5B.5 REANALYSIS OF WEST PACIFIC TROPICAL CYCLONE MAXIMUM INTENSITY 1966-1987

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1. INTRODUCTION

Recently published studies (Emanuel 2005; Webster et al. 2005) have found upward trends in tropical cyclone (TC) intensity in the western North Pacific. These studies, however, were based on historical best track intensities, which have many shortcomings due to operational procedures, data quality and to the frequency/quality of intensity estimates available (i.e., Chu et al. 2002). While many discrepancies (typos, interagency differences etc.) were discussed in Chu et al. (2002) no significant changes to the intensity record were performed – meaning there are still problems with the intensities in the best track dataset.

Prior to 1988, aircraft reconnaissance was available in this region and reliable minimum sea level pressure (MSLP) observations were often available to aid the Joint Typhoon Warning Center in intensity assignment. During this period, however, the operational methodology used to assign maximum 1-minute sustained wind speed (MWS) given the MSLP (i.e., the wind-pressure relationship) was not constant or applied consistently. The use of different wind-pressure relationships in this region has likely resulted in variations in TC intensity that are of the same order as recently reported upward trends. In addition to inhomogeneity of the wind estimation method, it has been shown that the heavy reliance upon the Atkinson and Holliday (1977) (AH77) wind-pressure relationship (WPR) has resulted in a systematic underestimation of the MWS for tropical cyclones of typhoon strength and greater during 1974-1987 (Knaff and Zehr 2006). This reliance is illustrated in Figure 1. During 1966-1973, a different WPR was apparently in use while during 1974-1987 the best fit to the wind vs. pressure data is nearly identical to that of AH77.

As an attempt to remove the inhomogeneties in the best track associated with evolving WPRs, this study makes use of a recently developed WPR that estimates MWS based on MSLP and accounts for variations of latitude, environmental pressure, translation speed and TC size. This newly developed WPR is based on 15 years of aircraft reconnaissance estimates of MSLP in the Atlantic (3534) and East Pacific (267), best track estimates of MWS and storm location, and information about the environmental pressure and tropical cyclone size from the NCEP reanalysis. Independent testing of this WPR during the 2005 Atlantic Hurricane season resulted in nearly normally distributed errors with a bias of 1.7 kt, mean absolute error of 6.0 kt, and standard deviation of 7.9 kt, based on preliminary best-tracks (Knaff and Zehr 2006).

The purpose of this study is twofold: to determine how much of the reported trends in West Pacific tropical cyclone intensity are potentially due to the differing operational WPRs and to explore the effects such a reanalysis will have on the basin wide climatological numbers of TCs stratified by intensity. To this end, this study will perform a homogeneous reanalysis of maximum surface winds associated with West Pacific TCs when aircraft based MSLP estimates are available (i.e., 1966-1987) using this new technique. This study will focus on the maximum intensity of each storm with a long-term goal of a thorough intensity reanalysis in combination with a satellite-based intensity reanalysis (i.e., following Dvorak 1975; 1984). The resulting TC climatology and temporal trends will be discussed in the context of Emanuel (2005) and Webster et al. (2005).

2. DATASETS

Two versions of the western North Pacific best tracks were examined for the period 1966-1987 including those available from the Joint Typhoon Warning Center (JTWC) and described in Chu et al. (2002), and those from the Hurricane Risk Analysis program for the western North Pacific (Neumann 1987). These data were identical with respect to intensity for the years 1966-1987; producing identical intensity climatologies.

Minimum sea level pressures (MSLP) collected during aircraft reconnaissance and estimated from flight-level geopotential heights and/or dropwindsonde MSLP measurements came from the Automated Tropical Cyclone Forecasts (ATCF; Sampson and Schrader 2000) for 1966-1977 and 1979-1987 and from the Annual Tropical Cyclone Reports (Morford, and Lavin 1978, cited 2006) for 1978. Each MSLP estimate has a date/time and

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location associated with it. Figure 2 shows the time series and variability associated with the MSLP during this period. Note that the means and variabilities are not shown for 1974, 1978, and 1987 because some of the MSLP fixes are missing for 1974 (these will be hand digitized at a latter date), only the time around the maximum intensities were hand digitized in 1978, and aircraft reconnaissance ended in August 1987. There are only slightly negative trends associated with the average MSLP or annual minimum MSLP during this period.

Six-hourly NCAR/NCEP Reanalysis fields (Kalnay et al. 1996) were used for the estimation of tropical cyclone size and environmental sea level pressure in this study.

