A Pressure-Based Analysis of the Historical Western North Pacific Tropical Cyclone Intensity Record

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ABSTRACT

The western North Pacific Ocean is the most active tropical cyclone (TC) basin. However, recent studies are not conclusive on whether the TC activity is increasing or decreasing, at least when calculations are based on maximum sustained winds. For this study, TC minimum central pressure data are analyzed in an effort to better understand historical typhoons. Best-track pressure reports are compared with aircraft reconnaissance observations; little bias is observed. An analysis of wind and pressure relationships suggests changes in data and practices at numerous agencies over the historical record. New estimates of maximum sustained winds are calculated using recent wind–pressure relationships and parameters from International Best Track Archive for Climate Stewardship (IBTrACS) data. The result suggests potential reclassification of numerous typhoons based on these pressure-based lifetime maximum intensities. Historical documentation supports these new intensities in many cases. In short, wind reports in older best-track data are likely of low quality. The annual activity based on pressure estimates is found to be consistent with aircraft reconnaissance and between agencies; however, reconnaissance ended in the western Pacific in 1987. Since then, interagency differences in maximum wind estimates noted here and by others also exist in the minimum central pressure reports. Reconciling these recent interagency differences is further exasperated by the lack of adequate ground truth. This study suggests efforts to intercalibrate the interagency intensity estimate methods. Conducting an independent and homogeneous reanalysis of past typhoon activity is likely necessary to resolve the remaining discrepancies in typhoon intensity records.

1. Introduction

Studies addressing tropical cyclone (TC) activity in the western North Pacific (WP) suggest contradicting trends. Analyses by Emanuel (2005) and Webster et al. (2005) of TC activity based on the Joint Typhoon Warning Center's (JTWC) best-track data (1970–2005) showed increasing intensity trends. Webster et al. (2005) show an increasing trend in the strongest TCs and a decrease in moderate intensity TCs. Emanuel (2005) showed increases in the potential destruction index, an integral of the maximum winds cubed, also using the JTWC best tracks. Conversely, Wu et al. (2006) found decreasing intensity trends in best-track data from the Japan Meteorological Agency (JMA) and the Hong Kong Observatory (HKO). A later attempt by Kossin et al. (2007) used an objective analysis of satellite data (post-1980s) to analyze global and basin-wide statistics, finding no

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significant trend in the WP. These latter results were consistent with the findings of Klotzbach (2006), who examined a shorter time series of the JTWC best-track data (1986–2005). We posit that the differences in these analyses are not caused by the approach taken but by the dataset used.

These apparently contradictory results have led to several studies that concentrate on the details of how intensities were derived and how those methods have changed over time. Best-track data are finalized following each season; they generally have not been reanalyzed using current methods or knowledge. Knaff and Zehr (2007) showed how the operational use of the Atkinson and Holliday (1977, hereafter AH77) wind–pressure relationship (WPR) changed the resulting JTWC best-track estimates of maximum sustained wind speed (MSW). Furthermore, they also conclude that the AH77 WPR, while being based on quality wind data, was regressed on the raw data rather than data that was binned in intensity ranges and then averaged. This resulted in some low MSW estimates after about 1972, especially for the most intense TCs. Using aircraft-based central pressure records (1966–87) and the Knaff and Zehr (2007) WPR, Knaff and Sampson (2006) showed that some of the lifetime maximum wind (LMW) estimates in the JTWC best-track data were likely low biased, which likely led to an upward trend in intensity during the 1970–2005 period. Kwon et al. (2006) investigated differences in climatological indices between JTWC and JMA, but infer minimum central pressure (MCP) values from the JTWC MSW estimates. More recently, Durden (2012) investigated pressure changes in the WP basin, but their analysis was limited to the JMA best-track dataset, which relies on the Koba et al. (1991) WPR. Also recently, Mien-Tze (2012) investigated WPRs currently in use, but primarily focused on the 1991–2010 time period. Together, these studies depict the great number of inconsistencies in the TC intensity data that are large enough to matter when considering trends.

Other studies have examined differences in the MSW intensity metric. Song et al. (2010), along with Knapp and Kruk (2010), discuss interagency wind differences from an empirical view. Both Ren et al. (2011) and Yu et al. (2007) investigate differences of storms in common among three agencies [the China Meteorological Agency (CMA), JMA, and JTWC]. In particular, Ren et al. (2011) discuss specific operational procedures at each agency that may be enhancing differences in intensity estimates. Ying et al. (2011) examined the differences between typhoon seasonalities from three agencies. Finally, Maue (2011) used winds to analyze hemispheric activity via accumulated cyclone energy (ACE) and has shown a clear decrease in TC activity since 2005. These results underscore the perception that the differences between best-track MSW estimates are significant and important to intensity analyses.

