1A.5 Quantifying Inter-agency Differences in Tropical Cyclone Best Track Wind Speeds

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1. INTRODUCTION

Given the significant impact of tropical cyclones (TCs) on life and property worldwide, the World Meteorological Organization (WMO) has designated several agencies around the world to forecast and monitor TC development and movement for their area of responsibility. These Regional Specialized Meteorological Centres (RSMCs) also perform a post-season analysis of tropical cyclones to determine the best estimate of a cyclone's position and intensity during its lifetime, a process described as "best tracking". Additionally, other agencies also provide forecasts and best track data as required by their nation. However, the best-tracking process is temporally inhomogeneous by construction because available data and techniques and general knowledge have changed over time. Furthermore, procedures and data availability differ at each agency. Thus, the resulting best track intensities from the RSMCs have temporal and spatial heterogeneities.

In light of these differences, it is important to understand and document the resulting interagency differences of the cyclone intensities, particularly if temporal or spatial trends are to be discerned in the data. Using JTWC best track data in the Western Pacific, Emanuel (2005) showed an increase in tropical cyclone activity while Webster et al. (2005) found that the strongest tropical cyclones are increasing. In contrast, Wu et al (2006) analyzed data from the Hong Kong Observatory (HKO) and the RSMC Tokyo which showed no such increases. Given that trends in TC activity vary substantially based on the dataset used, the differences in wind speeds amongst the reporting agencies need to be investigated and documented. While it has been suggested that differences between some agencies are irreconcilable (Lander 2008), others have looked at how intensity estimates differ between some agencies (Kamahori et al. 2006; Nakazawa and Hoshino 2009). Missing from these analyses is the simple comparison of the intensities between each agency in cases where multiple agencies best-track the same cyclones.

Given the need to understand the location and intensity of TCs worldwide and that numerous agencies provide best track data for each ocean basin, it is necessary to determine the interagency differences in reported best track intensities.

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This paper focuses on wind speed because it is a widely used value for storm intensity, is used to derive regulations and/or estimate damages and is integral in calculation of basin wide statistics such as the accumulated cyclone energy (Bell and Chelliah, 2006).

In all, three main questions are answered herein, with more specific details found in Knapp and Kruk (2010). 1. What are the mean interagency differences in reported wind speed? 2. How have these differences changed over time? 3. Do differences in operating procedures account for differences in reported winds between agencies?

To answer these questions, a compilation of best track data from various agencies is required, which is described in the next section. The questions above are then answered in order in the following sections followed by some concluding remarks.

2. DATA

In order to perform an inter-comparison of the tropical cyclone winds reported by each agency, historical best track data is required. Such an analysis is made possible by the International Best Track Archive for Climate Stewardship (IBTrACS) because it is a collection of global tropical cyclone best track data (Knapp et al., 2010). Tropical cyclone best track data are combined in IBTrACS to facilitate inter-comparisons by collocating reports in time and space (Kruk et al., 2010). For each storm having reports from more than one agency, each agency's originally reported position, wind speed and intensity are available in IBTrACS.

The agencies included in this study are:

- Australian Bureau of Meteorology (BoM as TCWC Perth, Darwin, Brisbane),
- Fiji Meteorological Service (FMS, as RSMC Nadi),
- India Meteorological Department (IMD, as RSMC New Delhi),
- Japan Meteorological Agency (JMA, as RSMC Tokyo),
- MeteoFrance –La Reunion (MFLR, as RSMC La Reunion),
- Meteorological Service of New Zealand (MSNZ, as TCWC Wellington),
- China Meteorological Administration's Shanghai Typhoon Institute (CMA),
- Hong Kong Observatory (HKO), and
- U.S. Navy/Air Force JTWC.

One significant difference between the agencies is that different wind speed averaging periods (cf. Table 1) are used in reporting the tropical cyclone's maximum sustained wind (MSW). Herein, we compare the raw MSW reports from each agency, which generally convert from one to another via a multiplicative factor. When needed, the wind speed time period is denoted as a subscript of MSW; for example, MSW_{10} is the 10-min maximum sustained wind. In doing so, the techniques used to convert between wind speed averaging periods will be apparent in comparisons via systematic biases, such as the linear regression slopes.