3. METHODOLOGY

3.1 Estimates of tropical cyclone size

Operationally, tropical cyclone size is described by the radial extent of gale force winds or the radius of the outer most closed isobar. Size can also be evaluated by the wind fields in the reanalysis data. Ideally, size would be determined by the radius of zero tangential winds; however this quantity is very difficult to measure. Fortunately, the average tangential winds calculated from the reanalyzes in the annulus of 400-600 km (V_{500}) correlates with tropical cyclone size. Figure 4 of Knaff and Zehr (2006) shows the relationship (R^2 = 0.25) between V_{500} and the average radius of 34-kt winds reported in the NHC advisories (1995-2004). Additionally, tropical cyclone size is influenced by differences in intensity and latitude. In order to evaluate a range of tropical cyclone sizes for differing intensities and locations, a normalized size parameter is needed.

To remove the influence of TC intensity and latitude from the size estimate, V_{500} is divided by the value of the climatological tangential wind 500 km from the center (V_{500c}), which is estimated using a modified rankine vortex (Eq. 1),

$$V_{500c} = V_{\max}\left[\frac{R_{\max}}{500}\right]^{x}, \qquad (1)$$

where x (Eq 2), and $R_{\max}$ (Eq. 3) in km are functions of latitude (λ) in degrees and intensity ($V_{\max}$) in kt.

$$x = 0.1147 + 0.0055V_{\max} - 0.001(\lambda - 25) \qquad (2)$$

$$R_{\max} = 66.785 - 0.09102V_{\max} + 1.0619(\lambda - 25) \qquad (3)$$

Coefficients for this modified Rankine vortex model are taken directly from the operational Atlantic wind radii Climatology and Persistence model described in Knaff et al. (2006).

For each aircraft fix a value of V_{500} is estimated by interpolating values calculated at adjacent analysis times to the time associated with the fix. The value of V_{500} is then normalized by dividing this value by V_{500c}, which is based upon the original best track estimate of $V_{\max}$. This normalizing procedure results in a relationship between V_{500}/V_{500c} versus the radial extent of gale force winds to $R^2 = 0.40$.

3.2 Estimating environmental pressure

Since it is the gradient of pressure that is best related to the wind field, studies of tropical cyclone pressure wind relationships should address both central pressure and the environmental pressure (the ambient pressure outside the tropical cyclone). In this study, an environmental pressure is estimated for each fix by calculating the azimuthal mean pressure in an 800 to 1000 km annulus surrounding the cyclone center at each adjacent reanalysis time. The final estimate is determined by interpolating the reanalysis estimates to the time of the aircraft fix. A pressure deficit (ΔP) is estimated by subtracting P_{env} from the MSLP provided by the aircraft fix.

3.3 Accounting for translation speed

The translation speed of a storm has a small influence on maximum surface winds in a tropical cyclone, which it is desirable to account for in this study. To estimate the influence of storm motion, a storm relative maximum surface wind speed (V_{srm}) is estimated by $V_{srm}=V_{max}-1.5c^{0.63}$ (Schwerdt et al. 1979), where V_{max} is the maximum surface winds and c is the storm motion in units of kt.

3.4 Estimating winds from MSLP

A unified WPR was derived by using multiple linear regression in Knaff and Zehr (2006). The predictors are tropical cyclone size, latitude and intensification trend. The intensity trend was considered initially as a potential predictor, but was found statistically unimportant. The resulting multiple regression equation for predicting MSLP given a maximum wind speed estimate is

$$MSLP = 23.286 - 0.483V_{srm} - \left(\frac{V_{srm}}{24.254}\right)^{2} - 12.587*S - 0.483*\lambda + P_{env} \qquad (4)$$

,where V_{srm} is the maximum wind speed adjusted for storm speed, S (i.e., = V_{500}/V_{500c})is the normalized size parameter, and λ is latitude (degrees). P_{env} is added to the resulting ΔP to create $MSLP$.

One could solve Eq. 4 for V_{srm}, but analogous to solving for the gradient wind, the solution has two roots. The WPR can also be derived as a separate regression equation to estimate V_{max} given ΔP and storm motion (c). In the development of this regression equation (Eq. 5), the square root of ΔP is used as an additional predictor in addition to ΔP, size and latitude.

$$\begin{aligned} V_{\max} &= 18.633 - 14.960S - 0.755\lambda \\ &- 0.518\Delta P + 9.738\sqrt{|\Delta P|} + 1.5c^{0.63} \end{aligned} , \qquad (5)$$

where c is the storm translation speed [kt].

Both relationships shown above have been shown to provide higher correlations with independent Atlantic observations than the Dvorak (1984) Atlantic WPR (Knaff and Zehr 2006).

3.5 Assessing changes in maximum wind speeds

TC location, 6-hourly speed, intensity, environmental pressure and size are interpolated to the MSLP fix time. TC location, speed and intensity come from the best track files; environmental pressure and size are estimated from the NCEP/NCAR reanalysis. Cases within 30 km of land were removed from the sample, as were cases where the best track data were incomplete. The resulting match-ups result in 6082 data points. Then independent estimates of maximum sustained 1-minute winds are created for the 6082 cases using equation 5.

