Is There Any Hope for Tropical Cyclone Intensity Prediction? —A Panel Discussion

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Abstract

The outlook for tropical cyclone intensity forecasts from operational and from research perspectives was discussed during a panel discussion at the 19th Conference on Hurricanes and Tropical Meteorology. Whereas the operational requirement at the National Hurricane Center is to predict maximum 1-min sustained wind speeds at specific locations, the research community is addressing the prediction of the maximum wind or minimum sea level pressure in the storm. Commonality was found in the forecast strategies for subjectively predicting storm intensity. The panelists suggested improvements may be gained from additional observations, better conceptual and theoretical models of storm structure and behavior, and enhancements in statistical and numerical models.

The discussion period brought out opposing viewpoints on a number of topics. Both new observations and better use of the existing observations were believed to be necessary. The limitations and advantages of remotely sensed data for this problem were raised. The most vigorous debates were on the physical processes, such as existence or nonexistence of coupling between outer and inner core structure, and whether convection is simply a response to forcing or is an essential contributor to uncertainty in intensity forecasting. Several participants suggested that uncertainties related to the sea surface temperature and its evolution also contribute to the intensity forecast problem. Some specific suggestions for improving intensity forecasts are given in terms of new observations, new basic understandings, and new applied developments.

1. Introduction

One of the emerging issues in tropical cyclone forecasting is the ability to predict the intensity, and thus the potential damage, of these dangerous storms. This was a particularly appropriate topic for the 19th Conference on Hurricanes and Tropical Meteorology during 6–10 May 1991, which followed by only a few days the Bangladesh storm that killed more than 125 000 people and caused enormous damage. The panel discussion was organized by R. L. Elsberry, and the other five co-authors served as panel members. Miles Lawrence (1991), conference program chairman, provides summaries of the intensity forecasting sections during the regular conference sessions. This report summarizes the presentations of the panel members and some key issues raised during the subsequent discussion period. Since a substantial fraction of the more than 100 people in the audience participated in the one-and-a-half-hour discussion period, this is clearly a topic in which viewpoints are widely divided. One objective of this summary is to bring attention to the topic and encourage new efforts in observations, analysis, research, etc., to improve tropical cyclone intensity warnings to the public.

2. Statement of the problem

Some background and definitions are helpful to understand the nature and complexities of the problem. The intensity of the tropical cyclone generally is expressed as the maximum wind speed or the minimum sea level pressure. Mark DeMaria used Fig. 1 to define five stages in the development of Hurricane Joan in the Atlantic. Other storms may have very different time intervals during the various stages. In DeMaria's pregenesis stage, a cloud cluster or tropical disturbance may be identified as a potential hurricane seedling. In areas such as the Atlantic, perhaps only one in ten of these seedlings achieves the organization and maximum wind speeds of a tropical depression. Although other definitions of genesis exist, the main point is that tropical cyclones form from a preexisting disturbance. Notice that Hurricane Joan had a five-day organizational stage, during which the intensity changed very little. A more or less steady intensification stage followed, during which Joan first achieved maximum intensity. During the mature stage, a significant decrease in intensity was followed by another intensification. Willoughby et al. (1982) and Willoughby (1990) have observed such cycles in a number of hurricanes with intensities greater than 50 m s^{-1}, and have proposed a mechanism involving the shrinking of concentric eyewall cloud rings to explain this phenom-

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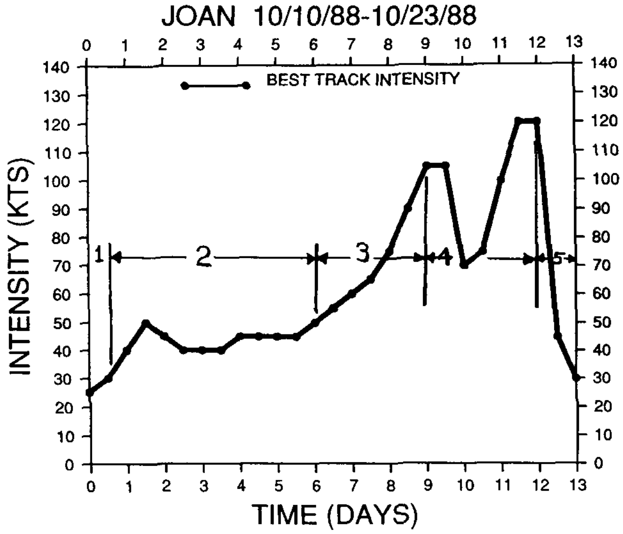

FIG. 1. Stages of tropical cyclone development [1) Pregenesis, 2) organization, 3) steady intensification, 4) mature, and 5) decay] as defined by Mark DeMaria for Hurricane Joan during 10–23 October 1988.

enon. The decay stage may occur rapidly over land or may occur over colder water. Cases of "extratropical transition," in which a tropical cyclone interacts in some manner with an extratropical system, is an important forecast problem for many midlatitude countries and for transiting ships. Whereas the vertical shear associated with the extratropical cyclone and accompanying jet stream may destroy the tropical cyclone, a merger with the convectively driven tropical cyclone may result in dramatic intensification of the hybrid system.

Among the uncertainties in the tropical cyclone intensity problem are the physical processes involved at different stages. Greg Holland used Fig. 2 to illustrate the possible mechanisms. Large amounts of latent heat release occur in the convective clouds near the center. The inward-pointing arrows on the inside of the eyewall in Fig. 2 represent the increase in intensity as the eyewall shrinks to smaller radii. Because the ultimate source for the latent heat release is evaporation from the warm tropical oceans, the sea–air flux of latent and sensible heat is an essential process. Surface heat and moisture fluxes from the ocean, as well as the entrainment mixing at the base of the ocean mixed layer, that are induced by the high winds in the tropical cyclone lead to decreases in SST in a wake region behind (especially on the right side of) the storm. A maximum intensity for a given sea surface temperature (SST) was empirically determined by Merrill (1988), and a theoretical upper bound was derived by Emanuel (1988). Because the energy is acquired from the ocean over a large domain and is converged toward the center in the boundary layer, the processes in that layer are a potential factor in intensity changes. In particular, entrainment fluxes at the top of the boundary layer may play a role in determining the properties of the air that eventually enters the bottom of the eyewall and outer rainbands.