Even the supposedly consistent Dvorak intensity estimates (Dvorak 1975, 1984) have resulted in significant differences in intensity as estimated by different agencies in the WP basin, as implied in Knaff et al. (2010). Furthermore, Nakazawa and Hoshino (2009) investigated differences in the Dvorak technique–based *T* and current intensity (CI) numbers between JMA and JTWC. They show that during the early and mid-1990s differences between Dvorak intensity estimates between JTWC and JMA are large, with the JTWC estimates being significantly higher. Kamahori et al. (2006) looked at TC days, which is a measure of storm lifetime. Again, there were significant differences. These studies suggest that, even recently, the Dvorak-based intensity estimates show significant differences. The causes of these differences are as yet unresolved, but are likely related to 1) how and what rules (or constraints) are applied to satellite imagery to arrive at the Dvorak *T* and CI estimates, noting the evolution of the Dvorak technique discussed in Velden et al. (2006a,b); 2) the undocumented and inhomogeneous use of ancillary data such as passive microwave imagery; and 3) inadequate ground truth for interagency calibration.

Observations of MSW and MCP were primarily limited to aircraft reconnaissance before routine geostationary satellite coverage allowed the use of the Dvorak technique. Before satellites, MCP was by far the more reliable observation (Sheets and Grieman 1975; Typhoon Post Analysis Board 1953) while winds were primarily estimated from observations of sea state or via WPRs, which vary throughout the time period. From a historical perspective there seems to be several, possibly insurmountable, problems with the records of MSW. These include the availability of routine aircraft information, which ended in 1987; lack of documentation on WPRs; and significant differences in operational estimates based on satellite information. From the above discussion it is easy to infer that the time period, dataset, and intensity metric used for analyzing intensity trends dramatically affect the interpretation of the historical records of intensity. Such differences are a likely cause of the seemingly contradictory intensity trend results that others have reported.

We suggest that a comprehensive analysis of WP TC intensities based on pressure (instead of wind speed) may be more appropriate and insightful in the WP basin. Specifically, we will pursue answers to the following questions:

1) Is pressure more consistent between agencies than wind during the presatellite era?
2) If so, what does analysis of the pressures imply about the historical typhoons? (Do we see storms that increase and/or decrease in LMW?)
3) Can one construct a pressure-based time series of activity? If so, can we say something about historical activity in the WP and close the gap on the previously disparate conclusions by objectively investigating typhoons using pressure reports?

The following is our attempt to adequately answer these questions using International Best Track Archive for Climate Stewardship (IBTrACS; Knapp et al. 2010), the newly recovered ''typhoon analogs'' dataset (TD-9635), and modern WPRs. This study builds upon the work of Knaff and Sampson (2006), but extends that work to the entire life span of the cyclone and conducts a more comprehensive analysis of the pressure-based intensity estimates. We also make use of many acronyms, so a description of the acronyms used in this paper is provided in Table 1 to aid the reader.

TABLE 1. Acronyms used in this study listed by category: agencies and places, datasets, publications, and tropical cyclone related.

Acronym	Description
Agencies and places	
JTWC	Joint Typhoon Warning Center
JMA	Japan Meteorological Agency
HKO	Hong Kong Observatory
CMA	China Meteorological Agency
NCDC	National Climatic Data Center
WP	Western North Pacific
Datasets	
IBTrACS	International Best Track Archive for Climate Stewardship
TD-9635	Typhoon analogs dataset (data only from the WP)
TD-9636	Global Consolidated Tropical Cyclone dataset
AR	Aircraft reconnaissance
Publications	
AH77	Atkinson and Holliday (1977)
KZ07	Knaff and Zehr (2007)
ATCR	JTWC's annual tropical cyclone reports
ATR	JTWC's annual typhoon reports (changed to ATCR in 1980)
Tropical cyclone related	
TC	Tropical cyclone
MSW	Max sustained surface wind speed
WPR	Wind–pressure relationship
LMW	Lifetime max wind
MCP	Minimum central pressure
ACE	Accumulated cyclone energy
CI	Current intensity in the Dvorak (1984) intensity estimation technique
RMS	Root-mean-square error
ROCI	Radius of outer closed isobar
SS	Saffir–Simpson hurricane intensity scale (Simpson 1974)

2. Tropical cyclone data

Three datasets are used here to analyze historical TC activity: IBTrACS, TD-9635, and the digitized aircraft reconnaissance data. The IBTrACS dataset compiles best-track information from various agencies worldwide (Knapp et al. 2010). The combination allows for a simple intercomparison of parameters from different agencies. The TD-9635—originally called typhoon analogs—was uncovered recently at the National Climatic Data Center (NCDC). The digitized typhoon fix data, which represent satellite and aircraft reconnaissance center ''fixes'' of historical TCs for the period 1950–87, were provided by JTWC (1966–87) and by a recent digitization at NCDC of earlier typhoon records (see the appendix). The digitized data also provide a means to validate MCP reports in the different best-track datasets.