Maximum intensities of the best tracks are then compared with those from the 6082 cases. An alternative estimate of the maximum intensity of a given tropical cyclone is created if there is a maximum MSLP-based wind speed estimate within 12 hours of the best track maximum intensity. Seasonal summaries of the best track intensities and the MSLP-based intensities are then compared during the years 1966-1987.

4. RESULTS

4.1 1966-1987 sample statistics

There are several assumptions made in the analysis performed in this study. Most important are that the size of tropical cyclones can be estimated by the method used in Knaff and Zehr (2006) even in the period before routine satellite imagery and soundings. Another assumption is that the TCs in the western North Pacific behave similarly to those in the Atlantic and Eastern Pacific. In this section, we will present some statistics for the 6082 data points analyzed in this study.

Table 1 shows the mean statistics associated with this dataset and compares it to the combined Atlantic and Eastern Pacific data set used in Knaff and Zehr (2006). Note intensities are shown both before and after reanalysis for the West Pacific. Some of the statistics are similar (i.e. speed, intensity, and intensity trend), but as expected there are differences in size, MSLP, latitude and environmental pressure. The West Pacific storms are larger and have a larger range of possibilities – roughly 1 standard deviation bigger than their Atlantic counterparts. The West Pacific environmental pressure is close to 1009 and has a larger standard deviation. Finally, the latitudes of storms in the West Pacific are generally lower than the mostly Atlantic sample.

Another issue brought up by this table is that the maximum winds exceed the 170 kt reported in the Dvorak table and a realistic question to answer is whether winds of this intensity could exist in a tropical cyclone? On one hand, the low pressures found in some of the West Pacific typhoons could support these winds if the radius of maximum winds (RMW) was near average. On the other hand, observations of tropical cyclones with extremely low MSLP achieve such low MSLP when the RMW is very small (<5 nmi). The methodology used here, however, does not make use of the RMW since it is often hard to estimate. It is therefore likely that there is a slight over estimation for storms with eyes that are observed to be smaller than average (R_{max} < ~22 nmi, ~40 km) .

Similarly, if the calculated ΔP is small and the translational speed is slow, the WPR can produce rather weak MWS estimates. In the 6082 cases, 8 had reanalyzed MWS less than 15 kt. This produced a minimum of MWS is 2.85 kt for the dataset, which was based on the following input; ΔP = -0.8 hPa, $\lambda = 27.2^0$, c=8.0 kt, S=0.663.

Yet another question of this reanalysis concerns the size parameter. To assess the use of the size parameter we will list the largest and smallest storms with at least 100 kt intensities in the best track. Table 2 shows the smallest and largest storms with intensities of at least 100 kts along with the average normalized size (i.e. V_{500}/V_{500c}) when the storm had winds greater than 100 kt. The satellite pictures and discussion contained in the JTWC's annual tropical cyclone reports (1967-1987) confirm that these classifications are likely justified. This is somewhat surprising given the data used in the NCEP reanalysis in the late 1960's and early 1970's.

Finally, Table 3 lists the strongest 10 typhoons in the best track and following reanalysis along with the maximum winds and closest observed MSLP. It is notable that Super Typhoon Tip is no longer in the list following reanalysis – keeping in mind that Tip had a very large circulation associated with it and a relatively low environmental pressure (1005.9) at minimum MSLP. Other storms being more intense than Tip have been inferred by others using Dvorak

(1984) estimates (e.g., Hoarau et al. 2006) In the reanalyzed intensities, latitude (lower), size (smaller), and forward speed (fast) all played a role in upwardly revising these intensities. However, these comparisons highlight the variability in intensity obtained by simply changing the methodology used to assign MWS. Since the AH77 WPR does not behave as other WPR for TCs with winds greater than 65 kt, there is a general upward revision of the entire best track with respect to maximum winds speeds when reanalyzed. The next subsection will discuss the changes in tropical cyclone climatology with respect to maximum wind speeds following this reanalysis.

4.2 Climatological statistics (1966-1987)

The best track climatology of the number of tropical storms, and category 1-5 strength typhoons is shown in Table 4. Resulting statistics are identical to those Webster et al. (2005) used to assess trends in the number of category 1, category 2 & 3 and category 4 & 5 storms in the western North Pacific. Table 4 also shows the resulting climatology following a reanalysis of maximum wind speed following Knaff and Zehr (2006). The reanalysis results in a mean increase of 1.5 Category 4 and 5 storms per year and an increase of the mean intensity of 6 kt (as shown in Table 1).

We now compare the results with those of Webster et al. (2006) in their Table 1 (Note that there is an error in Webster et al.'s Table 1 for the period 1970-1979; the number of Category 4 & 5 storms from 1975-1989 should be 75 from the best track accounting for 32% of all typhoons not 85 and 25%, respectively). Following reanalysis of the maximum intensities the number of Category 4 & 5 storms increase from 75 to 93 or 32% and 39% of all typhoons, respectively. In the latter period (1990 – 2004) there are 116 storms of this intensity or 42% of typhoons. So instead of a 16% increase from one 15-year period to the next as reported by Webster et al. (2005) there is more likely a 3% increase – a discrepancy of 13%.

