# 7. TROPICAL CYCLONE (TC) SUPPORT SUMMARY

## 7.1 COMBINED SSM/I- AND IR-DERIVED RAINRATES FOR THE TROPICS

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Infrared (IR) derived rainrate techniques focus on the cloud-top temperatures to infer rain. These IR techniques typically associate colder cloud tops with higher rainrates. However, there are a number of incorrect assumptions associated with this underlying methodology and a number of alternative explanations have been proposed. The method proposed here takes advantage of the superior rainrate measuring capabilities of the DMSP SSM/I sensor and combines it with the advantages of the frequent updates of infrared geostationary imagery and the associated wide synoptic coverage of geostationary imagery.

The technique basically merges the SSM/I imagery and the IR geostationary imagery by a histogram type matching program after collocating geostationary data that has been mapped to the SSM/I type resolutions (in this case 28 km). The rainrates from the SSM/I are matched with the brightness temperatures from the IR imagery when the SSM/I data are available. A data base is created that serves as a reference table for converting IR temperatures to rainrates over a much larger domain than the swath width of the SSM/I pass.

The technique improves when the number of matches between the SSM/I rainrates and the brightness temperatures from the IR imagery in the reference data base is large. The results have been enhanced recently by the fact there are now four (4) operational SSM/Is available. Thus, for each IR image, the method is applied and a rainrate product is created. The resulting image of rainrates can be used for several purposes: a) a snapshot of current rain over a large domain; b) as input to numerical models using the reverse physical initialization technique; and c) to accumulate the rain over time to give a time series of rainrates for a given TC.

The snapshot rainrate picture and a time series animation of the individual images are very informative about the rain in and around a TC. The rainbands and their evolution are the main features displayed. This helps to augment the SSM/I 85-GHz imagery that is the focus of a study on TC structure and intensity. Preliminary results incorporating these rainrates into NOGAPS via physical initialization (Gregg Rohaly) are very promising and are currently undergoing tests.

Accumulation images are enlightening due to the fact that the images readily depict the diurnal maximums associated with the IR signature of TCs. This type of data may help determine which TCs are wet versus dry and alert forecasters to those TCs that can be particularly troublesome from the standpoint of flooding when they reach landfall. Verification studies are ongoing with P-3 airborne radar data in the Atlantic Ocean and with limited NEXRAD sites in the Northwest Pacific Ocean.

## 7.2 THE AUTOMATED TC FORECASTING SYSTEM

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The Automated Tropical Cyclone Forecasting (ATCF) System, developed by NRL Monterey, is a computer based application designed to automate and optimize the forecasting process at operational Navy TC warning centers. ATCF was initially installed on PC DOS-based computers at the JTWC in 1988. ATCF version 3.1, installed at JTWC during 1997, is UNIX-based with an X-Windows interface similar to what is seen in Windows 95 applications. This X-Windows interface has markedly simplified navigation through the system, thereby reducing the time required to generate forecasts. Another significant improvement is that ATCF now allows users to track and forecast many storms concurrently. ATCF continues to attract a great deal of interest and has upgrades scheduled for the next few years. Major highlights for these upgrades include integration of satellite derived products such as cloud and water vapor tracked winds, and a redesign of the tropical cyclone database to allow 120-hour track forecasts and wind radii quadrants.

## 7.3 GEOPHYSICAL FLUID DYNAMICS-NAVY (GFDN) TC MODEL

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In May, 1996, FNMOC started running the Navy implementation of the Geophysical Fluid Dynamics Laboratory (GFDL) TC model, GFDN, in support of JTWC. The GFDN is a triple-nested movable mesh model, including initialization, forecast, and diagnostic sections. Some key features include: three computational nests with resolution 1°, 1/3°, and 1/6°, convective adjustment, surface fluxes, second order turbulence, infrared and solar radiation, a bulk subsurface layer, and parameterization of surface features by vegetation type.

The model is initialized from the NOGAPS analysis and the TCBOGUS message issued by JTWC. The TC component is removed from the global analysis, and replaced by a synthetic vortex generated by an axi-symmetric version of the forecast model constrained by the structure indicated by the TCBOGUS message. An asymmetric (beta-advection) component is also added to the synthetic vortex. Boundary conditions are updated periodically from NOGAPS forecast fields.