Analysis of interagency differences is, however, limited to oceanic basins with significant overlap between agencies. As a result, an inter-comparison is not possible in the North Atlantic because data from only one agency is publicly available (the National Hurricane Center operating as RSMC Miami). Furthermore, identical wind speed averaging periods and interagency communications act to minimize the differences in the Eastern Pacific. Thus, discussion of differences hereafter is limited to the Western Pacific (WP), Northern Indian (NI), Southern Indian (SI), and Southern Pacific (SP) Oceans.

3. QUANTIFYING INTERAGENCY DIFFERENCES

Current interagency differences are analyzed by comparing wind speeds for identical cyclones for the most recent pentad centered on 2006 (2004-2008). This allows enough points to minimize minor inter-annual variations but is short enough a period so as to decrease the chances of performing comparisons during a change in operational procedures. The analyses are performed by mapping wind speed from one agency against the wind speed from another agency. Theoretically, a linear fit with unit slope implies unbiased agreement between the agencies while groupings away from a 45-degree line suggest differences between the agencies. The analysis produces an interagency systematic difference (via the slope of a linear fit) and random difference (via noise about the linear fit). However, because there are errors in reported wind speeds from both agencies (i.e., neither is known to be correct and without error), a standard linear regression is inappropriate. Instead, a linear fit is made to the data which allows for errors in both the ordinate and abscissa values, specifically the fitexy algorithm from Press et al. (1992) is used. The standard error of estimate (σ) is used to characterize the mean deviation from linearity and is calculated as:

$$\sigma = \sqrt{\frac{\sum\left(MSW - MSW'\right)^2}{n-2}} \tag{1}$$

Where MSW is the maximum sustained wind for the agency presented on the ordinate and MSW' is the estimate of MSW from the linear fit and *n* is the total number of points in the comparison. Thus, σ generally represents the noise in the linear relationship between two agencies.

Several salient points can be deduced concerning the estimated MSW in the historical best track archive. First, recalling that the wind averaging period reported by IMD is 3-min, then consequently, one would expect the wind estimates as provided by IMD to be less than the 1-min data from JTWC. However, the slope of the difference is further from 1.0 – that is, the slope is closer to that of the 10-min winds in the Southern Indian Ocean (Figure 1). A comparison of the 10-min wind to 1-min winds (JTWC) in the SH (Figure 2) are in the range of 0.8-0.9 while the Western Pacific is lower, ranging from 0.6 to 0.7 (Figure 3). This suggests greater interagency agreement in the SH for the same storm, while larger differences exist in the WP. There also seems to be little difference between the 10-min wind reported by HKO and the 2-min wind reported by CMA, as denoted by a slope of 1.01 and a noise factor of 5 kt. In addition, over 90% of the wind speed estimates provided by HKO and CMA are within 10 kt of JMA, yet large differences still exist between JMA and the JTWC (Figure 3).

Interagency differences indeed seem reconcilable. The values are related linearly and it appears possible to compare wind speeds from one agency with another via a linear correction. Finally, agreement between each of the RSMCs/TCWCs is generally better (lower σ) than when compared to JTWC. This is not especially surprising since the JTWC is not sanctioned by the WMO, has broader mission goals over a larger area of responsibility and produces annual best track data with little to no communication with other international agencies (Robert Falvey, personal communication).

4. TEMPORAL VARIATION OF INTERAGENCY DIFFERENCES

A similar analysis is used to investigate how the interagency differences have changed in time. First, based on the above analysis, statistics for an earlier pentad are shown in Figures 1-3. Chu et al. (2002) state that JTWC best track data quality is best after 1984. Therefore, in lieu of such quality information for other agencies, the period 1985-1989 was used as a comparison pentad (or the earliest pentad after 1985 when data is available). Second, yearly matchups are used to create a time series of annual interagency slope and noise based on the linear fit; these are plotted for each basin. The time span of the comparisons is limited by when the wind speed reports began for the reference agency. Again, the reference agency is not considered the “true” estimate but is used for comparison purposes to help show temporal changes between various agencies.