External influences also affect the tropical cyclone intensity. Recent attention has been focused on the upper-tropospheric effects associated with juxtaposition of the tropical cyclone and midlatitude troughs or tropical upper-tropospheric trough (TUTT) cells. Such an interaction may create an external momentum flux convergence that is extended to the interior via an almost inertially neutral outflow layer in the mature tropical cyclone. Other external influences include the vertical shear in the environment and the vertical vorticity gradient with latitude.

A schematic of these possible contributions to tropical cyclone intensity changes and the positive/negative feedbacks is given in Fig. 3. For more details, see Merrill (1989). The schematic indicates the complexity of the intensity prediction problem. It is possible that other physical processes, or at least different combinations of those shown in Fig. 3, may contribute during the five stages of development in Fig. 1.

3. Panel presentations

The panelists included operational forecasters and researchers who were known to have opposing views with respect to the topic. The panel discussed three

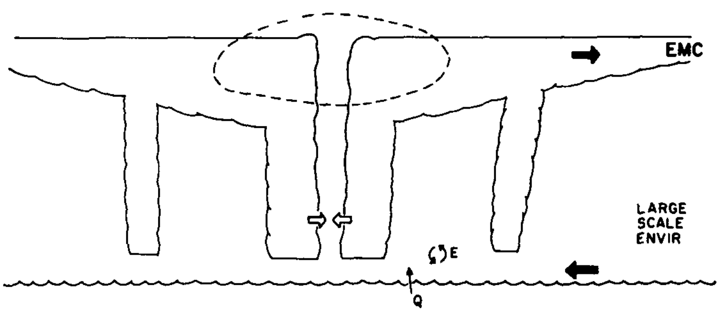

FIG. 2. Schematic of the possible physical processes involved in tropical cyclone intensity change. Large-scale environmental influences, and especially the eddy momentum flux convergence (EMC), may occur at large distances from the center. Contributions of surface fluxes of heat and moisture (Q) from the ocean and entrainment mixing (E) are indicated in the inflow layer. The open arrows represent the shrinking eyewall cycle. According to Greg Holland, observations within the dashed circle are critically needed to resolve uncertainties as to the mechanisms linking the low-level processes to upper-level outflow.

TABLE 1. Observation sources and averaging time (minutes) for estimating the maximum 1-min sustained surface wind speed at the National Hurricane Center (H. Gerrish). Note that the World Meteorological Organization standard of 10-min averages is used in most countries except the U.S.

	Averaging Time (Minutes)
SURFACE WINDS:	
Land stations & SWARS	1
C-man & ASOS	2
Oil rigs	2
Moored buoys	8.5
Drifting buoys	10
Ships	10
RAMOS	60
WINDS ALOFT:	
Rawindsonde	2 to 4
Omega dropwindsonde	3
Satellite cloud drift	30
Satellite VAS gradient	Instan.
Satellite water vapor	60
Recon minobs	0.17 or 1
Recon ASDL (filtered)	1
Doppler radar (Mean in echo vol @ 3 rpm)	<0.01

main topics: 1) forecast requirements and observations, 2) forecast strategies, and 3) the future outlook from operational and research viewpoints.

a. Forecast requirements and supporting observations

The intensity forecast requirements at the National Hurricane Center (NHC) are directly related to warning procedures for landfalling storms. Emergency managers make evacuation decisions based on the predicted maximum 1-min sustained surface wind speed. Thus, NHC is charged with providing the present and forecast values of the 1-min sustained surface wind speed for specific locations such as major cities. Such a forecast includes the prediction of the storm location, the intensity, and the wind distribution with respect to the center. An obvious question arises as the representativeness of such surface wind predictions, because the wind has convective-scale variations that are a function of the static stability and surface roughness. Although an observed minimum central pressure of the storm will be reported, the NHC advisory package never contains a minimum central pressure forecast.

A standard part of meteorological practice is that a good forecast starts from a good analysis. However, the maximum 1-min sustained surface wind is not routinely observed at the surface or aloft. Table 1 is a summary of the presently available observations at NHC. Notice that the averaging time for surface reports ranges from 1 to 60 min. Since the World Meteorological Organization uses a 10-min mean wind, international observations are not compatible with the NHC requirements, and these reports must be converted to 1-min winds. Averaging times for the winds aloft range from less than 1 min to 60 min. Many of these reports are averaged over horizontally or vertically oriented volumes and may not be representative of the sustained surface wind.

An important distinction then exists between the NHC definition of the intensity problem, in terms of sustained surface winds at specific sites, and the remaining panelists who focused only on the maximum winds near the center. This focus on storm intensity is true for the Joint Typhoon Warning Center (JTWC) because their customers are the local forecasters who are tasked to convert the JTWC storm intensity forecast to appropriate warnings. Thus, C. P. Guard (director, JTWC) presented a cautiously optimistic view that 24-h storm-intensity forecasts to perhaps 5-kt (2.5 m s^{-1}) accuracy may be possible for nonrapidly intensifying storms. Mundell's (1991) study of the JTWC intensity forecasts indicated widely different error characteristics for rapidly intensifying cases (deepening > 24 mb day^{-1}) versus the entire 1984 sample (Fig. 4). Since the onset of rapid deepening is not well predicted, these cases lead to a substantial negative error bias and a greater standard deviation. Similarly, onset of rapid filling also is not well forecast (not shown), and correspondingly large positive error biases would be expected. Another implication of Fig. 4 is that annual mean intensity forecast errors will tend to be largest during seasons with an abundance of rapid deepeners (and vice versa).