For completeness, Table 5 lists the storms increased to Category 4 and decreased to Category 3 during the reanalysis of V_{max}.

The reanalysis has changed the reported trends in tropical cyclones in the western North Pacific as shown in Figure 3. Before this reanalysis effort, steep upward trends existed for the most intense typhoons. Following this reanalysis, upward trends still exist, but these are not as steep and more consistent with the observations of MSLP. Furthermore, with the addition of 1966-1969 in the climatology the trend in Category 4 & 5 typhoons nearly vanishes (Figure 4).

5. SUMMARY, CONCLUSIONS AND RECOMONDATIONS

The observed minimum sea level pressure (MSLP), possibly the most accurate measure of TC intensity, was utilized along with estimates of tropical cyclone size, environmental pressure, latitude, and storm motion to reanalyze the maximum sustained 1-minute wind speed (MWS) using a technique developed in Knaff and Zehr (2006). The result of reanalysis of the period 1966-1987 was first to increase the mean intensity by about 6 kt, and secondly increase the number of category 4&5 TCs (i.e. storms with intensities > 114 kt) by 1.5 per year. This last result is very important in light of the recent papers discussing upward tropical cyclone intensity trends (Emanuel 2005; Webster et al. 2005 and Trenberth 2005). Following the reanalysis of V_{max} there is still a slight upward trend in the number of Category 4&5 TCs in this region during 1970-2004, but this trend is not nearly as steep as those reported in Emanuel (2005) and Webster et al. (2005) Furthermore, it should be pointed out that the addition of the years 1966-1969 nearly reduces the observed trend in Category 4 & 5 to zero – highlighting one of the pitfalls of trend analysis and its dependence on end point values. It therefore appears that much of the trends reported in Emanuel (2005) and Webster et al. (2005) can be explained by simply using an improved/different WPR.

Since historically WPR (and operational procedures) have been based on cyclostophic balance approximations, these results also demonstrate how information related to tropical cyclone size, latitude, and environmental pressure can provide better estimates of tropical cyclone intensity. Such information should be used not only to reanalyze the past best track datasets, but to provide better operational estimates of V_{max} and MSLP.

Finally, the authors admit that this paper has only focused on the maximum intensities and their climatology. As a result, these results only begin to highlight some of the problems with this basin's best track intensities. However, implied in these results is the assertion that similar problems exist in other basins. The best tracks in those basins also should be reanalyzed in a similar way. The authors strongly suggest that the information obtained by estimating V_{max} from MSLP (when available) should be used in combination with other intensity estimation techniques, namely reanalyzed Dvorak intensity estimates, to reanalyze the best track intensities in all basins. Once such a reanalysis is done, and only then, can the tropical meteorological community properly assess long term trends of tropical cyclone intensity.

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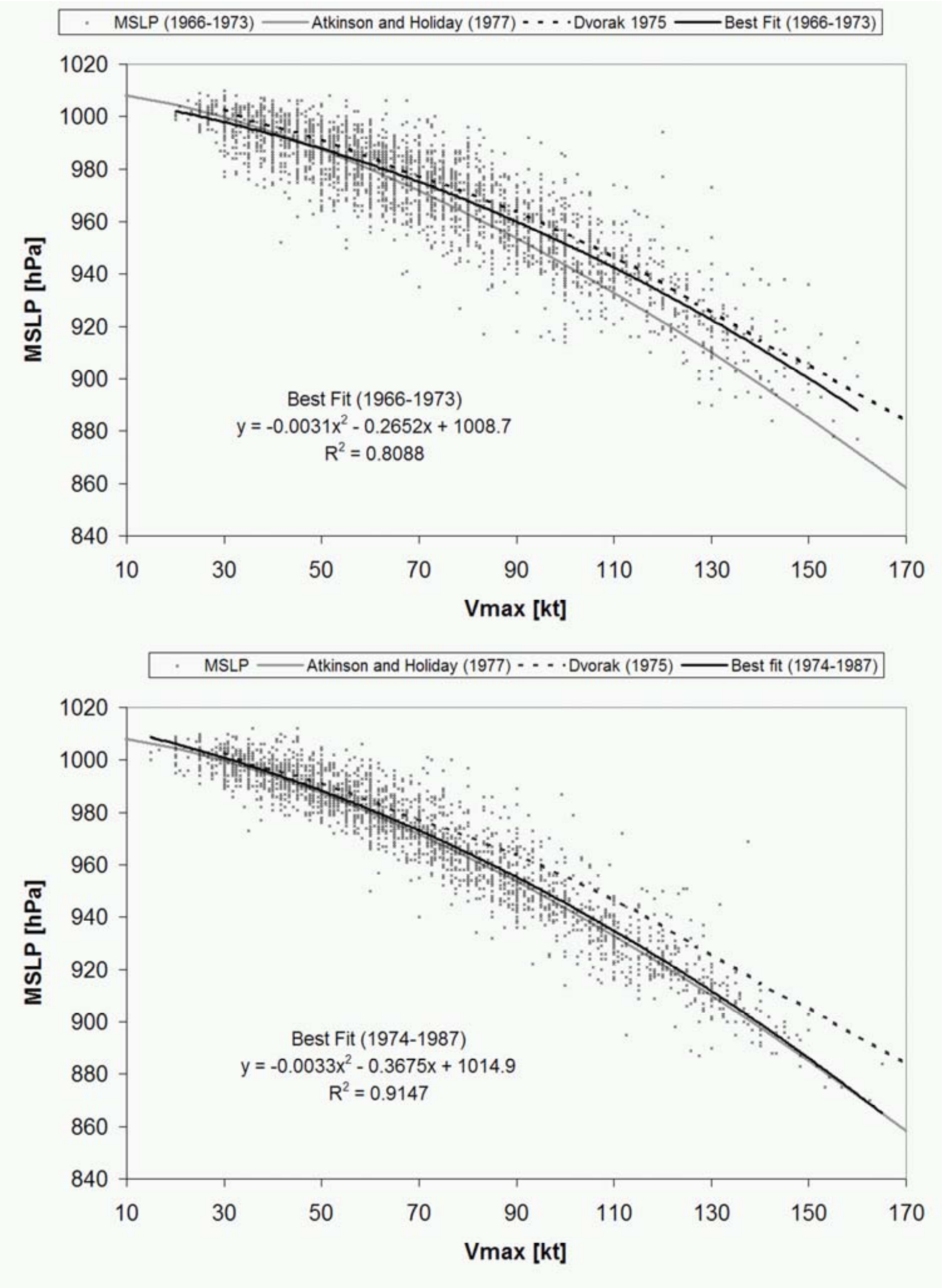