a. *Aircraft reconnaissance observations*

Aircraft observations of TCs in the WP basin began near the end of the second World War (Weatherford and Gray 1988) with more routine TC reconnaissance beginning in the early 1950s (Reade 2011). This weather reconnaissance included reported instrument observations (position, direction, height of aircraft, etc.), as well as manual observations (e.g., size and shape of eyewall, surface wind speed based on sea state). From Simpson (1952), surface wind observations were often manually estimated based on ''the amount of surf present and the general appearance of the sea.'' Moreover, higher wind speeds have a relatively large margin for error due to fewer pictures of sea state at high wind speeds and that the seas appear different under varying amounts of light. Elsberry et al. (1975) also note that errors can occur when reconnaissance flights may not have ''penetrated through the highest wind speed region.''

Conversely, observations of MCP were more accurate. In general, MCP was observed with dropsondes or extrapolated to the surface based on knowledge of the aircraft height (Willoughby et al. 1989). Dropsonde estimates are dependent upon the proximity of the sounding to the center of the vortex (Simpson 1952). Atkinson and Holliday (1977) estimate that MCP based on a combination of dropsonde-based and extrapolated MCPs have accuracies of ±5 hPa. Such accuracies, however, are possible only when flying directly through the center of circulation.

The methods used by reconnaissance pilots to observe typhoons and hurricanes changed significantly during the late 1940s and early 1950s. Hagen et al. (2012) describe the practices in place during that time for the North Atlantic. More intense storms were not always penetrated; instead, they were circumnavigated due to safety concerns. This is confirmed for the western Pacific where the 1946 annual report lists most of the fix flights as circumnavigation once a specific wind speed threshold was reached or when turbulence became severe. Nevertheless, the observations of pressure are more reliable than wind during this period. In fact, the 1952 Annual Typhoon Report states (Typhoon Post Analysis Board 1953):

> In a reconnaissance penetration, the sea level pressure is one of the parameters which can be measured accurately without introducing the variability of human estimations. This is not true of the measurement of surface wind speeds.

Aircraft reconnaissance (AR) reports used here include digitized fix data from JTWC and data from a recent effort at NCDC to digitize earlier AR reports. The JTWC fix data span 1966–87 (except for a missing year in 1978). The NCDC data were keyed and span 1950–65 and 1978 (filing the gap in the JTWC data). The fix data from JTWC and NCDC provide TC center fixes, including position, central pressure, and maximum surface winds. More details on the newly keyed NCDC data are provided in the appendix.

Aircraft reconnaissance practices have changed over time. During the AR era, fixes of position and intensity were made. The daily frequencies of the digital aircraft reconnaissance fixes are shown in Fig. 1. This figure does not include the rescued data (prior to 1966) since only fixes with pressure were keyed, thus the dataset was not complete for this plot. In the early 1970s, typhoons were observed on an average of 4 times daily with intense typhoons (MCP < 940 hPa) being observed about 5 times per day. This decreased substantially to about 3 times per day in the mid-1970s and rebounded in the 1980s to about 4 times per day. However, when considering the AR observations having both position and intensity, the temporal differences are smaller: from about three fixes per day to two fixes per day in the mid-1970s then back to three in the late 1980s. Also, the number of AR fixes with intensity estimates does not appear to depend noticeably on a cyclone's intensity. Therefore, it is unlikely that changes in observation procedures would cause changes in MCP reports during this period, given the small change in frequency of the intensity estimates from aircraft reconnaissance.

b. Available best-track data

The IBTrACS dataset was developed at NCDC as a collection of best-track data from agencies and other sources from around the world (Knapp et al. 2010; Kruk et al. 2010). Sources of best-track data for the western North Pacific include agencies (JTWC, JMA, HKO, and CMA) and other dataset compilations, such as typhoon analogs (TD-9635) and a previous NCDC collection (TD-9636). The IBTrACS MSW values are used in this study with no modification or normalization for different wind speed averaging periods.

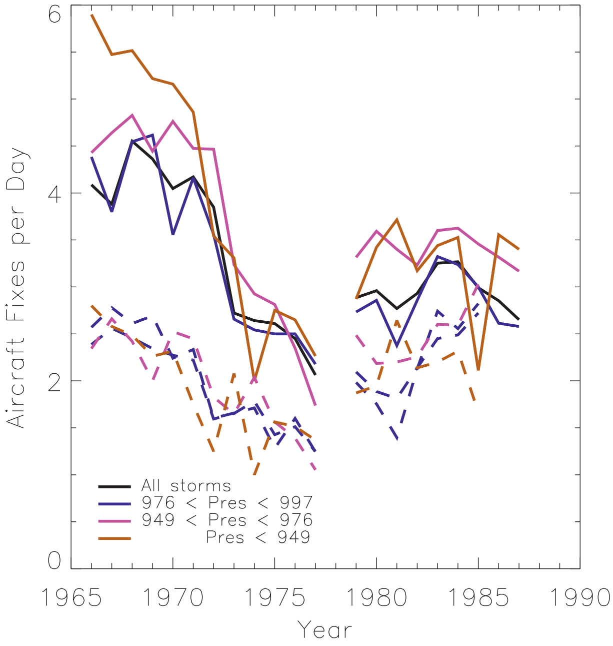

FIG. 1. Annual frequency of aircraft reconnaissance fixes plotted by storm intensity: all storms, weak systems (976 < pressure < 997 hPa), moderate systems (949 < pressure < 976 hPa), and strong systems (pressure < 949 hPa). Center fixes with intensity estimates are shown as dashed lines while center fixes of position only are solid lines.