FNMOC ran GFDN on the off time (06/18Z) watches whenever a TCBOGUS for a western Pacific TC was received. The model applied the highest priority off time TCBOGUS to the off time NOGAPS analyses (available ~ 1015/2215Z) and used the forecast fields from the previous real time (00/12Z) NOGAPS for boundary conditions. These forecasts were available to JTWC by about 1130/2330Z, in time for their subsequent 12/00Z warnings. Beginning 11 September 1996, if JTWC issued more than one western North Pacific TCBOGUS, the second priority message was applied to the preliminary NOGAPS off time analysis (available ~ 0745/1945Z). These forecasts were available by about 0845/2045Z.

The GFDN provided high quality tropical cyclone track guidance in the western Pacific basin. It had excellent detection capability, especially for cyclones of tropical storm intensity or greater. Mean track error decreased with cyclone intensity, while the forecast intensity error increased. Due to its perceived positive impact on the official forecasts, FNMOC now runs GFDN in all basins within JTWC's area of responsibility.

## 7.4 SSM/I-DERIVED TC STRUCTURE

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Monitoring TC structure, structure change and intensity via visible and infrared imagery is inherently limited due to upper-level cloud obscuration and the subjective nature of the current Dvorak rules for low-end systems before an eye takes shape. Thus, the satellite analyst has a difficult task of accurately determining the TC structure, structure changes and the associated intensity. This statement is even more true at night, when visible data is not available to assist the analyst and coarse resolution infrared (IR) data is the only consistent data set for utilization.

The Special Sensor Microwave/Imager (SSM/I) is a passive microwave imager onboard the Defense Meteorological Satellite Program (DMSP) platforms. The frequencies utilized by the SSM/I have the ability to penetrate many upper-level clouds allowing for a clearer view of the mid- and lower-level structure within a TC. This is crucial to removing one of the main barriers for effective use of visible/IR imagery. The 85-GHz channel on the SSM/I is of particular interest since the spatial resolution is still fair (12-15 km) and is oversampled, meaning the inherent resolution is superior to 15 km.

The Naval Research Lab in Monterey, California (NRL-MRY) has taken advantage of the 85-GHz channel and the associated sampling pattern by adopting a mapping routine developed by Gene Poe at NRL-DC. This mapping routine can accurately map 85-GHz data at resolutions as fine as 1-2 km. In addition, the mapping routine allows the user to map the SSM/I data to the same resolution as coincident visible/IR data from the Operational Linescan System (OLS) on the DMSP or the corresponding geostationary data at nadir. Our studies reveal the remapped 85-GHz data agrees remarkably well with the features one can analyze in the visible/IR data, when clear cut items are in view (e.g., mesoscale convective clusters, eye, eyewall, and rainbands).

The 85-GHz imagery is able to map the rainbands, eyewall and eye very well since it responds to scattering due to both raindrops and ice particles by virtue of dramatically lowered brightness temperatures. Thus, although cirrus type clouds will preclude an analyst from seeing many or all spiral banding features of interest, the 85-GHz data can clearly depict these dominant items that are necessary for understanding the TC's structure and their changes over time. Time histories of 85-GHz data for a given TC clearly map the evolution of the rainbands, eyewall and eye as the storm develops, matures and then decays.

Of particular interest is the ability to map eyewall cycles. These cycles manifest themselves when the original eye becomes very small and intense. The TC forms a secondary eyewall further out, the circulation supporting the inner eye is cut off and the inner eye collapses. The outer eye then takes over and gradually shrinks in diameter as the storm regains its original structure. Intensity changes are linked to this internal process.

Since the SSM/I can map the TC structure so well, we have developed an automated technique to analyze the 85-GHz imagery and output an estimated TC maximum sustained wind speed. This has been done via a neural network approach where the SSM/I images are represented by Empirical Orthogonal Functions (EOF). Thus, the patterns (e.g., rainbands, eyewall) in the 85-GHz images are contained within the EOFs.