Figure 1. MSLP vs best track maximum surface winds (Vmax) interpolated to the time of the observations and associated best fit relationships to these data for 1966 -1973 (a) and 1974-1987 (b). Also shown are the Atkinson and Holliday (1977) and Dvorak (1975) pressure wind relationships.

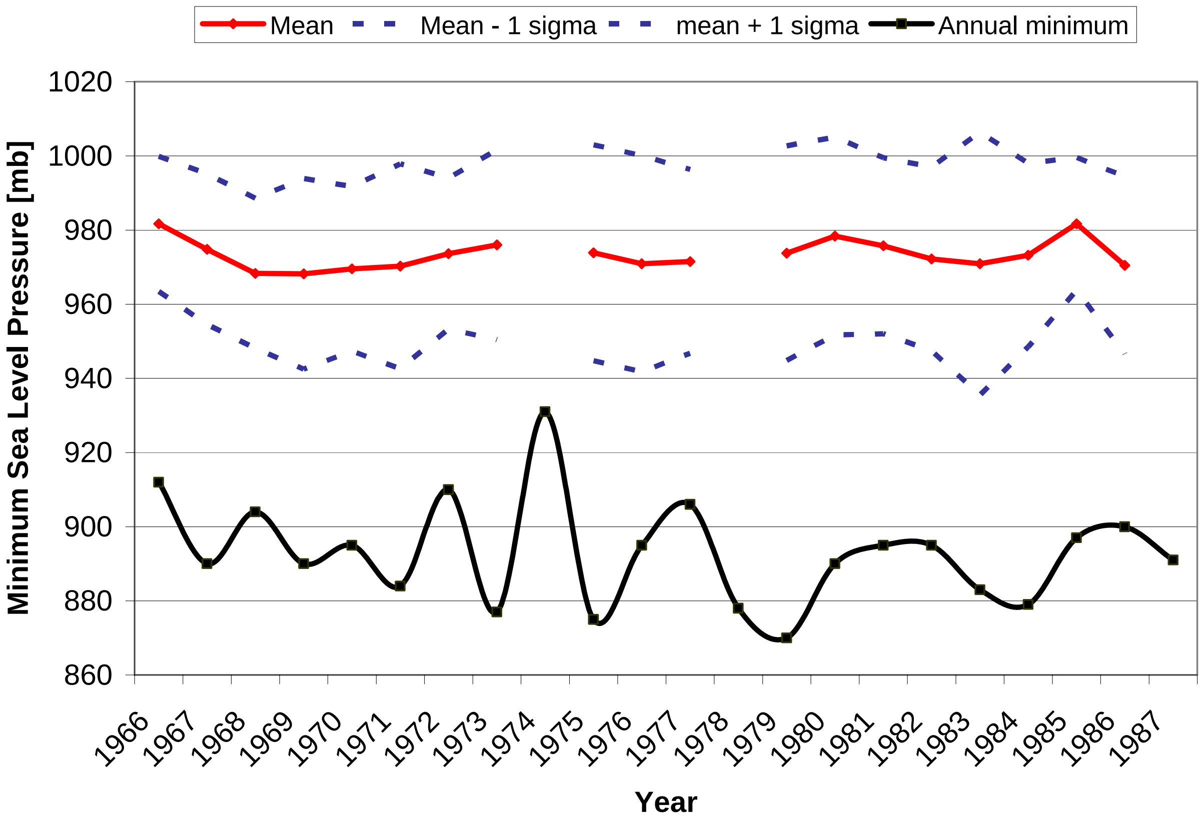


Figure 2. Time series of annual average MSLP reported in the tropical cyclone fixes (red) and annual minimum MSLP (black). Variability is shown in the dashed blue lines that are annual averaged MSLP plus and minus one standard deviation. See text for more details about the MSLP fixes. Means and variability not shown for 1974, 1978 and 1987 as explained in the text.

Table 1. Sample average statistics of the West Pacific TC used in this study along with those found in Knaff and Zehr (2006) for a sample of mostly Atlantic TC for comparison. Modified intensity statistics are shown in red italics.

	Number	Latitude	Size	Intensity [kt]	Intensity Trend [kt/12-h]	P_{env}	Speed [kt]	MSLP
Atlantic/E. Pacific (1990 – 2004)								
Mean	3801	23.67	0.49	72.15	2.55	1014.25	9.6	979.6
Max		44.2	1.22	155.00	43.30	1025.10	32.8	1020
Min		10	-0.21	24.20	-45.00	1004.50	0	905
Stdev		6.37	0.22	29.18	10.12	2.53	4.6	23.6
Western North Pacific (1966 – 1987)								
Mean	6082	18.85	0.64	67.84 *74.36*	3.31	1008.90	9.6	973.13
Max		43.4	2.27	165.00 *182.88*	55.00	1018.80	44.2	1012
Min		4.4	-0.28	15.00 *2.85*	-53.30	999.10	0	870
Stdev		6.6	.27	28.38 *30.61*	10.46	2.75	4.7	24.9

Table 2. A list of the largest and smallest TC, with best track intensities greater than 100kt, that occurred during the years 1966 – 1987. Also listed is their average size (V_{500}/V_{500c}) calculated during the time that intensities were greater than 100kt.