Improvement in storm intensity forecasts was a primary goal of JTWC forecasters during the 1990 season, and the mean 24-, 48-, and 72-h errors were reduced to 9.8, 15.4, and 20 kt, respectively. Compared to the long-term means of 12.5, 19.1, and 23.4 kt, these errors represent improvements of 22%, 19%, and 15%, respectively. Even though the 1990 season included five rapid deepeners that are difficult to predict, the intensity errors were nearly equivalent to the best previous season (1973), which had only one rapid developer. As will be indicated below, some uncertainty exists in the accuracy estimates from different observational platforms. In the western North Pacific, where reliance is primarily on a single platform (satellite), some smoothing of the intensity changes

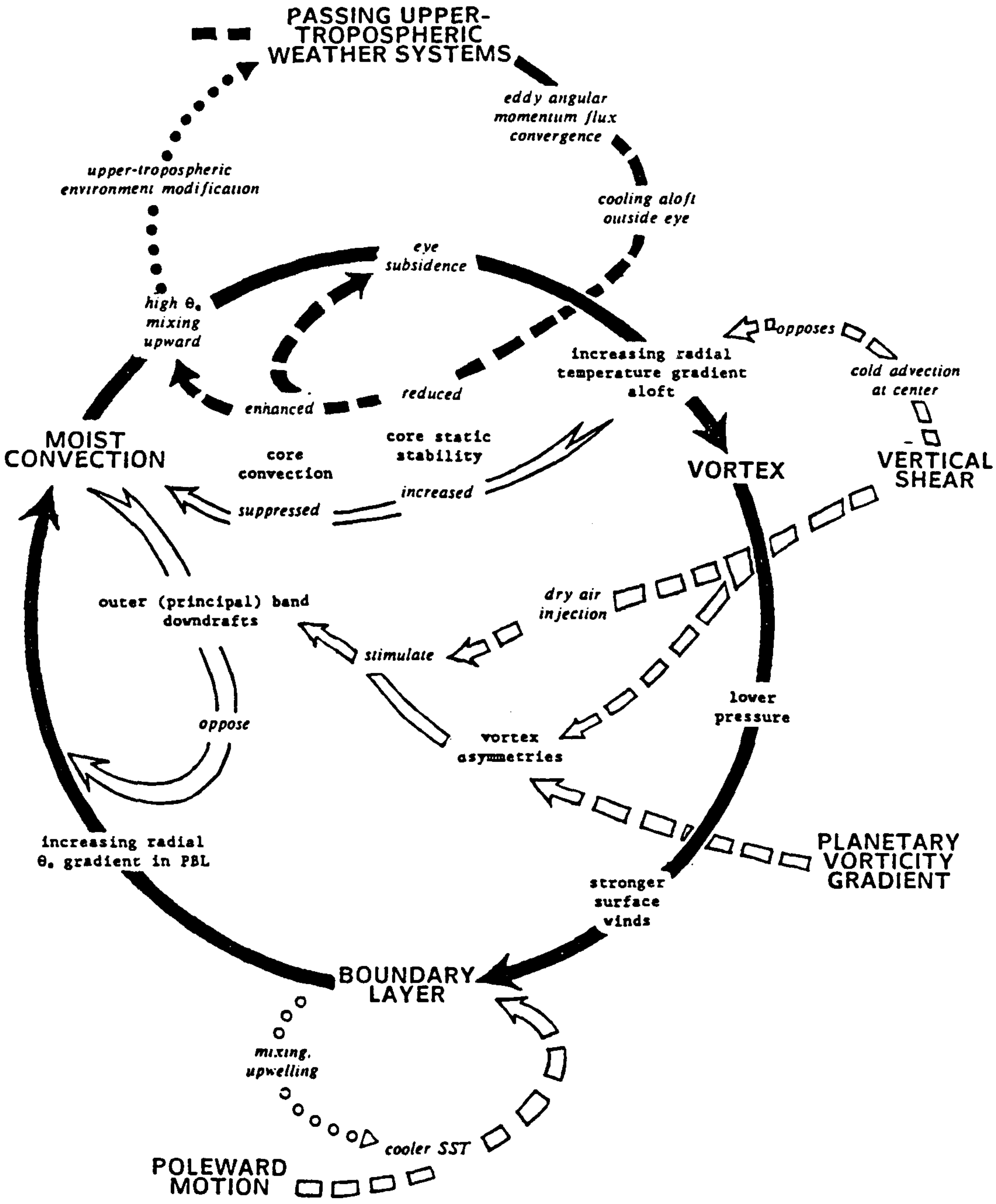

FIG. 3. Processes influencing tropical cyclone intensity change. The black circle represents internal positive feedbacks between the vortex, the boundary layer, and moist convection. Negative internal feedbacks are shown as white arrows. Dashed arrows indicate positive (black)/negative (white) environmental influences, and dotted arrows denote modification of the environment by the tropical cyclone (Merrill 1989).

may have contributed to smaller errors. Nevertheless, the overall improvement, especially for the rapid deepeners that involve the most risk and potential damage, is the basis for cautious optimism by Guard.