Considerable effort has been expended to create a data base of 85-GHz images of TCs of varying intensity in order to train and validate the neural net. The current data base has over 500 high quality SSM/I images, with which the neural net has used ~ 450 for training and ~ 50 for validation. Earlier efforts suffered from a small data base and limited EOFs that could be used before the neural net encountered memorization problems. In addition, earlier studies revealed that typical RMS errors were > 20 kt when no a priori information was used.

Numerous methods were studied using a priori data in the form of best track intensities (6 or 12 hours before SSM/I image) or the warning intensity at the time of the image. Results improved dramatically as one might expect and RMS errors were 4 and 7 kt respectively.

The latest neural net runs using the expanded 500-set data base now indicate that we can get below the 20-kt RMS error with no a priori knowledge. These results likely indicate that we are approaching the statistical accuracy of the western Pacific best track intensity data base since it is largely based on Dvorak values. We estimate that the limit using this data base is ~ 15 kt.

Work is ongoing to focus on those Atlantic TCs with aircraft reconnaissance and the limited Pacific cases that have high confidence due to additional observations (e.g., islands, ships) being available. These data sets are now being updated in a semi-automated manner during the 1997 season. The SSM/I data are now finding more use for intensity and location related efforts as the capabilities of the 85-GHz data are becoming better understood.

## 7.5 OPERATIONAL USE OF SCATTEROMETER DATA FOR TCs

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Scatterometer surface wind vectors from both ERS-2 and more recently from the NASA Scatterometer (NSCAT) are utilized by JTWC for mapping the ocean surface wind field in and around tropical cyclones (TCs) in a quasi-real-time mode. Scatterometer data continued to show good potential for identifying the early potential of developing TCs and gave JTWC an initial estimate of minimum intensity observed within the system. While both ERS-2 and NSCAT are active sensors, NSCAT offered some potentially superior capabilities due to its inherently better resolution of 25 km versus 50 km for ERS-2 and its two 600-km swaths, instead of the single 500-km swath for the ERS satellites. (Unfortunately the satellite carrying the NSCAT sensor stopped transmitting 30 June 1997).

The double swath coverage afforded daily and sometimes twice daily coverage for all TCs, versus the occasional hit with ERS. Thus, the potential to use the data had grown considerably. During the evaluation, questions related to the frequency differences between the two sensors and how the wind directions are derived were investigated.

NSCAT operated at ~ 15 GHz instead of ~ 5 GHz for ERS and thus was susceptible to heavy rain. Under light wind conditions, heavy rain produced anomalously high wind retrievals; while under strong winds, heavy rain caused lighter than normal winds to be produced. Thus, the user needed to know when rain contamination was occurring. NRL-MRY is continuing to investigate several methods to resolve this issue using both SSM/I and geostationary IR data sets for future NSCAT launches.

The SSM/I produces rainrates over its 1400-km swath that are physically based and have undergone extensive validation in the Precipitation Intercomparison Projects (PIP) efforts. It should be noted several of these cases also included TC-type conditions. However, one rarely gets a reasonable matchup with SSM/I overpasses and NSCAT data. Thus, we have produced a rainfall method that incorporates both SSM/I data and the more frequent geostationary IR data.

Through this method we will be able to identify NSCAT values that are contaminated by rainfall, and then to accurately specify the contamination over each NSCAT cell so as to apply a rainrate correction factor for each wind value.

Selecting wind directions for scatterometers is also difficult, since the current retrieval algorithms produce 2-4 possible vectors. Various methods exist to dealias, or select, one wind direction. This usually involves the first guess from a global model, which is a problem, since most global models do not have the resolution needed to resolve the inner circulation of a TC. A number of techniques are under study to determine how best to dealias the NSCAT data with as little dependence from models as possible.

## 7.6 CONTINUED STUDY OF WIND DISTRIBUTION FORECAST CAPABILITIES AT JTWC

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While US and international TC warning centers have performed forecast verifications for decades, the verifications have primarily been limited to the forecast position and intensity. There has been a reluctance to-date by the warning centers to validate the predicted distribution of the over-water gale-, storm-, and hurricane-force near-surface winds. This reluctance has resulted in little formal documentation of the extent of the ability of the centers to forecast the surface wind distribution. A study was initiated in 1995 to ascertain the characteristics of JTWC TC wind distribution forecasts. The study was continued in 1996, and in addition, a preliminary evaluation of the wind distribution output of the GFDN model. The research has revealed several interesting and important characteristics of the wind distribution forecasts.