Largest TCs

Name	**Year**	**Storm Number**	**V_{500}/V_{500c}**
June	1975	23	1.57
Tip	1979	23	1.52
Carla	1967	29	1.27
Pamela	1976	6	1.20
Nora	1973	17	1.18
Gilda	1967	33	1.12
Betty	1972	14	1.11
Lola	1986	3	1.10
Abby	1983	5	1.10
Vanessa	1984	25	1.04

Smallest TCs

Name	**Year**	**Storm Number**	**V_{500}/V_{500c}**
Ellen	1983	10	0.25
Rose	1971	21	0.26
Kathy	1966	25	0.27
Lucy	1968	3	0.27
Ike	1984	13	0.30
Faye	1978	15	0.32
Dinah	1980	27	0.34
Wynne	1987	7	0.35
Cora	1975	15	0.40
Rita	1972	8	0.59

Table 3. A list of the most intense TC (in terms of maximum 1-minute sustained winds) occurring in the western North Pacific 1966-1987 in the current best track and following a reanalysis of maximum intensity. For the reanalyzed intensities the MSLP at that time is also listed. Rita (1978) and Louise (1976) both had maximum intensities that occurred not associated with their minimum MSLP. For those cases the MSLP at maximum intensity is listed first followed by the minimum observed during the storm's life cycle.

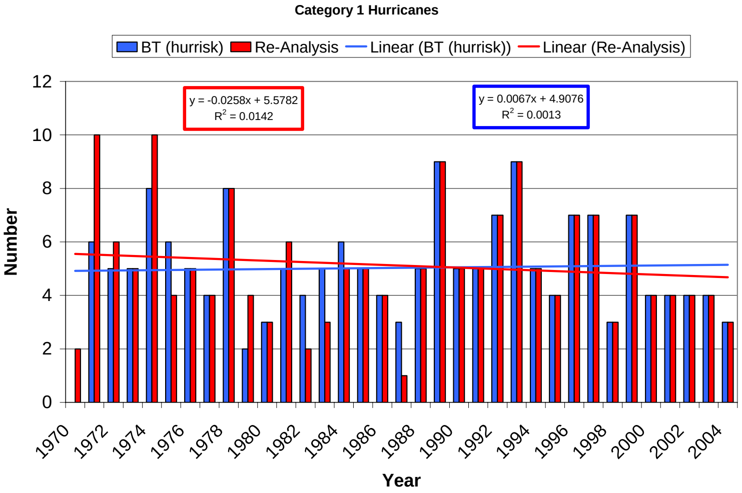
Most Intense in the Best Track (1966-1987)			
Name	**Year**	**Number**	**Intensity (kt)**
Tip	1979	23	165
Carla	1967	29	160
Opal	1967	20	160
Nora	1973	17	160
Kit	1966	4	160
June	1975	23	160
Irma	1971	34	155
Vanessa	1984	25	155
Rita	1978	28	150
Dot	1985	21	150
Most Intense in the Reanalysis (1966-1987)			
Name	**Year**	**Number**	**Intensity (kt), MSLP (mb)**
Rita	1978	28	183 882, 878
Irma	1972	34	175 884
Betty	1987	9	174 891
Forrest	1983	11	172 883
Wynne	1980	23	171 890
June	1975	23	171 875
Vanessa	1984	25	171 892
Nora	1973	17	169 878
Judy	1979	13	168 887
Louise	1976	22	167 905, 895