The periods of record of these various sources is provided in Table 2. The NCDC TD-9635 dataset has a limited period of record (1945–76); it was first developed in 1972 and later extended to 1976 when continued production ended. JTWC has the longest record of MSW, but the shortest record of MCP. HKO has the same period of record for MCP and MSW starting in 1961. CMA has the longest record for MCP of all agencies. The period of record of aircraft reconnaissance overlaps a portion of each record, but ends in 1987. Adoption of satellite reconnaissance by each agency depended on the agency's availability of data and procedures.

The TD- 9635 dataset is a recent addition to IBTrACS. It was originally produced as a joint U.S. Navy–NCDC venture to develop forecasts of typhoon development and motion (e.g., Brand 1973; Brand and Gaya 1971; Elsberry et al. 1975). TD-9635 provides estimates of parameters previously unavailable in other best-track

TABLE 2. Period of record for wind and pressure reports from datasets.

Dataset	Wind		Pressure	
	Start	End	Start	End
TD-9635	1945	1976	1945	1976
JTWC	1945	Present	2001	Present
CMA	1949	Present	1949	Present
HKO	1961	Present	1961	Present
JMA	1977	Present	1951	Present
AR	1945	1987	1945	1987
Satellite-based reconnaissance	1972	Present	1972	Present

TABLE 3. Summary of pressure differences between available best-track data and aircraft reconnaissance, where N is the number of matchups within 3 h of an observation and the mean, median, and standard deviation (σ) are shown.

	TD-9635	CMA	JMA	HKO
N	6311	8919	8908	7311
Mean (hPa)	0.1	0.2	0.0	0.4
Median (hPa)	0.0	0.1	0.0	0.0
σ (hPa)	5.2	5.5	5.6	5.2

datasets. In particular, 6-hourly estimates of MCP and the radius of outermost closed isobar (ROCI) are provided and used herein to estimate MSW from a WPR. Other environmental parameters, such as position of the 700-hPa ridge and trough, are also available in TD-9635.

It is prudent to investigate the quality of the TD-9635 data prior to use in this study. TD-9635 has 20 370 valid wind speed reports. Of these, JTWC has valid reports at 20 293 coincident times. The mean difference in MSW is 0.003 knot (kt, 1 kt = 0.51 m s^{-1}), the median is 0.000 kt, and the standard deviation of the differences is 0.56 kt (i.e., nearly identical). In fact, 99.96% of the MSW matchups are within 5 kt of JTWC. Therefore, we conclude the TD-9635 dataset is representative of JTWC MSW during this period.

Furthermore, the quality of MCP from TD-9635 can be checked with comparisons to AR data. Collocating TD-9635 and digital aircraft reconnaissance MCPs in time (within ±3 h) starting in 1950 (when reconnaissance data are first available) through 1976 (when TD-9635 ends) produces 6469 matchups, having a mean difference of 0.3 hPa, a median difference of 0.1 hPa, and a standard deviation of 6.9 hPa. Therefore, based on the wind comparisons with JTWC and pressure comparisons with aircraft reconnaissance, it appears that TD-9635 also contains reliable pressure estimates.

The MCP values from best-track data from other agencies in Table 2 are also consistent with AR pressure data. A summary of all available matchups (within a 3-h window) is provided in Table 3. The different numbers of matchups result from the various periods of record from the different agencies. In short, the overall differences (means or medians) are near zero and show little variation in standard deviation between agencies, only ranging from 5.2 to 5.6 hPa. Through time (Fig. 2), the random errors (i.e., standard deviation) between aircraft reconnaissance and best-track pressures are generally between 2 and 6 hPa. Differences in the bias time series appear for the period spanning 1959–65. The bias for each agency appears to diverge (with JMA having a large positive bias and HKO having a large negative bias) but then converge again around 1965. Analysis of differences during these years is not suggestive of any single problem, but rather that some storms have significant differences in pressure, such as Typhoons Elsie (1964), Tilda (1951), and Violet (1961). Aside from these deviations, the pressure values from the agencies appear consistent with AR overall (Table 3) and through time (Fig. 2).