In the previous section, we found that the interagency wind speeds were significantly different, especially in the Western Pacific. In this section, the analysis indicates that the interagency relationships have also changed significantly in time. Several comparisons demonstrate remarkable agreement implying that some coordination exists amongst the agencies or the use of similar procedures. For instance, the differences in MSW between FMS and MSNZ are near zero for a few recent years. In the WP, however, the differences are not zero but the reduced noise factor, when compared with JTWC, suggests at least some sort of coordination between CMA, JMA and HKO. Despite this coordination and improved noise factor, temporal differences are apparent. Some changes appear to be related to changes in procedures (e.g., the change in the JTWC vs. MSNZ slope in the late 1980s) that may be reconciled with further knowledge of operational procedures. Other variations, however, seem to imply differences which require a complete reanalysis to fully discern the best intensity (e.g., differences between JTWC and BoM in 1987). The next section will determine whether some of the differences noted in this and the previous section are consistent with known operating procedures.

5. CAN INTERAGENCY DIFFERENCES BE CORRECTED?

This section investigates whether the wind speed conversion factors account for the interagency differences by investigating the current practices at all agencies as well as the historical record for two agencies with documented changes in operational procedures: JMA and MFLR.

Procedures at many agencies specify adjustments to the result of the Dvorak technique. Many agencies convert the 1-min Dvorak wind speeds (MSW_1) to another wind speed averaging period with a multiplicative factor (Table 1). Some agencies that report a 10-minute wind speed (MSW_{10}) use 0.88, such as BoM (Harper et al., 2008; Trewin, 2008), MSNZ (Steve Ready, personal communication, 2009), FMS (Gary Padgett, personal communication, 2009) and MFLR (Philippe Caroff, personal communication 2009). Wu et al. (2006) report that 0.9 is used at HKO to convert their 1-min Dvorak intensity estimates to MSW_{10}. However, while Yu et al (2007) do not explicitly state the procedures at CMA to convert to a 2-min MSW, they do use 0.871 when comparing to JTWC wind speeds. At JMA, instead of a scaling factor, they use a separate mapping of current intensity (CI) to MSW_{10} based on Koba et al. (1991). The equation in Table 1 is a linear fit to the Koba and is presented purely for comparison with other wind speed conversions. Lastly, IMD reports a 3-minute MSW. However, based on comparisons when IMD best track data contains both CI and MSW, the IMD wind is different than the 1-min Dvorak wind in less than 7% of all reported wind speeds. Moreover, the IMD reported MSW_3 only deviates by more than 5 kt from Dvorak in less than 1% of all reported winds. Therefore, it appears that IMD uses the Dvorak wind table without any adjustment in most cases.

Before going further in the analysis, it should be noted that regardless of the time averaging period in use, the Dvorak CI has become the *de facto* standard for TC intensity in that all agencies use the Dvorak CI at some point in the satellite analysis (as evident above and noted by Levinson et al 2009). The implications of this apply to which data should be archived. Since all agencies start with a Dvorak analysis, the results of this analysis should be recorded – both the T-number and CI. Other information used to derive the intensity should also be recorded [e.g., the tropical cyclone analysis worksheet described in the appendix of Dvorak (1984)]. Some agencies already record CI (e.g., IMD and MFLR) alongside best track data while other agencies maintain the data in a separate dataset (e.g., ATCF “fix” data produced by NHC and JTWC). Ideally, all agencies would follow a standard format, such as that which is proposed by the WMO (and is in use by MFLR), to routinely record and archive T-numbers, CI and other relevant information used in determining the storm intensity.

In an attempt to make a more direct comparison of wind speeds between agencies, the wind speed conversion procedures from Table 1 are reversed to re-derive the original Dvorak intensity, MSW_1. The results are then compared with JTWC wind speeds, which use the Dvorak technique. Again, JTWC is not used as an estimate of the true 1-min wind speed but rather serves as an independent estimate of MSW_1. If the sole cause of the difference between wind speeds at JTWC and other agencies is the wind speed conversion, then the result should be a slope close to 1.0 with no bias.

