). As the guidance improves in the coming years we expect to see an increase in guidance that more closely captures these dramatic increases/decreases in intensity.

Recommendations:

1. Increase sharing of data among forecast centres. More guidance has been developed since the last IWTC and sharing this guidance among the forecast agencies benefits all centres.
2. Continue development of NWP models, statistical models and probabilistic guidance with special focus on cases with large forecast errors.

3. Continue to increase the availability of TC intensity guidance by making methods developed in the eastern North Pacific and Atlantic available in other basins.
4. Investigation of new and innovative verification metrics and methods to aid in the elimination of the occasional very poor intensity forecasts.
5. Encourage research activity to investigate and understand the physical causes and the impact observation quality/availability on very poor intensity forecasts.

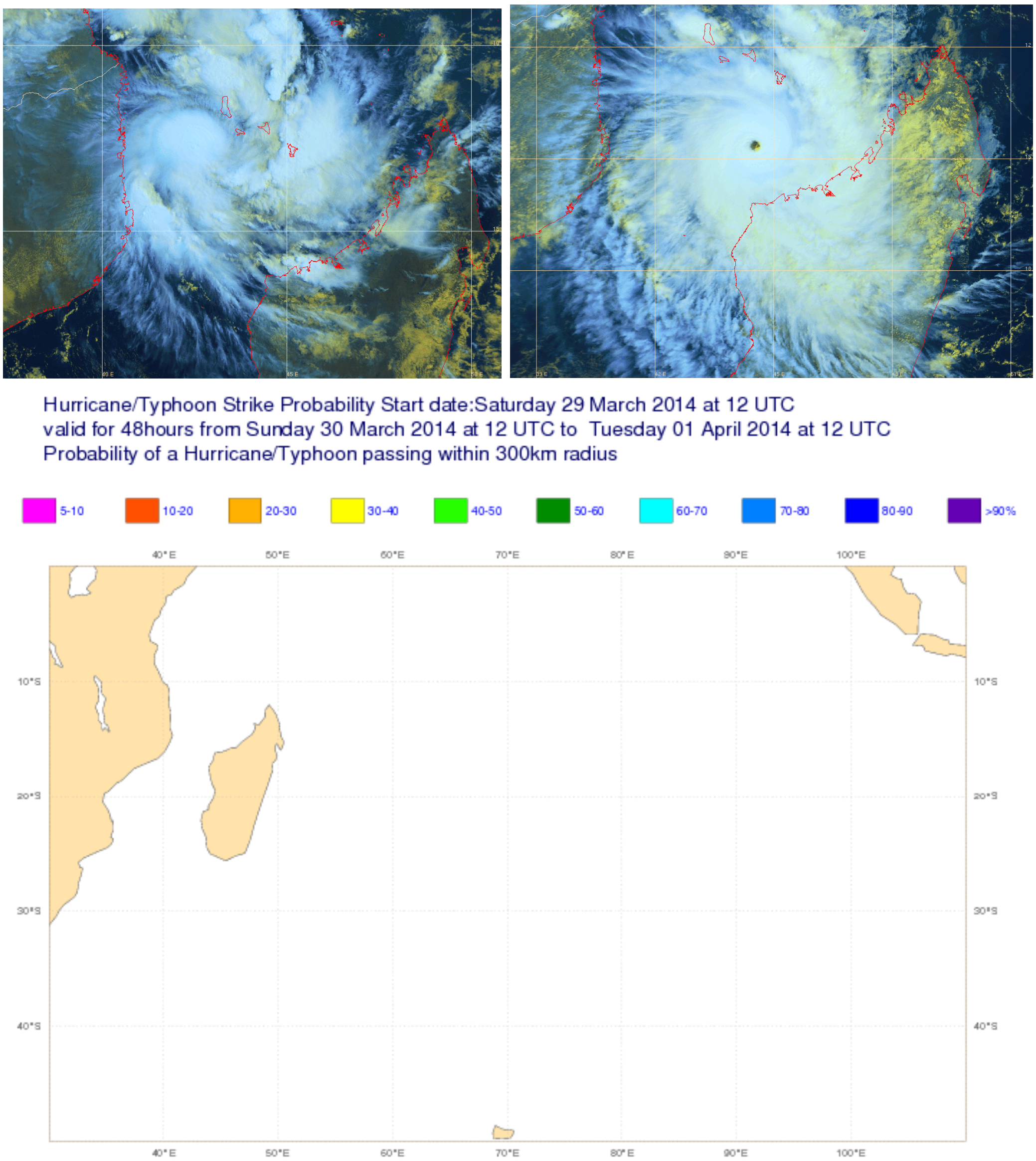

Figure 15. Hurricane strike probability from EPS (European Centre Ensemble) 29 March 2014 at 12 UTC valid for the 48 hours period from 30 March at 12 UTC to 01 April at 12 UTC. The hurricane probability was still at zero on 29 March at 12 UTC (TC HELLEN was then a tropical storm), while TC HELLEN became a very intense cyclone 24 hours later (sat images :top left = Metop 2, 29 March at 0635 UTC; top right = Noaa 19, 30 March at 1042 UTC).

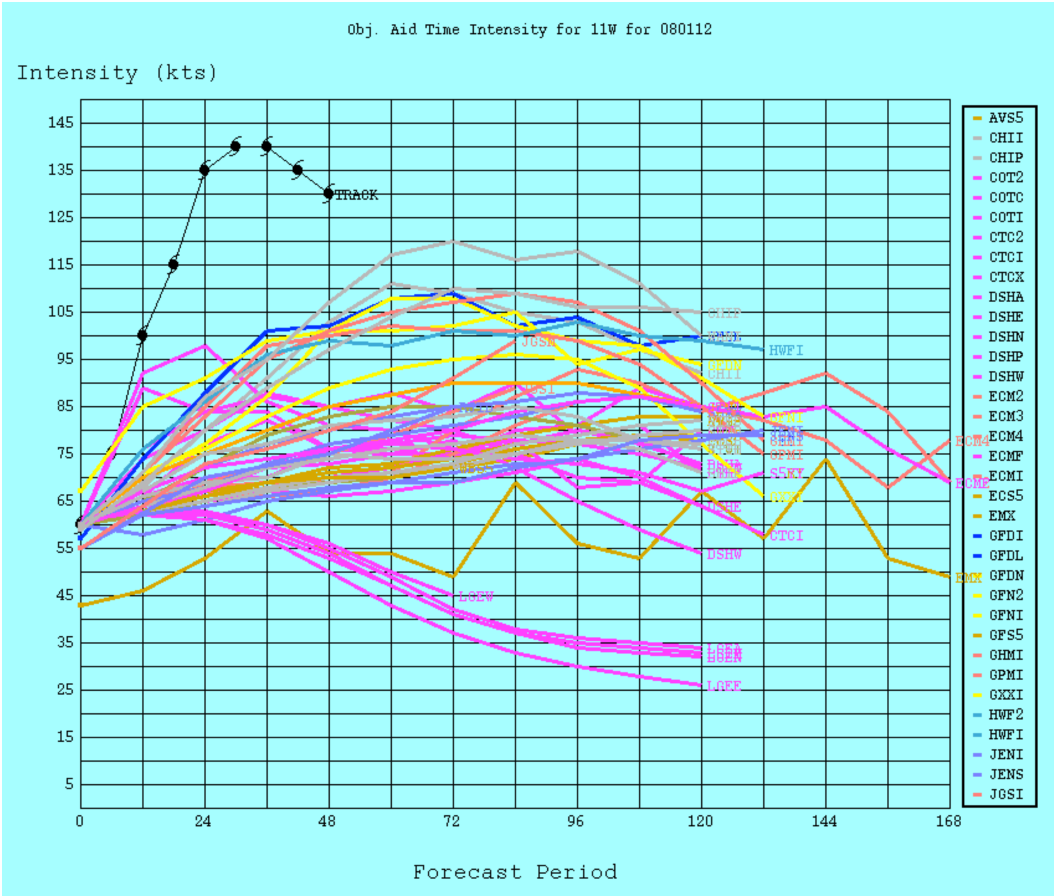

Figure 16. Selected intensity guidance (rainbow colours) initiated on August 1, 2014 at 12 UTC and verifying best track intensity (black typhoon symbols) for Halong (11W).
Note that all the forecasts are well below the verifying intensity between 24 and 48 h.