In summary, best-track pressure data from HKO, JMA, CMA, and TD-9635 appear to be consistent with aircraft observations.

c. *Empirical estimates of agency procedures using wind–pressure relationships*

The MSW is related to MCP in tropical cyclones by their wind-pressure relationship, a full review of which is provided by Harper (2002). The AH77 WPR was widely used in the early 1970s through the 1990s. More recently,

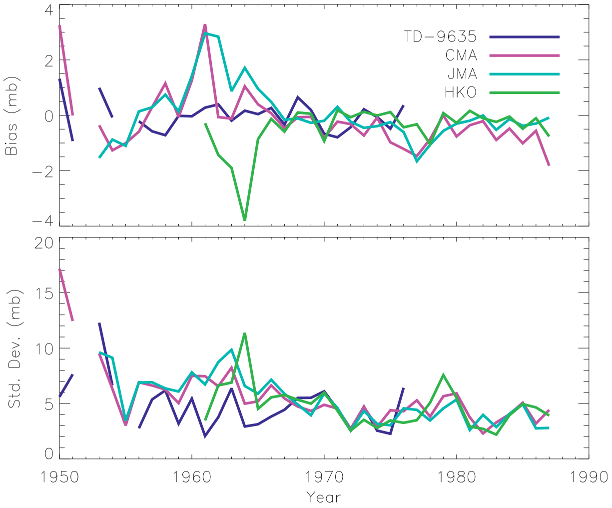

FIG. 2. Annual statistics comparing minimum central pressure from aircraft reconnaissance and BT data for various agencies: (top) bias difference of best track minus reconnaissance and (bottom) its standard deviation.

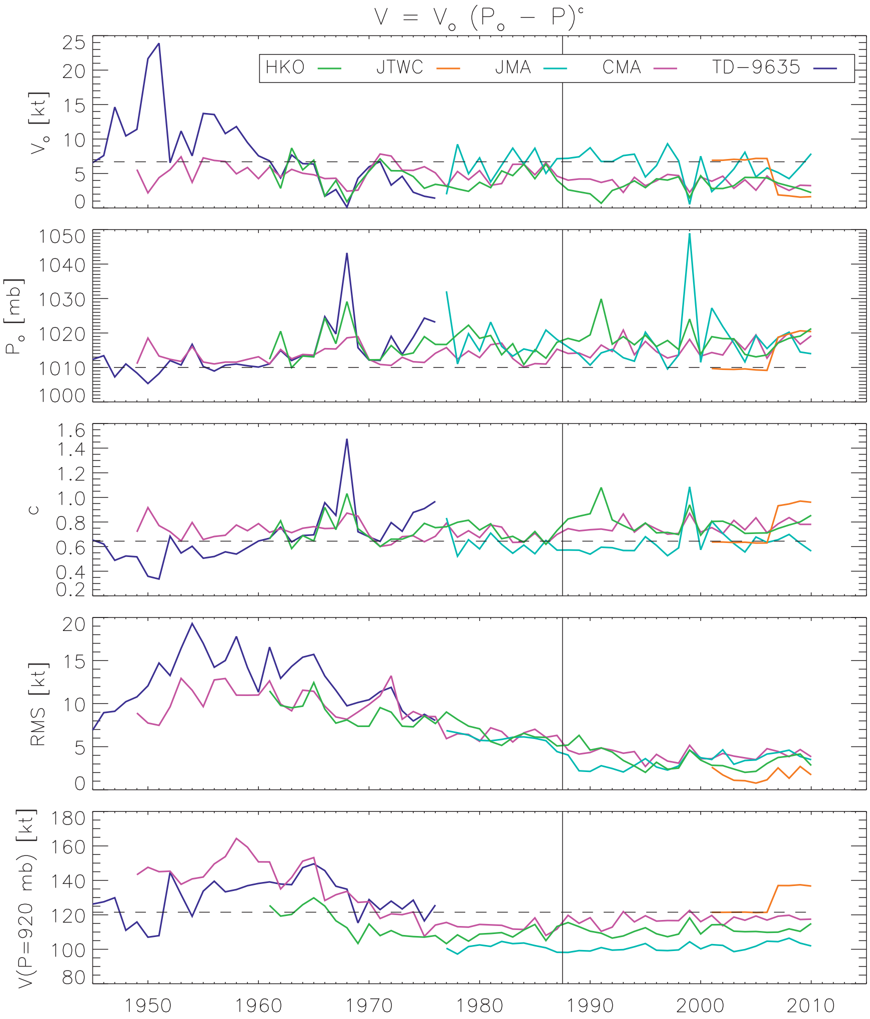

FIG. 3. Annual time series of empirically estimated WPR parameters, based on the form $V = V_o(P_o - P)^c$. The RMS is the root-mean-square error of the wind for the empirically derived parameters. The quantity $V(P = 920)$ is the wind speed (in kt) corresponding to a central pressure of 920 mb using the empirically derived parameters. Dashed lines represent the AH77 values and the vertical line designates the end of AR during 1987.