A much less optimistic status report was provided by Holland (Australian Bureau of Meteorology Research Centre), who reported that their intensity forecasts were not even as accurate as a persistence and climatology forecast. The Australian requirements for intensity-related forecasts are similar to those of NHC in that the landfall surface wind distribution must also be specified based on the prior storm structure over the ocean. Holland agreed that the critical need was

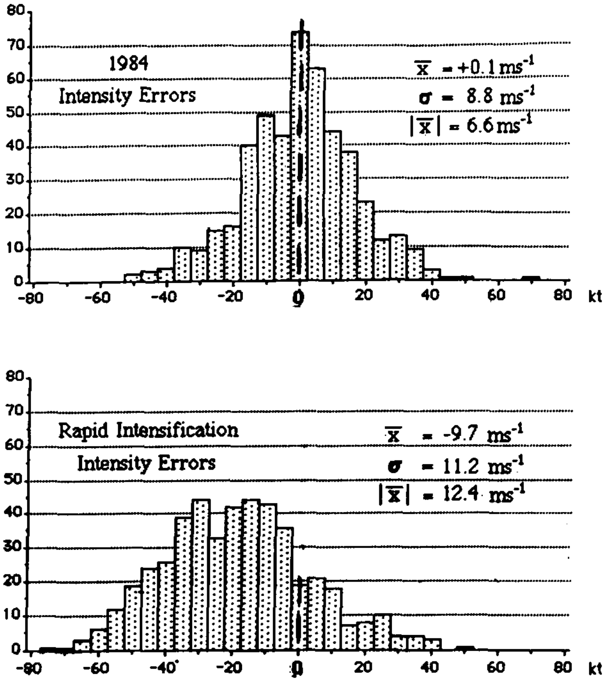

FIG. 4. Occurrences of intensity forecast errors (kt) at Joint Typhoon Warning Center during the 1984 season (top) and for a sample of rapidly intensifying storms (bottom). The sample means, standard deviations, and average magnitudes are shown in the insets, with units converted to meters per second (Mundell 1991).

for improved forecasts during the few periods of rapid sustained intensity changes, rather than small improvements in the more frequent situations of small changes. Holland emphasized the importance and the difficulty of the forecasts during extratropical transition.

Holland attributed the lack of skill in intensity forecasting to a lack of research emphasis on this topic. In a survey by McBride and Holland (1987) of all the tropical cyclone forecast centers, the track forecast was of such an overriding emphasis that little attention was being given to intensity forecasting. A majority of the centers did not even validate the intensity as part of their operational practices. Clearly, the requirements at these centers are very different from NHC.

The extent to which this lack of emphasis at other centers is due to absence of observing and forecasting tools, or to a lack of understanding, is unknown. Nevertheless, as track forecasts are improved, the relative importance of intensity forecasts is likely to increase. Hal Gerrish noted that the American public is well aware of the satellites, airplanes, and radars that NHC has to observe tropical cyclones. They expect that accurate intensity forecasts of these storms must emanate from such high technology. Such high expectations may lead to overly stringent requirements, such as the maximum 1-min sustained wind that NHC is tasked to achieve.

b. Forecast strategy

As indicated above, the first step in the forecast process is to obtain an estimate of the present intensity. The basic tool at nearly all centers is the Dvorak technique for interpreting satellite imagery, which provides a current intensity (CI number, in 0.5 increments) that can be converted to a maximum 1-min wind speed. In some other countries, the CI number is converted to a maximum 10-min wind speed, which can introduce confusion because an average over 10 min will be smaller than an average over 1 min. The NHC assumes the accuracy is about 0.5 CI, which is equivalent to 5 kt for tropical depressions, but is 15 kt for the most intense hurricanes.

The NHC is the only forecast center with regular aircraft reconnaissance. These aircraft winds are typically observed at three levels and must be converted to a surface wind speed by a subjective wind reduction. The NHC assumes the accuracy of the flight-level winds is 4 kt. However, Gerrish showed a number of storm chronologies with large dispersion among the intensity estimates by various observational platforms. For example, wind speed estimates within a few hours of 1200 UTC 18 October 1990 in Nana (Fig. 5) ranged from less that 40 kt to about 90 kt. A scatter of about 30 kt persisted for the next 30 h, which indicates the considerable uncertainty in storm intensity when the winds are estimated from multiple observing platforms.

Since the NHC only has one objective intensity

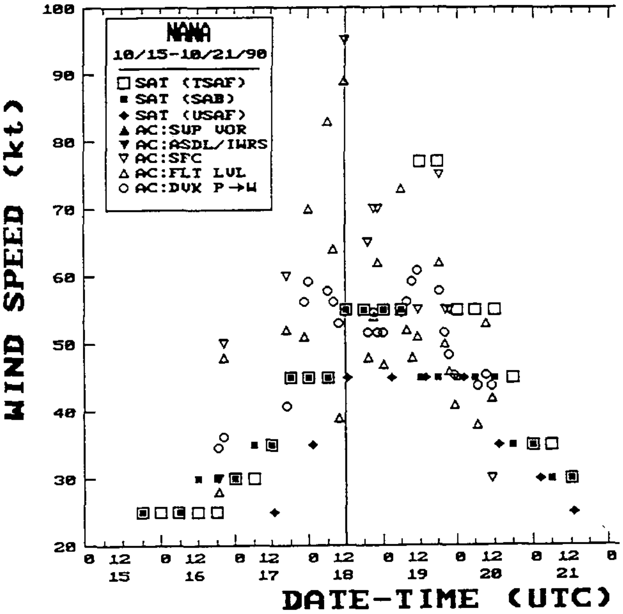

FIG. 5. Maximum wind speed (kt) estimates from various observational platforms (see insert for symbols) for Hurricane Nana during 15–21 October 1990 as received by the National Hurricane Center (H. Gerrish). Note the wide range of estimates at 1200 UTC 18 October (vertical line).

prediction tool (a statistical-climatology model called SHIFOR), the present forecast strategy is a combination of subjective techniques. Favorable or unfavorable environmental conditions, such as downstream vertical shear, are inferred from the animated satellite imagery (including the water vapor imagery). The 24-h forecast rules of the Dvorak technique are applied. Future intensity trends are related to the storm structure using the Willoughby et al. (1982) contracting concentric eyewall model. Finally, global model guidance is incorporated if the model has recently indicated the correct intensity trends. Considering the uncertainty in the initial intensity estimate and the subjectivity of the forecasts, the evacuation plans should anticipate potential errors in the NHC warnings and take a cautious approach of overwarning.