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Acronyms used in the report

ACCESS	Australian Community Climate and Earth System Simulator
ADT	Automated Dvorak Technique
AL	Atlantic basin
ALADIN	MeteoFrance regional model
AMSU	Advanced Microwave Sounding Unit
AOR	Area Of Responsibility
ARP	MeteoFrance Arpage (global)
AROME	MeteoFrance high resolution cloud resolving model
ATCF	Automated Tropical Cyclone Forecast System®
BoM	Bureau of Meteorology (Australia)
Cd	momentum drag coefficient
Ch	enthalpy exchange coefficient
CHIPS	Coupled Hurricane Intensity Prediction System
CHII	Interpolated CHIPS model
CLIM	Climatology aid
CMA	Chinese Meteorological Agency

COAMPS	Coupled Ocean/Atmosphere Mesoscale Prediction System®
COTC	COAMPS-TC
COTI	Interpolated COAMPS-TC
CPHC	Central Pacific Hurricane Center (USA)
DSHP	Decay SHIPS
EP	Eastern North Pacific basin
EPS	European Center Ensemble
ECMWF	European Center for Medium Range Weather Forecasting
EMXI	Interpolated ECMWF model intensity forecast
ERC	Eyewall Replacement Cycle
FSSE	Florida State SuperEnsemble
GFDL	Geophysical Fluid Dynamics Laboratory model
GFDN	GFDL model run by Navy (USA)
GHMI	Interpolated GFDL model
GFNI	Interpolated GFDN model forecast intensity
GFS	Global Forecast System (USA)
GFSI	Interpolated GFS model forecast intensity
GPCE	Goerss Predicted Consensus Error
GRAPES	Global/Regional Assimilation and Prediction System
GSM	Global Spectral Model
HWRF	Hurricane WRF
HWFI	Interpolated HWRF model
HFIP	Hurricane Forecast Improvement Project
ICON	An equally weighted consensus used at NHC
IMD	Indian Meteorological Department
IVCN	Equally weighted consensus used at NHC (only needs two members)
IV15	HFIP Stream 1.5 model consensus
JMA	Japanese Meteorological Agency
JTWC	Joint Typhoon Warning Center (USA)
LGEM	Logistic Growth Equation Model
LGEA/DSHA	SHIPS/LGEM using GFS track, winds, NAVGEM thermal fields
LGEN/DSHN	SHIPS/LGEM using NAVGEM track winds, thermal field inputs
NAVGEM	U.S. Navy Global Model
MSLP	Mean sea level pressure
NCEP	National Centers for Environmental Prediction (USA)
NCMRWF	National Centre for Medium Range Weather Forecasting (India)
NHC	National Hurricane Center (USA)
NHWRF	HWRF run at the NCMRWF
NOAA	National Oceanic and Atmospheric Administration (USA)
NRL	Naval Research Lab (USA)
NWP	Numerical Weather Prediction
OHC	Ocean Heat Potential (same as TCHP)
OFCL	NHC or CPHC official forecast
PEST	Predicted Ensemble Prediction System for Tropical Cyclones
RII	Rapid Intensification Index
RSMC	Regional Specialized Meteorological Center
SCIP	Statistical Cyclone Intensity Prediction model
SFMR	Stepped Frequency Microwave Radiometer
SH	Southern Hemisphere basin
SHIFOR	Statistical Hurricane Intensity FORecast (statistical baseline)
SHIFOR-5	5 day SHIFOR
SHIPS	Statistical Hurricane Intensity Prediction System

SHIPS-RI	SHIPS rapid intensification index
SPICE	Statistical Prediction of Intensity from a Consensus Ensemble
SST	Sea surface temperature
STIPS	Statistical Typhoon Intensity Prediction System
ST5D	statistical baseline for WP, IO and SH basins
ST10	STIPS ensemble
ST11	consensus, STIPS ensemble + GFDN forecast
S511	consensus, STIPS ensemble (with OHC) + GFDN forecast
S5XX	A consensus used at JTWC (contains STIPS)
S5YY	A consensus used at JTWC (contains SHIPS, LGEM and HWFI)
TC	Tropical Cyclone
TDO	Typhoon Duty Officer (U.S.)
TCHP	Tropical Cyclone Heat Potential (same as OHC)
TCWC	Tropical Cyclone Warning Center (Australia)
TUTT	Tropical Upper Tropospheric Trough
UKMO	United Kingdom Met Office
Vmax	Maximum near surface wind (intensity)
WP	Western North Pacific Basin
WRF	Weather Research Forecast model
VWS	Vertical Wind Shear
WANI	weighted analog intensity