Table 2 shows the comparison results by agency. In short, accounting for wind speed averaging periods does not fully explain the remaining biases amongst the agencies versus JTWC. Although slopes are closer to 1.0 than in Figures 1 through 3, there are still systematic differences in slope and the mean values.

Remapping intensities based on known Dvorak CI to MSW relationships decreases the differences between intensities from different agencies, as supported by the increased agreement between MFLR and JTWC. However, remapping intensities does not, nor cannot, explain all differences in cyclone intensity between agencies. For example, while the slope of the remapped JMA is near unity versus JTWC, the mean differences remained considerably different.

The comparison with JMA is particularly interesting in light of the study by Nakazawa and Hoshino (2009), who compared T-numbers and CI from JMA and JTWC. They found that the classifications between the agencies were statistically different during the periods of 1992-1997 and 2002-2005, with JTWC having consistently higher T-number (i.e., cyclones were more intense) during both periods. The analysis of the time series of comparisons in this article also reveals significant differences during these two periods - both before and after remapping to Dvorak-equivalent intensities. Nakazawa and Hoshino (2009) concluded that the T-numbers and CI were statistically identical during the period prior to 1991 and 1998-2001. However, in our analysis, the mean difference during these periods is still appreciably different. Future work in this area should directly compare the raw T-numbers from all agencies, but this will not be possible until such data are collected, digitized, and made publicly available.

Finally, the systematic differences between JMA and JTWC show temporal variation. While MFLR vs. JTWC shows a temporally constant relationship (via mean difference and slope) during the two periods after 1987, the comparison shows significantly varying mean differences between JMA and JTWC. The mean difference shows variations, with a range of 15 kt during the 1990s and 2000s even after remapping the intensities. Nakazawa and Hoshino (2009) related these systematic differences to differences in operational practices such as faster intensification of TCs and a delayed start to weakening the cyclone at JTWC. Resolving such differences requires a better understanding of operating procedures at each agency or complete reanalysis of the tropical cyclone intensities.

5. CONCLUSIONS

Tropical cyclone maximum sustained wind reports from numerous agencies that produce best track data were compared. The results of this analysis revealed that stated wind speed averaging periods from varying agencies do not always imply differences between reported wind speeds between agencies. For example, MSWs reported from HKO and CMA are nearly identical, yet each reports wind speeds using a different wind speed averaging technique. In addition, the conversion between wind speeds via a conversion factor should be thought of as a guide, not a rule, as each agency has access to different *in situ* data and independently performs the Dvorak analysis technique. Thus, each agency may have intensities that largely deviate from such simplistic conversions (e.g., 2000 very severe cyclonic storm 04B in the North Indian Ocean or 1987 Connie in the Southern Indian Ocean). Moreover, remapping intensities to a Dvorak-equivalent wind speed at JMA and MFLR significantly decreased interagency MSW differences but did not remove them.

It was also noted that, despite a WMO standard and regardless of the time averaging period in use by any agency, the Dvorak current intensity (CI) has become the *de facto* standard for TC intensity. Since all agencies start with a Dvorak analysis, the results of such analysis should be recorded – both the T-number, CI and other information used to derive the CI.

The results also indicated that temporal changes in interagency relationships exist. Such temporal discontinuities demand that caution be used when investigating temporal trends of tropical cyclone activity. An assessment of best track data reliability should be performed for each basin along the lines of Chu et al. (2002), which would assess when and where best track data can be used appropriately. This assessment should be performed by those most familiar with best track data and its construction. Such an analysis would then put changes in tropical cyclone frequency, intensity or distribution noted by others in the context of the known temporal and spatial heterogeneities of best track data.

Finally, it is important to note that interagency differences might be satisfactorily resolved given better documentation of procedures, but any remaining discrepancies that are uncomfortably large, or which yield substantially different interpretations of secular trends would likely require the major effort of a complete reanalysis of tropical cyclone intensity.

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4. REFERENCES

Bell, G. D. and M. Chelliah, 2006: Leading Tropical Modes Associated with Interannual and Multidecadal Fluctuations in North Atlantic Hurricane Activity, **19,** 590-612.