The operational warning time wind distribution was found to be of insufficient quality to use as the verification source. This required a comprehensive reanalysis of the actual wind field data in order to develop a validation data base. Several sources of data were used, and the analyses were checked both for spatial and temporal consistency. JTWC hand-plotted surface-gradient composite analyses, sectional charts, hand-plotted time sections, and raw data messages were the primary sources of conventional data. Also, Doppler radar, scatterometer, and microwave imager remote-sensing data were used.

A statistical breakdown of the data sources used to verify the 35- and 50-kt (17- and 26-m/sec) wind revealed that the most common data source for verification of 35-kt winds (17-m/sec) was ship data and for 50-kt (26-m/sec) winds was land observations. In 1995, ERS-1 scatterometer data were evaluated as a validation source and was found to be very good. As a result, scatterometer became a major source of over-water validation data. To put the wind distribution errors in perspective with the total forecast, wind distribution errors were compared with the average annual JTWC track forecast errors for the various forecast periods. The 1996, results were similar to the 1995 results. Major findings are summarized below:

a. Absolute wind distribution errors

An accurate initial analysis is highly favorable for an accurate subsequent wind distribution forecast; in the < 24-hour forecast periods, the total wind distribution forecast error is comprised nearly equally from track forecast error and error in determining the extent of the winds; at 72-hr, the track forecast error contributes 6-8 times more to the total error than does the 72-hr wind analysis error;

and, thus, after 24 hours, the track error becomes the greatest contributor to the overall wind distribution error.

b. Average wind distribution forecast error (bias)

In general, the bias shows that in 1995, JTWC under-analyzed and under-forecast the strong sector wind distribution and over-analyzed and over-forecast the weak sector wind distribution, thus under-forecasting the asymmetry. In 1996, there was a tendency to under-analyze and under-forecast both sectors for 35-kt (17 m/sec) wind distribution. For the 50-kt (26 m/sec) wind distribution, the tendency was to under-forecast both sectors, even though the weak sector winds were over analyzed.

## 7.7 A PRELIMINARY STUDY OF GFDN-GENERATED WIND DISTRIBUTION FORECASTS

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The GFDN, the Navy adaptation of the GFDL high resolution hurricane model, provides a graphic display of the wind distribution predicted by the model. A preliminary study was conducted to assess the accuracy of the GFDN wind distribution predictions. The validation data base was taken from the study on JTWC wind distribution forecast capabilities. The absolute and average forecast errors were compared with those of the JTWC. The preliminary findings of the study are: (1) the model significantly under-forecast the strong sector winds and over-forecast the weak sector winds (to a lesser extent) for 35-kt (17 m/sec) winds, thus under-forecasting the asymmetry; (2) for 50-kt (26-kt m/sec) winds, both the strong and weak sectors were under forecast. The study also revealed that there were some boundary problems with the output that have since been corrected.

## 7.8 PROGRESS ON A RESEARCH QUALITY, CONFIDENCE-BASED TC INTENSITY DATA BASE

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Work continued on the confidence-based TC intensity data base (IDB). This data base is needed because, in general, TC best-track (BT) IDBs are not of sufficient quality to be used as validation data for TC intensity research. There are several reasons for this shortfall, the most basic reason being that there is no way to discern the quality of the data on which a specific BT intensity is based. Different data platforms provide intensity data of varying accuracy, and from this knowledge, one can infer a certain level of confidence in that data.

a. Methodology of data base development

After determining the need for improving the JTWC IDB, a list of reasons for the needed changes was compiled. Examples of these are: landfall data not originally available, re-analysis of aircraft data, etc. Then, various data types were assessed for their accuracy in providing surface wind speeds, and each type was assigned a relative confidence value. Next, the JTWC "fix files" were reassessed and corrected where possible. Landfall data are being obtained from other countries, and these are being incorporated into the fix data base from which the IDB is developed. Translation speed, stability considerations, intensity spin up-spin down considerations, and appropriate wind-pressure relationships are also being used to make corrections.

b. Proposed Format and Availability

Once modifications are made, they will be put into a new data base, modified slightly from that of the preexisting JTWC BT data base. In addition to the data available in the JTWC format, the modified format includes the updated intensity value, the magnitude of the change, the coded reason for the change, and the relative accuracy or confidence of the intensity value. Initially, the data base will include data from the 1990s. Eventually, it will be expanded to the 1980s, 1970s, and earlier periods. The data base will reside on a web page in late 1997, and will be periodically updated as new data becomes available.