The basic forecast strategy at JTWC is also subjective, but the intensity forecast is guided by a conditional climatology that is keyed on the initial location and intensity, the recent intensity trend, and the month. The most detrimental environmental influence restricting intensification is the vertical wind shear, which is assessed using satellite loops, numerical model predictions, and a hand-drawn upper-level (100–300-mb) wind analysis. Intensification more rapid than the conditional climatology is based on the Mundell (1991) criteria for rapid intensification (e.g., sea surface temperature exceeding 28°C). Another favorable factor in the western North Pacific is the likely establishment of two efficient outflow channels. Since the equatorward channel is typically present, this subjective rule requires juxtaposition with a midlatitude trough, or a TUTT cell to the northwest or a TUTT cell to the east within 10°–12° latitude of the cyclone center.

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Although a certain degree of "artful application" seems to be required, a more systematic modification of the conditional climatology to take into account these subjective rules has reduced the JTWC intensity forecast errors during 1990. It would be interesting to see if a similar technique with similar subjective environmental influence rules could be applied in the Australian region, where no intensity prediction skill exists.

c. Future outlook

According to Gerrish, the outlook for meeting NHC requirements for the maximum 1-min sustained wind will be bleak until the observational problems are solved. Because the NHC can not accurately determine the present horizontal wind structure, little hope exists for their intensity forecasting problem. It is emphasized that NHC has (by far) the best assets for specifying the storm structure (including the maximum wind speeds) because of the aircraft reconnaissance assets. However, the requirement for maximum 1-min winds at landfalling points is so stringent that it is probably impossible because it depends on convective scale and micrometeorological effects such as surface roughness distributions.

Some improvements in relationships for the reduction of aircraft flight-level winds to surface winds are being tested by Mark Powell of the Hurricane Research Division. Although some improvements may occur over water with a stability-dependent boundary-layer model, the complex modification of the over-water winds at the coast will introduce additional uncertainty for the specific land stations at which NHC must forecast. Powell is also trying to incorporate the time history of flight-level winds in the intensity estimates. The 1991 Interdepartmental Hurricane Conference has recognized the surface wind estimate problem and will recommend improvements.

Guard is cautiously optimistic that the 24-h accuracy of storm intensity forecasts can be improved from 10 kt to 5 kt. Without aircraft reconnaissance, JTWC must depend on remote-sensing techniques. Guard feels advances in detecting storm intensity can be achieved by quantitative microwave sensor observations of the warm core aloft and the rain rate. Forecast improvements may come from an integrated, automated scheme that addresses favorable and unfavorable influences on intensification.

Holland emphasized the need for a complete conceptual model (e.g., Fig. 3 with somewhat quantitative estimates of the interactions). His example of a cloud-top temperature below −102°C from an infrared image implies a possible 4-km overshoot into the stratosphere, which would require an updraft exceeding 15 m s^{-1} at the tropopause. Upper-tropospheric observations are necessary to understand (and forecast) the physical processes that could generate the large convective available potential energies to sustain such updrafts. Finally, Holland suggested a new research initiative on tropical cyclone structure and structure change that might be patterned after the Tropical

TABLE 2. Assessment by DeMaria of the potential capability of numerical models and statistical methods for objective forecasting of tropical cyclone intensity changes during the five stages defined in Fig. 1. The assessment ratings are:

● Probably ■ Not sure ▲ Probably not

Stage	Numerical Models	Statistical Methods
1. Pregenesis	●	▲
2. Organization	▲	▲
3. Steady Intensification	■	●
4. Mature	▲	▲
5. Decay	■	●

Cyclone Motion (TCM-90) experiment (Elsberry 1990). The various components of the problem (including intensity change) would be identified via workshops and studies of existing datasets. Special observations (such as those proposed above) would be organized to validate specific hypotheses and develop a more complete conceptual model, as in Fig. 3.

Kerry Emanuel described a possible theoretical framework that expresses the intensity (I) as a product of a potential intensity (P) and the fraction of P that is being realized (F) at any time. In his theory, the P is a function of sea surface temperature (SST) and a mean outflow temperature (T_o), which are calculated from climatological maps. It is possible that local conditions can depart substantially from climatological values. For example, a local reduction of SST of 2.5°C would be sufficient to make $P = 0$. Similarly, T_o may be very sensitive to the vertical temperature structure in the upper troposphere. Even given complete observations in the region, the question is: What determines the value of F? Only in a very few cases (<5%) is $F = 1$, even though numerical situations with 2D models almost always attain $F = 1$ given sufficient time. In particular, how do the environmental interactions make $F < 1$? Internal processes may also reduce F in unknown ways. Nevertheless, Emanuel believes that the predictability limit may be as large as 1–2 cycles of the eyewall contractions of the type shown in Fig. 1 during the mature stage.

DeMaria assessed the potential capability of numerical models and statistical methods for objective forecasting of intensity change (Table 2). The statistical method might contain persistence, plus synoptic and dynamical model predictors. Global or regional numerical models are hydrostatic, with 20–30 vertical levels and parameterized convection. The major differences are that the regional models have a horizontal resolution of 20–40 km rather than, say, 50–100 km. Nested cloud-scale models with 1–10-km resolution also might be applied to the intensity problem. These nested models are nonhydrostatic and have 30–40 vertical levels. Such a model would have adequate horizontal resolution for the eyewall (say, 20-km radius of maximum wind) and would not require a convective parameterization scheme, which are considered to be limitations of the global and regional models. The deficiencies of observations and initialization techniques would be even greater for the cloud-scale model than for the global and regional models.