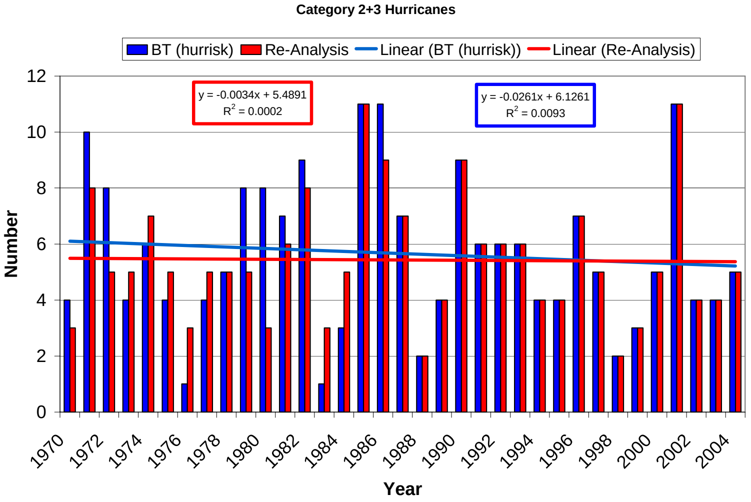
Table 4: A list of the resulting climatology of TC activity in the western North Pacific basin from the best track (left) and the reanalysis developed in this study (right).

YEAR	Best Track						Reanalysis					
	TS	**Cat 1**	**Cat 2**	**Cat 3**	**Cat 4**	**Cat 5**	**TS**	**Cat 1**	**Cat 2**	**Cat 3**	**Cat 4**	**Cat 5**
1966	10	4	8	3	3	2	10	9	5	2	3	1
1967	15	6	3	4	4	3	13	6	4	4	5	3
1968	7	6	1	5	4	4	3	4	4	3	9	4
1969	6	3	3	4	2	1	5	2	2	1	6	3
1970	12	0	1	3	4	4	10	2	1	2	3	6
1971	11	6	7	3	3	5	9	10	4	4	2	6
1972	8	5	1	7	5	4	7	6	2	3	8	4
1973	9	5	3	1	1	2	8	5	2	3	0	3
1974	16	8	5	1	2	0	13	10	4	3	2	0
1975	6	6	3	1	3	1	6	4	2	3	1	4
1976	11	5	0	1	7	1	9	5	2	1	4	4
1977	8	4	3	1	3	0	6	4	3	2	2	2
1978	13	8	4	1	1	1	11	8	2	3	2	2
1979	9	2	4	4	2	2	7	4	0	5	2	5
1980	9	3	3	5	3	1	9	3	1	2	7	2
1981	12	5	5	2	3	1	11	6	1	5	3	2
1982	7	4	3	6	4	2	7	2	3	5	7	2
1983	11	5	1	0	2	4	11	3	3	0	1	5
1984	11	6	1	2	6	1	11	5	0	5	2	4
1985	9	5	6	5	0	1	9	5	7	4	0	1
1986	9	4	7	4	2	2	8	4	3	6	3	4
1987	6	3	3	4	4	4	8	1	2	5	2	6

Table 5. A listing of storms that, during the reanalysis process of maximum intensity, changed to and from category 4. Listed are the year and storm name.

Increased to Category 4	
1967	Ruth
1968	Jean, Lucy, Carmen, Irma, Lola
1969	Susan, Cora, Grace, Helen, June, Kathy
1970	Iris
1971	Trix
1972	Ida, Olga, Pamela, Ruby, Therese
1975	Cora
1976	Olga
1977	Vera
1978	Faye
1979	Alice, Owen, Sarah
1980	Ellen, Joe, Marge, Vernon, Dinah
1981	Freda
1982	Nelson, Owen, Pamela
1986	Vera, Carmen, Joe
Decreased to Category 3	
1966	Irma
1971	Rose
1972	Phyllis, Tess
1976	Ruby
1984	Doyle