Knaff and Zehr (2007, hereafter KZ07) developed a more universal WPR, which Courtney and Knaff (2009) adjusted for lower latitudes and adapted for operational use.

When both MSW and MCP are provided in best-track data, one can diagnose how they were related at an agency by deriving an empirical wind–pressure relationship. Since comparison with the AR fixes shows agreement with MCP (cf. Table 3), any changes in empirically derived WPRs imply changes in an agency's operational procedures.

A common representation of a wind–pressure (V–P) relationship is

$$V(P) = V_o(P_o - P)^c \tag{1}$$

For example, the AH77 WPR uses Eq. (1) with $V_o = 6.7$ kt, $P_o = 1010$ hPa, and $c = 0.644$. Figure 3 shows the WPR equation parameters that were empirically derived annually from IBTrACS data for any data source that reported both MSW and MCP. While this fitting method deviates from recommendations by KZ07 regarding how the fit should be performed (i.e., observations should be binned and then fit), the focus here is on interagency and interannual differences rather than the absolute accuracy of any one formula. Such an analysis shows how operational procedures might have changed over time. The WPR parameters are shown in Fig. 3 as a time series along with the root-mean-square (RMS) error of the empirical fit and $V_{920,}$ the wind speed corresponding to MCP = 920 hPa.

The RMS values provide insights into how much an agency followed any WPR. For instance, AR ended in 1987, thus forcing agencies to estimate intensity from satellites more often, as is done in Dvorak (1984). The result is that after 1987, the maximum RMS is small (about 6 kt) because both wind and pressure were derived from the same satellite estimate. Conversely, RMS values in the early record (e.g., before 1970) show RMS values exceeding 15 kt, implying a consistent WPR was not routinely used to constrain wind to pressure or vice versa. It is of note that the RMS rarely shows a step change in any time series. The RMSs for TD-9635 and CMA gradually drift from more than 10 kt to near 5 kt in the 1980s. An exception is the JTWC switch to a different WPR in 2007.

The impact of any change in procedures can be seen in the V_{920} time series (Fig. 3, bottom). Given the small bias compared to AR pressure data, any change in this value implies that there is likely a temporal bias in the reported wind speeds that could preclude climatic analysis (i.e., direct comparisons between years with vastly different V_{920}). The CMA and TD-9635 show a drift from 140–160 kt in the early record to 120 kt in the 1970s. It is likely a change in operational practice caused this gradual change. Given the previous validation of MCP from CMA (cf. Fig. 2), it is possible that winds for CMA before 1970 are too high.

The differences in reported wind speed averaging periods appear in the time series of V_{920}. The winds are in their original wind speed averaging period because the empirically derived WPR uses the raw wind reports. The JMA time series of V_{920} is the lowest due to their adjustment to a 10-min wind speed. The introduction of the Koba et al. (1991) CI tables in 1987 also seems to not disrupt the V_{920} time series from JMA, verifying the temporal consistency described by Kunitsugu (2011). The V_{920} results for HKO and CMA are larger than JMA with JTWC having the largest V_{920} values in the post-AR era.

A prominent step change occurs in the JTWC record in 2007. While not very noticeable in the RMS time series, the changes in V_{920}, V_o, P_o, and c are evident. This is coincident with the change of the operational WPR from AH77 to a WPR[1] based on the AH77 data, as described in KZ07. The V_{920} speed increases from 120 to about 140 kt. Similarly, the WPR parameters depart from closely following AH77. Dvorak satellite analysis provides a CI number, from which wind is estimated. KZ07 also provides a set of tables of CI mapped to pressure based on storm size and latitude. Given the implementation of KZ07, the discontinuity is in the pressure record. It should also be noted that while KZ07 do not use a WPR of the form in Eq. (1), the empirical fit of the data here does show a rather consistent fit (i.e., low RMS). Nonetheless, the primary result is that the change in operational procedures at JTWC, as well as at other agencies, is apparent in the best-track data by examining both wind and pressure.

3. Tropical cyclone analysis using TD-9635 and KZ07

We use the KZ07 WPR to estimate MSW and compare with the reported MSW. The following discusses the impact of this approach on individual storms as well as annual activity during the TD-9635 period of record: 1945–76.

a. Analysis of individual storms

The KZ07 WPR estimates MSW (in kt) from MCP (in hPa) using

$$\begin{aligned}\mathrm{MSW} = 18.6 - 14.96S - 0.755\varphi - 0.518\Delta P \\ + 9.738\sqrt{\Delta P} + 1.5c^{0.63},\end{aligned} \tag{2}$$

where S is a normalized storm size parameter, φ is latitude (°), c is the translation speed of the system (in kt), and ΔP is 1008.9 − MCP. Latitude and translation speed are available from 6-hourly positions in TD-9635. ROCI is provided by TD-9635, which is converted to S via

$$S = \mathrm{ROCI}/8. + 0.1.$$

This conversion was derived empirically such that the resulting distribution of S has a mean of 0.65 and a standard deviation of 0.27, which approximates the distribution of S noted in Knaff and Sampson (2006) for WP typhoons.