DeMaria's assessments for accurately forecasting the intensity are a function of the storm intensity and the types of intensity changes that numerical models and statistical models can predict reliably. For example, the numerical models will be able to resolve the preexisting disturbance given enough observations. Although statistical models may predict the persistent stages adequately, the key forecast problem of when intensity changes will occur may not be solved by statistical methods. Predicting the intensity cycles during the mature stage in Fig. 1 will also be difficult with numerical models. Even with the horizontal resolution of the nested cloud model, the internal convective-scale processes may not be very predictable. Since external forcing from the environment may be involved, a numerical solution would require extremely high resolution near the center, as well as a large domain. If an ocean feedback process is involved, a fully coupled and nested ocean model may also be necessary.

4. Discussion topics

a. Observational requirements

Dan Petersen asked whether a data deficiency really exists with all the observational sources in the Atlantic region, or are the data not being properly used in the numerical models? In response, two representatives from the National Meteorological Center (NMC) expressed different views. Steve Lord emphasized the difficulty of the task because many of these observations are not obtained at the synoptic times, are only at a single level, and are noisy. The four-dimensional data-assimilation (4DDA) system is more effective for observations within rather narrow ranges of values. For the present horizontal resolution in the analysis, the aircraft observations over about 10–15 min must be combined into a single "super-observation." Makut Mathur believes the microwave rain-rate observations or other remotely sensed precipitation estimates can be incorporated into numerical models by nudging methods. Given new data and innovative initialization techniques, Mathur disagreed with DeMaria's pessimism with regard to the ability of numerical models to forecast intensity. Yoshi Kurihara, who has been doing research on the initialization problem for tropical cyclones, also was optimistic. He also emphasized the intensity prediction in the model is tightly linked to the track prediction capability. He believes the numerical model has limited forecast ability for short time-scale features, but will be even better than the statistical model for trends such as the magnitude of overall deepening during stage 3. Holland responded that predicting slow intensification correctly is not nearly so useful to forecasters as predicting the rapid deepening or the unexpected intensity change.

Jack Beven noted that the present dropwindsondes from turboprop aircraft do not resolve the outflow layer. He suggested that dropwindsondes from a proposed pilotless aircraft flying in the lower stratosphere would provide much better information that could be utilized by the numerical models. Lance Bosart agreed with the supposition that we need to make better use of the existing data. He observed that the NMC initialization system is fragile in the sense that it does not accept observations that depart significantly from the first-guess field provided by the numerical model. Nor is the system flexible in accepting new data types, because the expected variance relative to the first-guess field must be specified. If the initialization problem for tropical cyclones can not be handled better by the 4DDA system, perhaps some innovative, nonnumerical method must be developed.

b. Utility of remotely sensed data

Alan Weinstein raised the question whether new satellite observing systems (e.g., microwave imagers, SAR, or radar altimeters) could be applied to the intensity observation and prediction problem. Frank Marks responded that the satellites do not provide the minimum sea level pressure or the maximum wind speed. Guard agreed, but stated that both operational centers and research groups are working on improved algorithms for the SSM/I to derive surface wind structures (say, the radius of 30-kt winds) and that the rain rate is estimated in precipitation regions. Mathur repeated that NMC is trying to use the satellite-derived rain rates. However, SSM/I observations are in narrow strips that do not provide complete coverage in tropical regions. Since the SSM/I observations have only been available once a day, the 4DDA system has a difficult time maintaining the tropical cyclone during the three intermediate 6-h cycles until a new set of observations is available.

Jim West noted that the radar scatterometer on the European Research Satellite (*ERS-1*) will not provide real-time data until the mid-1990s. Because it is a research satellite, considerable negotiation has been required to acquire the observations for operational use. Emanuel suggested that a long time is needed to learn how to utilize new satellite observations in numerical analyses and forecasts. In most cases, the task is to adapt satellite-observed variables to meteorological variables, rather than an approach in which the satellite is designed to observe the required meteorological variables. Emanuel suggested that the most important variable to monitor the intensification to tropical cyclone stage is the midlevel moisture.

Ray Zehr suggested that satellite (or any other system) information should not be interpreted in isolation. Rather, the strategy should be to find optimum combinations of satellites, aircraft, and other observing systems and then merge this information with the guidance of statistical methods and numerical models.

c. Inner versus outer structure influences

Bill Gray proposed that the changes in inner core structure related to intensity are a separate problem from the changes in the outer structures that are due to environmental influences. He indicated that the 12–24-h intensity changes can be anticipated by monitoring the cloud-top infrared temperatures from satellites and the upper-level flow relative to the storm motion. Quoting C. Weatherford's research, Gray claimed the inner and outer tendencies are decoupled. These statements triggered rebuttals by Miles Lawrence and Hugh Willoughby, who insisted that the inner and outer tendencies are indeed coupled at times, with a tendency to see-saw in a regular manner. A conference paper (Samsury and Rappaport 1991) described such an operational application of the Willoughby et al. (1982) cycle. Roger Edson stated that forecasts of the outer wind structure are important in the western North Pacific, where large ranges in typhoon sizes are observed.