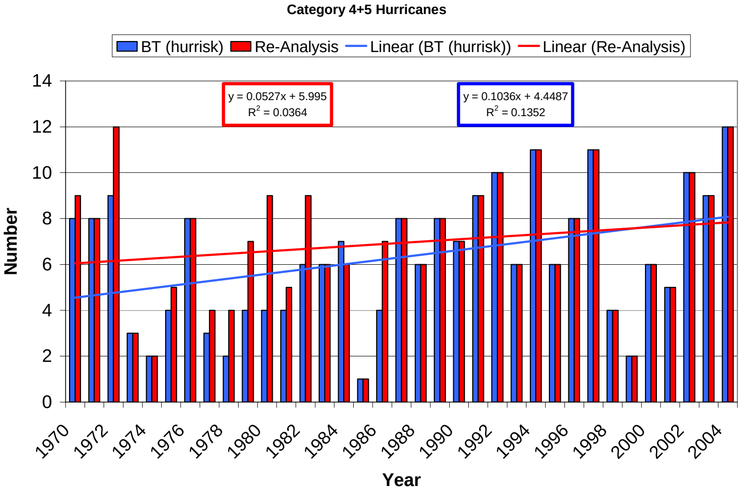


Figure 3. Time series of annual counts and associated trends of Category 1 (top), Category 2&3 (middle) and category 4&5 (bottom) for the western North Pacific basin 1970-2004 are shown. Blue and red bars and lines are associated with the best track (from Hurrisk) and the reanalysis of the MSLP data, respectively.

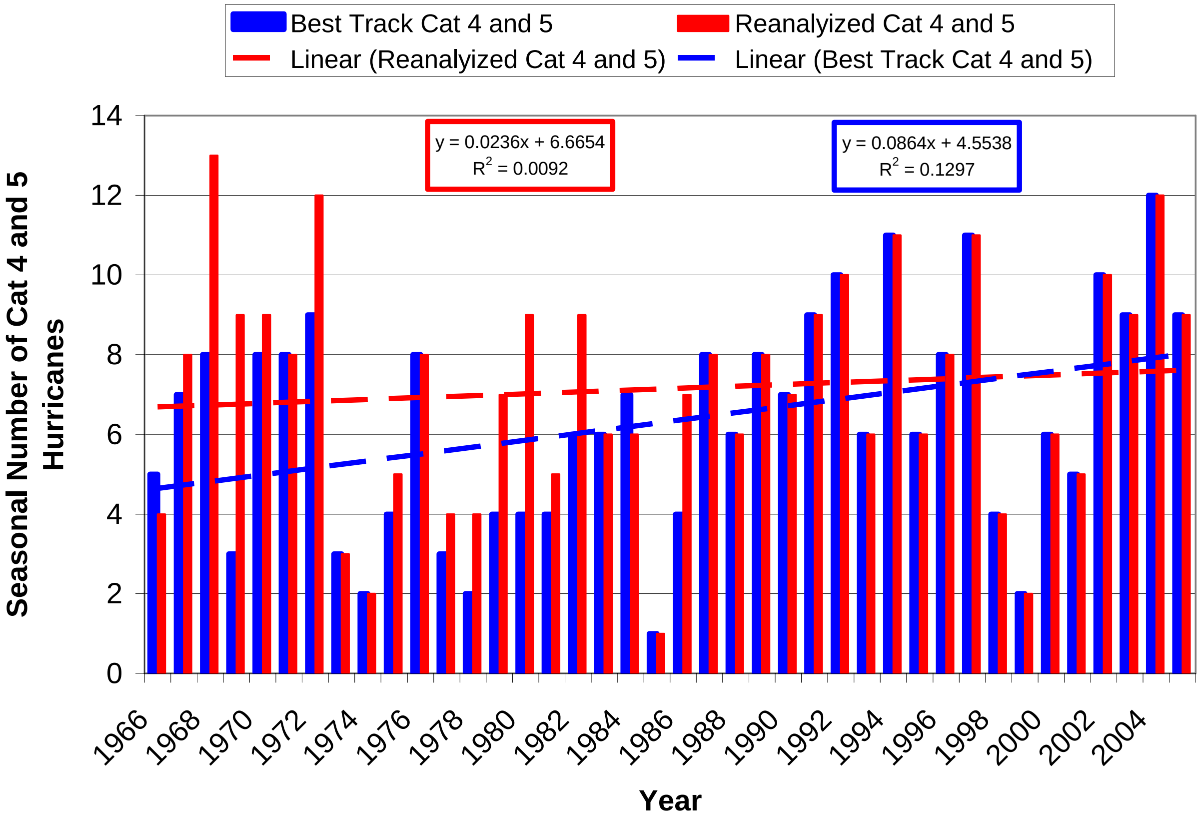


Figure 4. The annual counts and associated trends with category 4&5 TCs occurring in the western North Pacific Basin for the years 1966-2004 are shown. Notice the change in the trends as a result of the reanalysis. Again, blue and red bars and lines are associated with the best track and the reanalysis using the MSLP data, respectively.