## 7.9 A WIND-PRESSURE RELATIONSHIP FOR MIDGET TCs IN THE WESTERN NORTH PACIFIC

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A new wind-pressure relationship (WPR) that relates maximum sustained surface winds in TCs to the minimum central pressure has been developed for western North Pacific (WNP) midget TCs. Midget TCs have a high intensity inner core where the outer winds are from the inertial spin down of the belt of maximum winds. There is no outer core. The WPR was based primarily on carefully selected data of midget TCs making landfall on islands and coastal areas of the WNP. Some aircraft data were used where the small TC size could be confirmed and where it was clear that the aircraft was in the strong sector of the TC. The new WPR indicates that these small TCs can have the same winds as larger TCs, but with a 10-17 mb higher central pressure, which corresponds to a 10-20-kt difference in wind speed. It also indicates that as the intensity approaches 130 kt (62 m/sec), the WPR converges with the WPR used for more normal sized TCs. This is because the midget TC usually acquires outer core characteristics.

The regression equation for the new WPR (for WNP midget TCs) is:

$$Vmax = 17.548(Pn\text{-}Pc)^{0.4345}$$

Table 7-1 relates the maximum sustained wind with the minimum central pressure given by the new WPR (with Pn = 1010 mb) and that given by the Atkinson-Holliday WPR (Atkinson and Holliday 1977).

**Table 7-1** A comparison of the maximum sustained winds (Vmax) with the minimum central pressure (Pc) in millibars for (a) midget TCs (new WPR) and (b) normal-sized TCs (Atkinson-Holliday WPR) (A & H).

| Vmax | Pc midget | Pc A & H | Vmax | Pc midget | Pc A & H |
|---|---|---|---|---|---|
| | | | | | |
| 30 | | 1000 | 105 | 949 | 939 |
| 35 | | 997 | 110 | 943 | 934 |
| 40 | 1003 | 994 | 115 | 935 | 928 |
| 45 | 1002 | 991 | 120 | 928 | 922 |
| 50 | 1000 | 988 | 125 | 919 | 916 |
| 55 | 994 | 984 | 130 | 910 | 910 |
| 60 | 992 | 980 | 135 | 904 | 904 |
| 65 | 989 | 976 | 140 | 898 | 898 |
| 70 | 986 | 972 | 145 | 892 | 892 |
| 75 | 982 | 968 | 150 | 886 | 886 |
| 80 | 978 | 964 | 155 | 879 | 879 |
| 85 | 972 | 959 | 160 | 872 | 872 |
| 90 | 965 | 954 | 165 | 865 | 865 |
| 95 | 960 | 949 | 170 | 858 | 858 |
| 100 | 955 | 944 | | | |

## 7.10 A STUDY OF TC INTENSITY CHANGES USING THE DIGITAL DVORAK ALGORITHM

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One of the utilities installed in the JTWC's MIDDAS satellite image processing equipment is an automated routine for computing Dvorak "T" numbers for tropical cyclones that possess eyes. The routine, developed by Zehr (personal communication), adapts the rules of the Dvorak technique as subjectively applied to enhanced infrared imagery (Dvorak 1984) in order to arrive at an objective T number, or "digital Dvorak" T number (hereafter referred to as DD numbers). Infrared imagery is available hourly from the GMS satellite, and hourly DD numbers were calculated for all of the typhoons of 1996 (and for some of the typhoons of 1995).

A preliminary study of the time series of the DD numbers shows that, in some cases, they differ substantially from the warning intensity and also from the subjectively determined T numbers obtained from application of Dvorak's technique. The output of the DD algorithm, when performed hourly, often undergoes rapid and large fluctuations. If the DD numbers truly represented rapid (on the order of 3 to 6 hours) intensity fluctuations with magnitudes (30-40 kt) as large as seen with some typhoons, there are two topics for further research: (1) how are the extremely rapid fluctuations of estimated intensity, if they are genuine, to be incorporated into the warning? And, (2) how can the best tracks, having had these rapid fluctuations removed, be used to study the processes governing what may prove to be real intensity fluctuations of the magnitude indicated by the DD numbers?