Chu, J.-H., C. R. Sampson, A. S. Levine, and E. Fukada, 2002: *The Joint Typhoon Warning Center tropical cyclone best-tracks, 1945-2000.* Joint Typhoon Warning Center, 22 pp.

Dvorak, V. F., 1975: Tropical Cyclone Intensity Analysis and Forecasting from Satellite Imagery. *Monthly Weather Review*, **103,** 420-430.

——, 1984: *Tropical cyclone intensity analysis using satellite data*. *Technical Report (NOAA TR NESDIS 11)*, National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service, 47 pp.

Emanuel, K., 2005: Increasing destructiveness of tropical cyclones over the past 30 years. *Nature*, **436,** 686-688.

Harper, B. A., S. A. Stroud, M. McCormack, and S. West, 2008: A review of historical tropical cyclone intensity in north-western Australia and implications for climate change trend analysis. *Australian Meteorological Magazine*, **57,** 121-141.

Kamahori, H., N. Yamazaki, N. Mannoji, and K. Takahashi, 2006: Variability in Intense Tropical Cyclone Days in the Western North Pacific. *SOLA*, **2,** 104-107.

Knapp, K. R., M. C. Kruk, D. H. Levinson, H. J. Diamond, and C. J. Neumann, 2010: The International Best Track Archive for Climate Stewardship (IBTrACS): Centralizing tropical cyclone best track data. *Bulletin of the American Meteorological Society*, **In press**.

Knapp, K.R., and M.C. Kruk, 2010: Quantifying interagency differences in tropical cyclone best track wind speed estimates. *Mon. Wea. Rev.*, **in press.**

Koba, H., T. Hagiwara, S. Osano, and S. Akashi, 1991: Relationships between CI number and minimum sea level pressure/maximum wind speed of tropical cyclones. *Geophysical Magazine*, **44,** 15-25.

Kruk, M. C., K. R. Knapp, and D. H. Levinson, 2010: A technique for combining global tropical cyclone best track data. *Journal of Atmospheric and Oceanic Technology*, **27**, 680-692

Lander, M., 2008: A comparison of typhoon best-track data in the western north Pacific: Irreconcilable differences. *28th AMS Conference on Hurricanes and Tropical Meteorology*, Orlando, FL.

Levinson, D. H., H. J. Diamond, K. R. Knapp, M. C. Kruk, and E. J. Gibney, 2009: Toward a homogenous global tropical cyclone best track dataset. *Bulletin of the American Meteorological Society*, **In press**.

Nakazawa, T. and S. Hoshino, 2009: Intercomparison of Dvorak Parameters in the Tropical Cyclone Datasets over the Western North Pacific. *Scientific Online Letters on the Atmosphere*, **5,** 33-36.

Press, W. H., S. A. Teukolsky, W. T. Vetterling, and B. P. Flannery, 1992: *Numerical Recipes in Fortran 77: The art of scientific computing*. Vol. 1, Cambridge University Press.

Trewin, B., 2008: An enhanced tropical cyclone data set for the Australian region. *20th Conference on Climate Variability and Change*, New Orleans, LA, American Meteorological Society, 12 pp.

Webster, P. J., G. J. Holland, J. A. Curry, and H.-R. Chang, 2005: Changes in tropical cyclone number, duration, and intensity in a warming environment. *Science*, **309,** 1844-1846.

Wu, M. C., K. H. Yeung, and W. L. Chang, 2006: Trends in western North Pacific tropical cyclone intensity. *Eos*, **87,** 537-539.

Yu, H., C. Hu, and L. Jiang, 2007: Comparison of three tropical cyclone intensity datasets. *Acta Meteorologica Sinica*, **21,** 121-128.

Table 1 - Summary of wind speed averaging period, period of record and maximum reported intensities by basin and agency.