Mark Lander drew attention to the inhibiting effects of vertical wind shear across the center. Beven described cases in both the Pacific and the Atlantic in which the intensity changes appeared to be related to upper-level lows and shear zones. Gray agreed that the overall structure changes are related to several environment effects, but he continued to maintain that the ultimate sea level pressure (say, an 880-mb storm, versus 900 mb) can be monitored via the cloud-top temperatures in the inner core. Kurihara countered that several interrelated factors are involved in structure and structure change. The appearance at times that a single process is dominant may simply be due to the differences in response times in different portions of the vortex. For example, an external momentum flux convergence can produce a local momentum increase. An associated adjustment of the mass field may require some time in a low-latitude tropical cyclone. This type of adjustment process may be predictable if the forcing is well specified and the response to that forcing is handled carefully in the numerical model. By contrast, a forcing triggered by an internal instability or a microphysical process may not be predictable for very many hours. Kurihara's point is that it may be difficult to trace an intensity change to a single dominant forcing unless the response times are carefully considered.

d. Role of convection

As indicated above, large amounts of latent heat release occur in the eyewall and rainbands. The issue is whether the convection is a passive response to forcing or whether the uncertainties in the nature, magnitude, and distribution of the convection are an essential determinant in the intensity forecast problem. Richard Pfeffer argued that convection is a response to forcing, and that the large-scale environmental forcing is the dominant process. DeMaria concurred and stated the key issue is what restricts the achievement of the intensity that potentially could exist for that SST. That is, the negative influences due to the environment must be known if intensity predictions are going to be accurate.

According to Guard, the lag between the cloud-top temperature indicators and achievement of that maximum intensity is about 6 h during spinup and about 12–24 h during normal spindown. When rapid weakening is indicated by the cloud organizational changes, the lag time for spindown is reduced. Zehr believes that convection provides an indicator for perhaps 18 h, and is not just a passive response to other forcing. Perhaps internal instabilities are being triggered in association with the convection and the subsequent adjustment. Emanuel stated that the uncertainty in specification of the convection must limit the predictability on short time scales.

Although Mark Handel disagreed with DeMaria on the extent to which convection and its effects are known, he agreed that other factors govern the amount and distribution of convection. He endorsed testing of the simple theoretical construct suggested by Emanuel, and suggested monitoring of the low-level and midlevel moisture fields. As Marks pointed out, the vertical resolution on the satellite-derived moisture profiles is inadequate for such monitoring. Moisture parameters are not measured well even by aircraft, or by the present dropwindsondes.

Holland noted that the Dvorak intensity analysis scheme involves the central dense overcast and other features related to convection. However, the key rules are related to the organization of the convection, rather than the amount of convection. Gary Barnes believes the organization of convection is an absolutely essential factor in determining the local surface winds and for the central core intensity changes. The key is to understand how the low-level environment around the convective areas is modified. As satellite observations are not adequate, aircraft observations are necessary.

Marks observed that active convection makes up a small part of the cloud area, and perhaps 80% is due to stratiform clouds. Furthermore, the outer convective bands are relatively shallow. Whereas the eyewall convection may be effective as a mechanism for coupling in the vertical, it is less clear how the outer rainbands contribute.

Mort Glass advocated use of microwave sensors that give a quantitative measure of latent heat release or rain rate. Perhaps the time changes from the microwave sensors will provide an indicator of the overall system changes. As noted above, the gaps between the SSM/I swaths in the tropics and present return-view times are too large to make this a practical forecast tool.

A related issue is the storm intensity response to the large diurnal variations in convection in the tropics. Recent research by Gray's group suggests a significant diurnal response in the tropical cyclone winds. According to Guard, the diurnal convection cycle only has an effect on weaker storms and has no significant effect after the typhoon stage is attained. Bob Sheets concurred that the NHC has not detected an effect during the hurricane stage.

The above discussion reflects the divergent views on whether the internal dynamics of convection is a primary restricting factor in our ability to predict tropical cyclone intensity changes. While some participants believed that it was a restricting factor, others believed that external influences such as upper-level momentum flux convergences or SST are more important factors.

e. Sea surface temperature influence

David Raymond remarked that the tropical cyclone is a complete system and the observational system must also be complete. If the schematic in Fig. 2 is interpreted as a heat engine as Emanuel suggests, it involves a fuel tank (ocean), cylinders (eyewall convection), and exhaust pipes (upper-troposphere outflow). Whereas Holland had suggested the need for better observations of the exhaust system, Raymond believes the greatest uncertainty is in the fuel supply, because the SST and the depth of the ocean mixed layer are not known.

Wes Browning questioned whether Jenni Evan's statistics on the intensity response to the SST value conflicted with prior studies. Emanuel found no disagreement in that the SST provides an upper bound, but does not have a direct relation to the present intensity. According to his calculations, the cyclone intensity may be affected by an SST decrease of only 1°C. He made a plea for more observations and a better understanding of the ocean response to tropical cyclones. Willoughby noted a large database on SST response to hurricanes has been accumulated by Peter Black, which seems to support the need for an interactive ocean model to treat the mutual adjustment problem.

Edson indicated that the SST under the storm does not decrease by 1°C for the deep ocean mixed layers in the western Pacific and offered the opinion that SST is not an effect in day-to-day intensity changes. DeMaria countered that SST is important in a large-scale sense. Atlantic disturbances moving off Africa usually do not develop until they move farther west, where the SST exceeds 26°C. Although such a climatological SST threshold exists, the key factor then becomes the environmental influences that hinder achievement of the potential intensity.

5. Concluding remarks

The panel discussion achieved the purpose of sharing viewpoints on the outlook for tropical cyclone intensity forecasts. Although the following remarks should not be considered inclusive, some issues related to observing, understanding, and predicting intensity will be summarized.

a. Defining the problem

The tropical cyclone intensity problem is typically to observe and predict the maximum wind speed or the minimum sea level pressure. However, the tropical cyclone warning problem is actually related to the surface wind structure. Because of the needs of the disaster-preparedness agencies, the National Hurricane Center is tasked to forecast the maximum 1-min sustained wind speed at points along the coastal area. This is a much more stringent requirement than predicting the storm intensity, because both the tropical cyclone structure and structure change are involved. Knowledge of the vertical structure in the tropical cyclone boundary layer for various ocean and land roughness values, and for different static stabilities, is required. Furthermore, the maximum *1-min* wind will be related to convective-scale phenomena above the boundary layer. Thus, the outlook for forecasting such winds for more than a few hours is bleak. Consequently, most of the following remarks are related more to the cyclone structure and structure changes versus local wind estimation and forecasts.

b. Observational requirements

The horizontal wind structure in tropical cyclones can vary considerably from storm to storm. In the western Pacific, the storm size ranges from midget typhoons of a few hundred kilometers in diameter to huge typhoons that have cyclonic circulations over 3000–4000 km. Clearly, the warnings should take into account these size differences. Since the tropical ocean regions where these storms form is a data-sparse domain, improved remote-sensing techniques and other observational systems that will define the initial storm structure (including intensity) are required.