Another characteristic of the time series of the DD numbers emerges for most of the very intense typhoons: the DD numbers rise more quickly, and peak earlier, than do the subjectively determined T numbers. Also, within 24 hours of the peak, the DD numbers rapidly decrease to values as low as two T numbers below their peak value. A recovery is then observed before the DD numbers fall once again as the TC recurves and becomes extratropical. The cause of the rapid drop of the DD numbers after peaking is identifiable in nearly all cases of this phenomenon as the result of the formation of concentric eye wall clouds. A relatively precipitation-free moat forming between the concentric wall clouds causes the DD algorithm to yield a greatly reduced T number. When the outer wall cloud contracts and the inner wall cloud dissipates, the DD numbers rise. The behavior of the DD numbers may serve to highlight processes (such as eye wall replacement) and lead to a better understanding of them.

## 7.11 A LOOK AT GLOBAL TC ACTIVITY DURING 1995: CONTRASTING HIGH ATLANTIC ACTIVITY WITH LOW ACTIVITY IN OTHER BASINS

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The 19 named TCs in the North Atlantic (NAT) during 1995 were nearly a record for that basin. During the past three decades, only the year 1969 — with its 18 TCs of at least tropical storm intensity — was nearly as prolific. During 1995 and 1969 (two years that have been designated herein as "prolific" years in the NAT), the annual number of TCs in most of the other TC basins was well-below normal (to such an extent that even the annual global number of TCs during these two years was below normal). Despite the strong reduction of the annual number of TCs in most basins during the aforementioned NAT prolific years, there is no overall correlation between the annual number of TCs in the NAT and the annual number of TCs in any other major TC basin [i.e., the western North Pacific (WNP), eastern North Pacific (ENP), and Southern Hemisphere (SH)]. In fact, the only statistically significant correlations of annual numbers of TCs are weak positive correlations between the WNP and the ENP, between the SH and the WNP, and between the SH and the ENP. These weak positive correlations act to increase the variance of the annual global number of TCs.

There are only two large-scale atmospheric phenomena [i.e., ENSO and the Quasi-Biennial Oscillation (QBO)] that have been documented to have an effect on the annual number of TCs in the NAT and within the other TC basins. It has been shown that only within the NAT are the magnitude of these relationships strong. In all other major basins, the ENSO and the QBO have little, if any, effect on the annual number of TCs (although the formation regions of TCs within the WNP and the SH are shifted quite markedly by ENSO).

The global distribution of TCs during the NAT prolific years of 1969 and 1995 stands quite apart from the long-term relationships noted between the annual number of TCs in the NAT with the annual number of TCs in the other major TC basins. The ENSO and QBO can not alone account for the unusual distribution of TCs during 1969 and 1995. In fact, 1969 is considered by some to have been an El Niño year, while the global climatic anomalies during 1995 were considered by some to be representative of the cold phase of ENSO (i.e., La Niña). The only apparent commonality between 1969 and 1995 was that the QBO was in a westerly phase, a large-scale atmospheric condition experienced approximately once every two years.

The NAT prolific year of 1995 need not herald the return to a higher number of NAT TCs such as has been documented to have occurred during the decades of the 1940s through 1960s. In fact, the NAT prolific year of 1969 was, in retrospect, a "herald" of lower NAT TC activity during the 1970s through the 1980s. It is hypothesized that NAT prolific years such as 1995 and 1969 will always be a characteristic of the NAT time series, regardless of inter-decadal changes in the average annual number of TCs in the NAT.

That the NAT prolific year of 1995 was a signal of global climate change is unlikely, considering that the phenomenon has occurred in the past, and that the global distribution of TCs during the previous NAT prolific year —1969 — was so strikingly similar. Based on the peculiar similarities between the global TC distribution of 1969 and 1995, it is hypothesized that the phenomenon of NAT prolific years (accompanying "meager" years in other basins) has its roots in a specific (but infrequent) state of the global atmosphere which does not appear to be related to ENSO, the QBO, inter-decadal changes in the annual number of TCs in the NAT, or long-term global climate change. Its mechanism remains a mystery.