Agency	Avg. Period. (min)	MSW Start year	Max MSW (kt)	Wind Speed Conversion
	Western Pacific Ocean (WP)			
JMA	10	1977	140	$MSW_{10} = 0.60\ MSW_1 + 23.3$
CMA	2	1949	214	$MSW_{10} = 0.871\ MSW_1$
HKO	10	1961	165	$MSW_{10} = 0.9\ MSW_1$
JTWC	1	1945	185	MSW_1
	North Indian Ocean (NI)			
IMD	3	1990	140	$MSW_3 = MSW_1$
JTWC	1	1972	145	MSW_1
	Southern Indian Ocean (SI)			
La Reunion	10	1977	125	$MSW_{10} = 0.88\ MSW_1$
BoM	10	1973	135	$MSW_{10} = 0.88\ MSW_1$
JTWC	1	1956	155	MSW_1
	Southern Pacific Ocean (SP)			
BoM	10	1973	135	$MSW_{10} = 0.88\ MSW_1$
Nadi	10	1994	130	$MSW_{10} = 0.88\ MSW_1$
Wellington	10	1968	130	$MSW_{10} = 0.88\ MSW_1$
JTWC	1	1956	155	MSW_1

Table 2 - Comparison of wind speeds from each agency after converting back to MSW_1 ($MSW_{1,agency}$) with MSW_1 from JTWC. The slope is for $MSW_{1,agency}$ versus $MSW_{1,JTWC}$. Bias is the mean of $MSW_{1,agency}$ minus $MSW_{1,JTWC}$.

Agency	Slope	Bias (kt)
North	**Indian**	
IMD	0.77±0.002	7.3±1.7
South	**Indian**	
BoM	0.96±0.001	-5.2±1.2
La Reunion	0.92±0.0004	-1.3±0.7
Western	**Pacific**	
JMA	1.10±0.0003	6.4±0.7
CMA	0.85±0.0002	-2.1±0.5
HKO	0.82±0.0002	1.0±0.6
South	**Pacific**	
BoM	0.94±0.002	-8.5±2.0
Nadi	0.89±0.001	-6.4±1.4
Wellington	0.91±0.001	-6.3±1.3

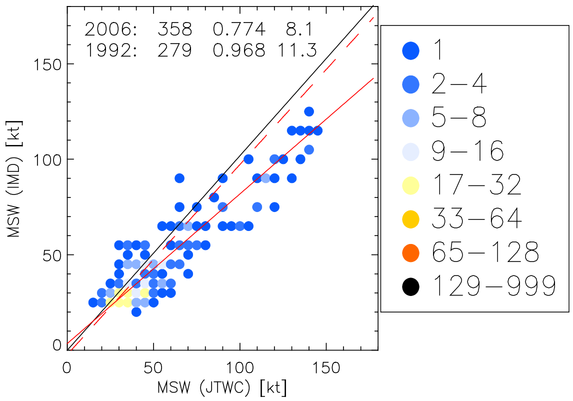

Figure 1 - Comparison of wind speeds at IMD and JTWC for pentad centered on 2006. Colored circles represent the number of occurrences at each point. Zero line denoted by black line. The linear regression statistics that are provided for two pentads – current (2006) and an earlier pentad (1992) – include the sample size, linear regression slope and linear regression standard error. Solid and dashed linear regression lines denote the 2006 the earlier pentads (1992), respectively.

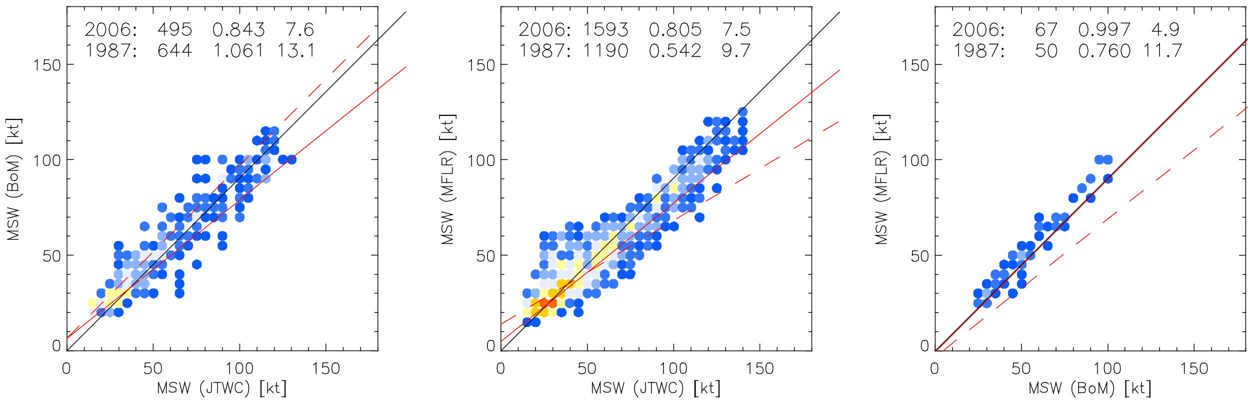

Figure 2 - Same as Figure 1 except for the Southern Indian Ocean comparing JTWC, MFLR and BoM.