The result is a pressure-based MSW estimate (MSW_p) at 6-h intervals during the lifetime of the storm. The new winds can change the LMW and ACE of a storm to pressure-derived values, LMW_p and ACE_p, respectively. The differences between MSW_p and MSW are verified using the annual tropical cyclone reports generated by JTWC (available online back through 1959 and in NCDC's archive prior to 1959). The following is a summary of the top four storms that have been most likely underestimated ($\mathrm{MSW}_p > \mathrm{MSW}$) and overestimated ($\mathrm{MSW}_p < \mathrm{MSW}$) between 1945 and 1976. While this analysis focuses on wind comparisons with TD-9635, it has implications for the JTWC record given the similarity between the two.

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[1] $\mathrm{MWS} = 4.4(1010 - \mathrm{MCP})^{0.76}$.

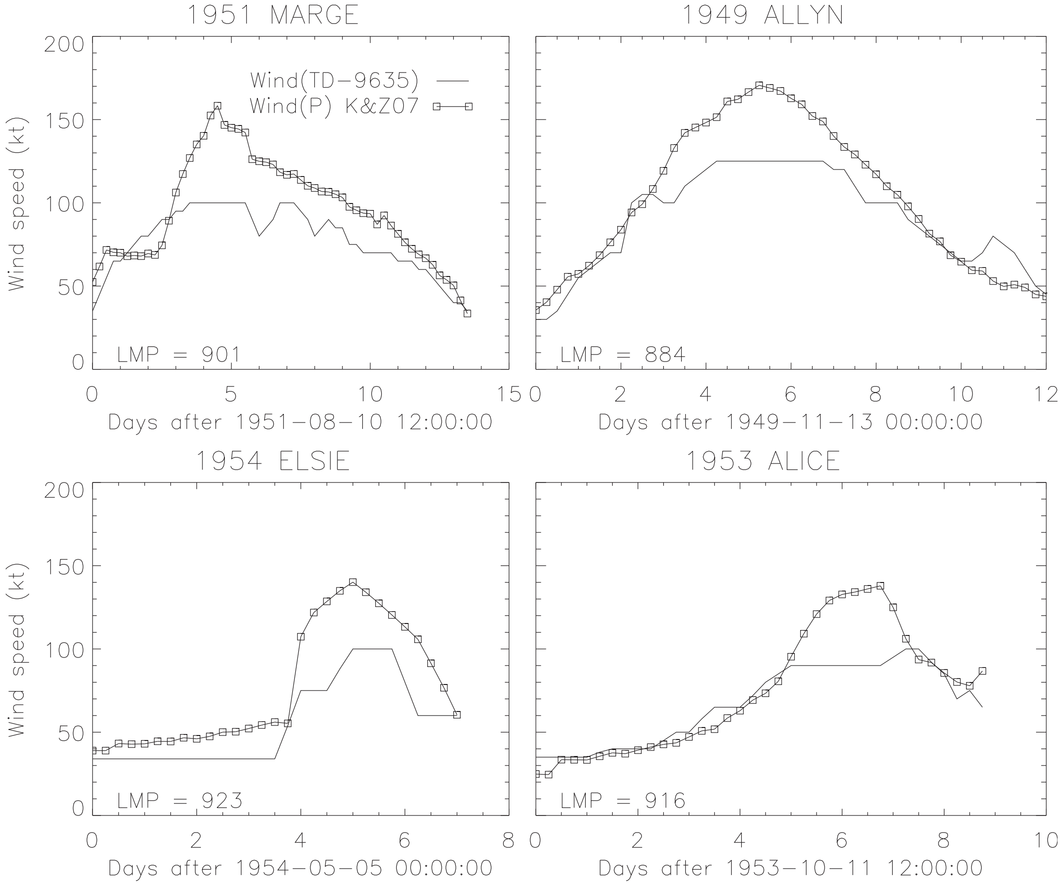

FIG. 4. Four typhoons with the largest increase in LMW between best-track (from TD-9635) and pressure-based winds (using KZ07) along with the LMP in hPa.

1) SOME TYPHOONS WERE LIKELY STRONGER THAN ORIGINALLY THOUGHT

The following storms had pressure-based winds that were much stronger than those reported in the TD-9635 (or JTWC) best-track data. Figure 4 shows the four typhoons with the largest increases in LMW when using the new analysis (along with their lifetime minimum central pressure, LMP). In many cases, the pressure-based winds look more realistic. For example, where LMW increases, the winds early and late in the period match the pressure-derived winds. However, at or near LMP, the MSW appears capped at either 100 kt (Marge, Elsie, and Alice) or 120 kt (Allyn).