References

Aberson, S. D., 2008: An Alternative Tropical Cyclone Intensity Forecast Verification Technique. Wea. Forecasting, 23, 1304–1310. doi: http://dx.doi.org/10.1175/2008WAF2222123.1

Bhatia, K. T. and D. S. Nolan, 2014: Prediction of tropical cyclone intensity forecast error. 31st Conference on Hurricanes and Tropical Meteorology, March 30 - April 04, 2014, San Diego, CA.

Cangialosi, J. P., and J. L. Franklin, 2012: 2011 National Hurricane Center forecast verification report. NOAA/NWS/NHC, 76 pp.
[Available online at www.nhc.noaa.gov/verification/pdfs/Verification_2011.pdf.]

DelSole, T., X. Yang and M.K. Tippett, 2013: Is unequal weighting significantly better than equal weighting for multi-model forecasting?. Q.J.R. Meteorol. Soc., 139: 176–183. doi: 10.1002/qj.1961

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

DeMaria, M., C. R. Sampson, J. A. Knaff, and K. D. Musgrave, 2014: Is tropical cyclone intensity guidance improving?. Bull. Amer. Meteor. Soc., doi:10.1175/BAMS-D-12-00240.1

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

Emanuel, K., C. DesAutels, C. Holloway and R. Korty, 2004: Environmental control of tropical cyclone intensity. J. Atmos. Sci., 61, 843-858

Falvey, R., 2012: Summary of the 2011 Western Pacific/Indian Ocean tropical cyclone season. Proc. 66th Interdepartmental Hurricane Conf., Charleston, SC, OFCM. [Available online at www.ofcm.gov/ihc12/Presentations/01b-Session/05-JTWC_2012_IHC_Final.pdf.]

Goerss, J. M., and C. R. Sampson, 2014: Prediction of consensus tropical cyclone intensity forecast error. Wea. Forecasting, 29, 750-762. doi: 10.475/WAF-D-13-00058.1

Leipper D. F., and D. Volgenau, 1972: Hurricane heat potential of the Gulf of Mexico. J Phys Oceanogr, 2, 218-224.

Kaplan, J., M. DeMaria, and J. A. Knaff, 2010: A revised tropical cyclone rapid intensification index for the Atlantic and eastern North Pacific basins. Wea. Forecasting, 25, 220–241. doi: http://dx.doi.org/10.1175/2009WAF2222280.1

Kharin, V. V., and F. W. Zwiers, 2002: Climate Predictions with Multimodel Ensembles. J. Climate, 15, 793–799. doi: http://dx.doi.org/10.1175/1520-0442(2002)015<0793:CPWME>2.0.CO;2

Knaff, J.A., and C.R. Sampson, 2009: Southern Hemisphere Tropical Cyclone Intensity Forecast Methods Used at the Joint Typhoon Warning Center, Part II: Statistical – Dynamical Forecasts. Australian Meteorological and Oceanographic Journal, 58, 9-18.

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, 80-92. doi: http://dx.doi.org/10.1175/1520-0434(2003)018<0080:SDTCIF>2.0.CO;2

Knaff, J. A., T. A. Cram, A. B. Schumacher, J. P. Kossin, and M. DeMaria, 2008: Objective identification of annular hurricanes. Wea. Forecasting, 23, 17–28. doi: http://dx.doi.org/10.1175/2007WAF2007031.1

Kossin, J. P. and M. Sitkowski, 2009: An objective model for identifying secondary eyewall formation in hurricanes. Mon. Wea. Rev., 137, 876–892. doi: http://dx.doi.org/10.1175/2008MWR2701.1

James P. Kossin and Matthew Sitkowski, 2012: Predicting Hurricane Intensity and Structure Changes Associated with Eyewall Replacement Cycles. Wea. Forecasting, 27, 484–488. doi: http://dx.doi.org/10.1175/WAF-D-11-00106.1

Kotal, S.D., Roy Bhowmik, S.K., Kundu, P.K. and Das, A.K., 2008: A Statistical Cyclone Intensity Prediction (SCIP) Model for Bay of Bengal. Journal of Earth System Science (Springer) 117:157-168

Kotal, S.D. and Roy Bhowmik S.K. 2013: Large-Scale Characteristics of Rapidly Intensifying Tropical Cyclones over the Bay of Bengal and a Rapid Intensification (RI) Index. Mausam, 64(1):13-24.