The upper troposphere seems to play a key role in the developing tropical cyclone. Although satellite techniques provide important information about this layer, more observations are required.

The upper troposphere seems to play a key role in the developing tropical cyclone. Although satellite techniques provide important information about this layer, more observations are required. For example, in situ observations are required to understand the physical processes by which a particular maximum wind speed at the surface evolves following a rapid decrease in the cloud-top temperatures observed in the satellite infrared imagery. The horizontal wind distribution in the upper troposphere is also important in understanding how remote forcing via eddy momentum flux convergence at about 1000 km can cause an intensity change in the central core. A jet aircraft that can probe the outflow layer would be helpful. Another alternative is a pilotless aircraft that would dispense advanced dropwindsondes from the lower stratosphere over a period of 1–2 days.

Observations of the sea surface temperature and its changes under the tropical cyclone appear to be necessary for understanding and forecasting wind structure (including vertical variations). Since the surface temperature change is related to the initial ocean mixed-layer depth, this quantity must also be observed.

c. New understanding requirements

A better understanding of the physical processes indicated schematically in Fig. 3 is required for all five stages of the tropical cyclone in Fig. 1. Key questions for the western North Pacific are: What causes the different size typhoons, and what are the physical processes that lead to wind structure changes? How are the outer and inner structure changes coupled? What triggers the development of the concentric eyewall cycle?

Vertical shear is cited by the forecasters as the primary impediment to achievement of the potential intensity for a given sea surface temperature. What is the physical process by which a vertical wind shear in the environmental flow is transmitted inward to the core of a mature tropical cyclone that has very little vertical shear?

Another factor in Emanuel's theoretical framework is the upper-tropospheric outflow temperature. What processes significantly change this temperature? Are these changes related to adjacent synoptic circulations such as midlatitude troughs or TUTT cells? Outflow channels are related to the presence of these adjacent circulations. What are the dynamics of the juxtaposition of these synoptic circulations that sometimes lead to an intensification of the tropical cyclone, and sometimes lead to destruction or to an extratropical transition?

Continued efforts must be made to improve the relationships between various observational wind measurements and the sustained surface wind speed. In addition to aircraft and satellite observations, new platforms such as Doppler radars or radar wind profilers also will produce wind measurements above the boundary layer that need to be related to surface wind speeds.

The role of convection in the eyewall and the rainbands is still controversial. From one perspective, the key question is, What is the forcing function for the convection? From an alternate viewpoint, How does this convection modify the adjacent environment to cause deepening of the tropical cyclone core, or to modify the low-level inflow into the tropical cyclone? That is, How do hurricane winds modify the convectively driven boundary layer and determine the entrainment and the boundary-layer structure? How does the coastal environment affect this vertical structure to determine the maximum winds in the habitation layer?

Although the empirical Dvorak technique is widely used, we do not understand the physical processes that relate the organization of the convection to the analysis of present intensity. A better understanding of such relationships should lead to better intensity-change forecasts than the empirical intensity forecasts.

The ultimate energy source for the tropical cyclone is evaporation from the ocean. Theoretical and numerical models indicate a great sensitivity of potential intensity to the SST. What are the physical mechanisms that determine the magnitude and horizontal distribution of the SST decreases? How does the initial ocean mixed-layer depth and its time evolution affect the SST decreases? How does this SST wake affect the vertical wind structure, the energy flux, and thus, ultimately, the horizontal wind structure in the tropical cyclone? Can we develop coupled air–ocean models that faithfully reproduce the tropical cyclone structure and oceanic responses simultaneously, and thus contribute to our understanding of this phenomena?

On what space and time scales are the tropical cyclone wind structures predictable in a deterministic sense? Is the outer wind structure predictable for much longer times than the inner core winds? Consequently, what are the likely limits of predictability for numerical and statistical models?

d. New applied development requirements

Continued efforts must be made to improve the relationships between various observational wind measurements and the sustained surface wind speed. In addition to aircraft and satellite observations, new platforms such as Doppler radars or radar wind profilers also will produce wind measurements above the boundary layer that need to be related to surface wind speeds. The scatterometer instruments on new satellites will produce surface wind estimates over some horizontal domain. How are these area-averaged values related to the maximum wind at a point?

The microwave sensors have an advantage over visible or infrared sensors because the microwaves penetrate clouds. Improved algorithms are required to estimate surface winds from microwave imager observations. The rain-rate observations should be included in numerical models to improve the initial conditions. The magnitude of the upper-tropospheric warm core might be monitored in the microwave band to produce a storm-intensity estimate.

Developmental efforts to improve the objective analysis, four-dimensional data-assimilation and initialization steps in numerical models are required for tropical cyclone structure. In particular, the various observational platforms produce data with different space and time resolutions. These data must be combined in an optimum way to obtain the best possible analysis of the initial tropical cyclone structure and the environment. While the operational numerical models are not likely to have small enough horizontal grid sizes to resolve the eyewall and the intensity, perhaps the trend in the intensity may be indicated. Another goal of such models may be to forecast the major features of the outer wind structure in tropical cyclones.

Whereas numerical models have limitations, it may be useful to develop objective guidance tools that use physically based predictors in the conceptual model. It is especially important to deal with the rapid intensification cases that involve the greatest risk of potential damage.

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