## 7.12 UPDATING TC SATELLITE-DERIVED POSITION CODE NUMBER CRITERIA USED BY JTWC

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In order to construct an accurate track history of a given TC from the many fixes obtained, it is desirable to have a methodology for determining not only the position, but also the reliability of that position. The Special Projects Section of Detachment 1, First Weather Wing (1WW) developed and published such a methodology in Pamphlet 105-10 (1WWP 105-10) entitled, Tropical Cyclone Position and Intensity Analysis Using Satellite Data (Arnold and Olsen 1974). One of the terms introduced in 1WWP 105-10 was Position Code Number (PCN). The PCN indicates the expected accuracy of the reported position. There are six PCNs: TCs with eyes (PCN 1 and 2); well defined circulation centers (CC) (PCN 3 and 4); and, poorly defined CC (PCN 5 and 6). Odd-numbered PCNs indicate geographical navigation of the gridding. Even-numbered PCNs indicate the gridding was based on satellite ephemerides alone.

Given the advances in technology, both in terms of image processing capabilities and the addition of new spectral windows, the process of assigning PCNs to TC fixes needs to be updated and improved. Specifically, the following recommendations are offered:

(1) the guidance currently available for determining PCNs should be updated to reflect changes in advances in technology and the decrease in the relative numbers of PCNs 3 and 4,

(2) a systematic categorization of fix types linked to specific PCNs (this includes concise documentation of the cloud features, sensor types, and specific image processing methodologies used to make the fix), should be made and

(3) the relative accuracy of the fixes from the new image categories requires validation.

Satellite Operations is currently using a newly developed list of PCN categories. After a year, the error statistics of the PCN categories will be examined.

## 7.13 A TECHNIQUE FOR ESTIMATING THE INTENSITY OF TCs WHICH ARE UNDERGOING EXTRATROPICAL TRANSITION

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A review of western North Pacific synoptic data from 1994 through 1996 revealed that the intensity estimates of a significant number of typhoons that became extratropical were underestimated by the tropical satellite reconnaissance network using Dvorak's (1975, 1984) techniques. Occasional use of Hebert and Poteat's (H&P) (1975) technique for estimating the intensity of subtropical cyclones on these recurving typhoons also resulted in intensity estimates which were too low.

The application of Dvorak's techniques to TCs undergoing extratropical transition resulted in the intensity being underestimated by as much as three T numbers below the actual intensity as verified by synoptic data (good examples of this problem are described in Seth's summary in the 1994 ATCR; and in Dan's (06W) summary in this ATCR).

A technique to address the underestimation of the intensity of TCs which are undergoing extratropical transition (XT) was developed. The XT technique borrows from both Dvorak and H&P in the application of the log10 spiral to the primary outer cloud band, and, as in H&P, an incorporation of the effects of excess translational speed. Additional factors include: the degree of organization of the central and peripheral low- and mid-level clouds, and the extent of any residual or regenerative deep convection between the LLCC and the primary outer cloud band. These four factors are evaluated for wind speed contributions in the final determination of the "XT" number. The XT technique is an additive process whereby the TC intensity is derived from the addition of contributions from each of the applicable factors. There is a direct equivalence of Dvorak T numbers and XT numbers. The XT technique should be used until the satellite imagery indicates that the system has completed its transition into an extratropical cyclone. At that point it is recommended that a technique developed by Smigielski and Mogil (1992) for the estimation of the central SLP of extratropical cyclones be used if continued analysis is warranted. Further details of the XT technique are found in Miller and Lander (1997).