Krishnamurti, T. N., M.K Biswas, B.P Mackey, R.G. Ellingson and P.H. Rusher, 2011: Hurricane forecasts using a suite of large-scale models. Tellus A, 63: 727–745. doi: 10.1111/j.1600-0870.2011.00519.x

Mohapatra, M., B. K. Bandyopadhyay and D. P. Nayak, 2013: Evaluation of operational tropical cyclone intensity forecasts over north Indian Ocean issued by India Meteorological Department, Nat Hazards, 68, 433-451, doi: 10.1007/s11069-013-0624-z

Musgrave, K., and M. DeMaria, 2014: Further Development of a Statistical-Dynamical Ensemble for Tropical Cyclone Intensity Prediction. 31st Conference on Hurricanes and Tropical Meteorology. [availble on-line at

https://ams.confex.com/ams/31Hurr/webprogram/Paper244167.html]

Osuri Krishna K., U. C. Mohanty, A. Routray, Makarand A. Kulkarni, M. Mohapatra, 2012: Customization of WRF-ARW model with physical parameterization schemes for the simulation of tropical cyclones over North Indian Ocean, Nat Hazards (2012) 63:1337–1359.

Qi, L., H. Yu and P. Chen, 2014: Selective ensemble-mean technique for tropical cyclone track forecast by using ensemble prediction systems. Q.J.R. Meteorol. Soc., 140: 805–813. doi: 10.1002/qj.2196

Roy Bhowmik S.K., Kotal, S.D. and Kalsi S.R, 2005: An empirical model for predicting decaying rate of tropical cyclone wind speed after landfall over Indian region. Journal of Applied Meteorology, 44:179-185.

Rozoff, C. M. and J. P. Kossin, 2011: New Probabilistic Forecast Models for the Prediction of Tropical Cyclone Rapid Intensification. Wea. Forecasting, 26, 677–689. doi: http://dx.doi.org/10.1175/WAF-D-10-05059.1

Sampson, C. R., and A. J. Schrader, 2000: The automated tropical cyclone forecasting system (version 3.2). Bull. Amer. Meteor. Soc., 81, 1231–1240.

Sampson, C. R., J. L. Franklin, J. A. Knaff and M. DeMaria, 2008: Experiments with a simple tropical cyclone intensity consensus. Wea. Forecasting, 23, 304-312. doi: 10.1175/2007WAF2007028.1

Tsai, H. C. and R. L. Elsberry, 2014: Applications of situation-dependent intensity and intensity spread predictions based on a weighted analog technique, Asia-Pac. J. Atmos. Sci., 50(4), 1-12. doi:10.1007/s13143-000-0000-0

Usui, N., S. Ishizaki, Y. Fujii, H. Tsujino, T. Yasuda, and M. Kamachi, 2006: Meteorological Research Institute multivariate ocean variational estimation (MOVE) system: some early results, Advances in Space Research, 37, 806-822.

Wada, A., N. Usui, and K. Sato, 2012: Relationship of maximum tropical cyclone intensity to sea surface temperature and tropical cyclone heat potential in the North Pacific Ocean, Journal of Geophysical Research, 117, D11118.

Weber, H. C., 2005: Probabilistic Prediction of Tropical Cyclones. Part II: Intensity. Mon. Wea. Rev., 133, 1853–1864. doi: http://dx.doi.org/10.1175/MWR2950.1

Weigel, A. P, R. Knutti, M. A. Liniger, and C. Appenzeller, 2010: Risks of model weighting in multimodel climate projections. J. Climate, 23, 4175–4191.

doi: http://dx.doi.org/10.1175/2010JCLI3594.1

Yu, H., P. Chen, Q. Li, and B. Tang, 2013: Current Capability of Operational Numerical Models in Predicting Tropical Cyclone Intensity in the Western North Pacific. Wea. Forecasting, 28, 353–367. doi: http://dx.doi.org/10.1175/WAF-D-11-00100.1