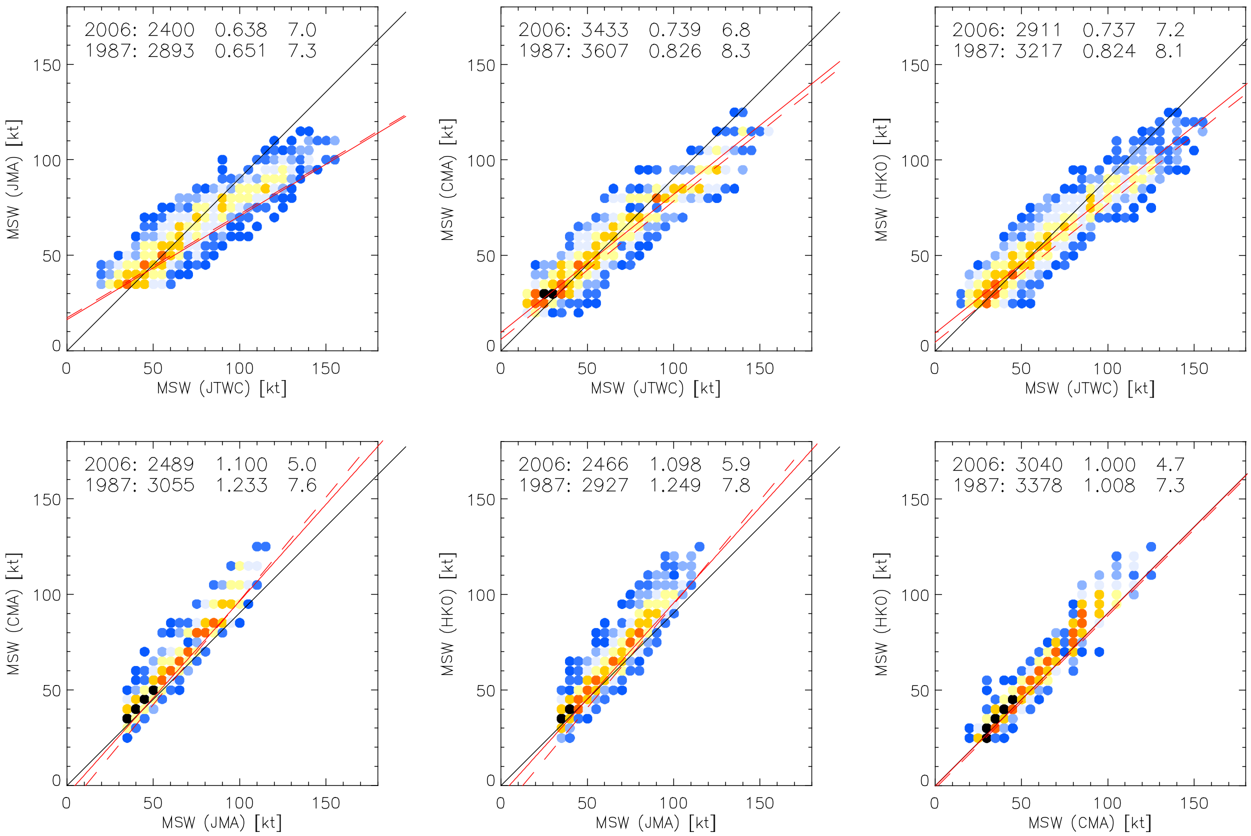

Figure 3 - Same as Figure 1 except for the Western Pacific Ocean comparing JTWC, CMA, JMA and HKO.