## 7.14 ON THE ABILITY OF OPERATIONAL DYNAMIC MODELS TO PREDICT TC INTENSITY

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For many years, operational dynamic models have been used to predict TC motion. In this area, the dynamic models generally out-perform baseline statistical measures of skill (e.g., CLIPER), and a steady improvement in their skill has been observed. More recently, increases in the spatial resolution, better physics, and (in some cases) improved bogussing techniques have rendered them capable of simulating TCs with realistic horizontal and vertical structure (e.g., a small region of very low pressure accompanied by high winds close to the low pressure center, and an outdraft cyclonic circulation in the upper troposphere). These dynamic models also have shown realistic genesis and development of TCs such as the deepening of tropical depressions to typhoons within credible time spans. The intensity diagnoses and intensity forecasts of TCs in the western North Pacific (WNP) during 1996, made by several operational dynamic models (for which the analyzed and forecast intensity of TCs was routinely available at the JTWC, Guam), are evaluated with respect to the final best-track intensities produced by the JTWC. Dvorak (1975, 1984) observed that, on average, TCs intensify at a rate of one so-called "T" number per day. Each rise of a T number represents a 10-15-mb increase of intensity at the lower T numbers, to increases of approximately 30 mb per T number at the higher T numbers. Dvorak also categorized fast and slow development as an increase of 1.5 T numbers per day and 0.5 T numbers per day respectively. Additional categorizations of TC rates of intensification are rapid deepening (Holliday and Thompson 1979) and explosive deepening (Dunnavan 1983); these are 24-hr central pressure drops of at least 1.75 mb/hr for at least 12 hours and 2.75 mb /hr for at least 6 hours respectively. The results presented herein are based upon a preliminary examination of the dynamic model's (and JTWC's) ability to predict the 24-, 48- and 72-hour intensities of several of the WNP TCs of 1996. The only statistic evaluated was a simple comparison of the models' intensity trends with the intensity trends derived from the JTWC best tracks. Intensity trends were evaluated in a permutation of several forecast intervals: 0 to 24 hours, 0 to 48 hours, 24 to 48 hours, etc. A model's intensity prediction was scored as correct if its trend was in the same direction as the best track; even if the model changed by only 1 mb in the right direction and the best track changed by 70 mb. A model's intensity prediction was scored as incorrect if the trend was against the best track; no change in model intensity was scored as incorrect if the best track exhibited any change. Examination of the intensity output of the various dynamic models also reveals some general characteristics. At the 0- to 24-hour forecast interval and the 0- to 48-hour forecast interval, most of the models have only modest skill over a random choice. At the extended forecast period of 48 to 72 hours, most of the models show no skill over a random choice. In fact, most of them are more often incorrect than correct. There are also large differences of skill from one TC to another.

Upon closer examination of the behavior of the model predictions of intensity, it is seen that the global spectral models have very small magnitudes of intensity change, while the regional models (e.g., GFDN), with their finer resolution and different physics packages, exhibit magnitudes of intensity change that are realistic. Also, the regional models have consistently higher skill over the global models at all permutations of forecast intervals. Further research is warranted to see if the models have any skill in flagging deviations of intensification from normal rates (e.g., rapid deepening, explosive deepening, and non-developing). A complete study of objective prediction of TC intensity must also include statistical intensity prediction schemes.

## 7.15 WATER VAPOR AND HIGH RESOLUTION VISUALLY TRACKED WINDS FOR TC APPLICATIONS

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Upper-level water vapor winds (Velden et al. 1997) and low-level cloud motion winds from high-resolution visible satellite imagery were derived and evaluated. These winds are derived from sequences of GMS-5 imagery accessed through the Bureau of Meteorology in Australia. Water vapor wind data sets were produced nominally at 12-hour intervals (00 and 12Z). However, during TC events, the frequency was increased to 6 hourly. The data sets were provided via Internet to JTWC for real time analysis. The data sets were also provided to FNMOC for inclusion into the operational NOGAPS model beginning in late July. Indications are the winds have made an immediate impact (improvement) on the NOGAPS upper-level analyses over the western North Pacific.

Special water vapor wind data sets were also produced over the Indian Ocean region during Naval exercises. These data sets were helpful in forecasting conditions for both the exercises, and TC monitoring in that region.

In 1996, UW-CIMSS began experimenting with a new product derived from sequences of high-resolution GMS visible imagery. Fields of high density, low-level cloud-tracked winds were derived and disseminated to JTWC for their evaluation. The fields were produced in the genesis region surrounding Guam at 00Z daily. However, during TC events the data set center was programmed to "float" with the center of the TC to provide coverage in the immediate TC environment. While several minor problems were discovered with the product, the winds show promise with further R&D to provide information on both TC genesis and size.

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