Typhoon Marge (1955) had the largest increase from LMW to LMW_p, from 100 to 158 kt, which is consistent with other information about Marge. Aircraft reconnaissance measured an MCP of 895 hPa during Typhoon Marge (Simpson 1952), which supports winds much greater than 100 kt. Simpson (1952) remarks that winds were measured in the range from 75 $\mathrm{mi\,h^{-1}}$ (mph; ~33.5 $\mathrm{m\,s^{-1}}$) to "more than 100 mph on the east and north sides of the vortex," where only a lower bound of MSW is stated (100 mph; ~44.7 $\mathrm{m\,s^{-1}}$), not an estimate of the *actual* maximum sustained wind.

The increase in LMW for Typhoon Allyn (1949) also supports a report of a lower bound. Postanalysis of the storm is documented by the Typhoon Post Analysis Board 15th Air Weather Service Detachment (1950), which noted that "the mission recorded the lowest 700 MB height ever recorded" of 6900 ft (where 1 ft = ~0.3 m). This corresponds to an MCP of approximately 888 hPa and suggests an MSW that is much higher than the reported 120 kt.

Similarly, the postanalysis report on Typhoon Elsie (1954) from U.S. Fleet Weather Central (1955) indicated "winds at the southern edge of the eye were over 100 knots"; however, a minimum 700-hPa height of 7910 ft corresponds to an MCP near 923 hPa. Thus, an increase from 100 to 140 kt appears reasonable.

Finally, the winds reported in the best track for Typhoon Alice (1953) correspond to the lower bound in

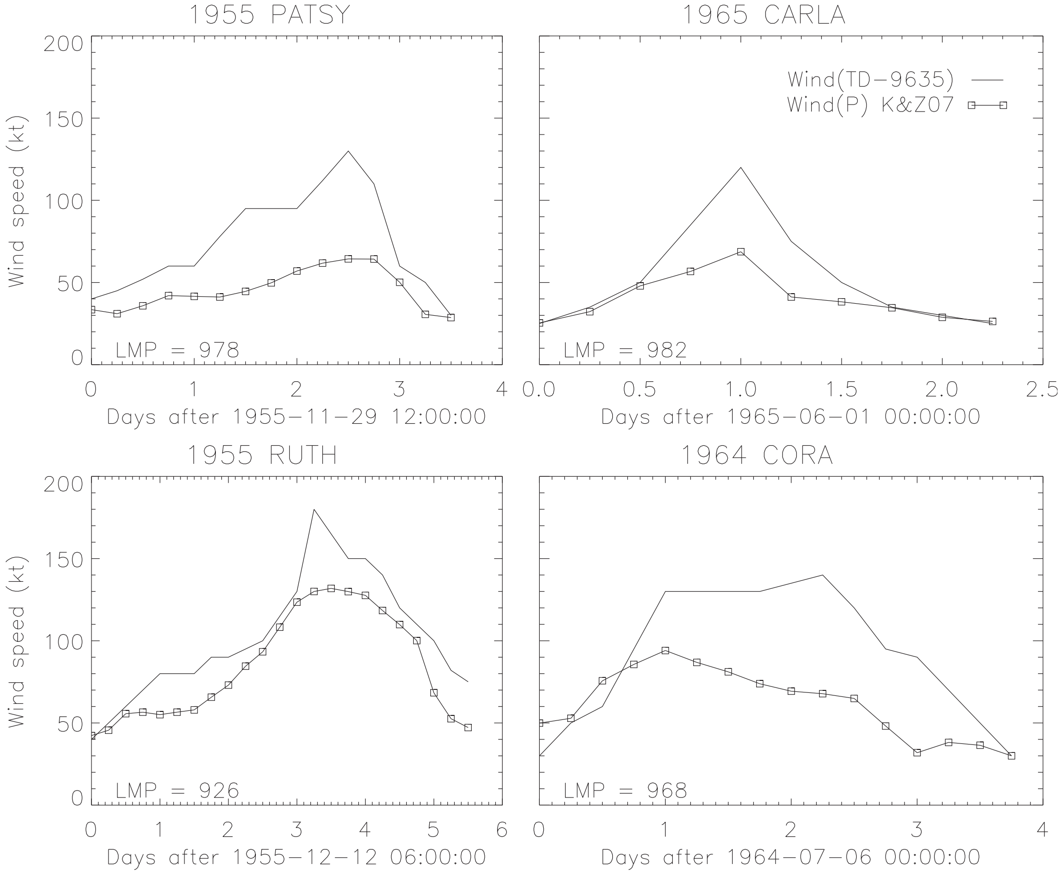

FIG. 5. As in Fig. 4, but for the four typhoons with the largest decrease in LMW.

the report, rather than an actual estimate. The lowest 700-hPa height was 7460 ft, corresponding to about 908 hPa. The report also stated, ''Since the flight was conducted at 700 hPa under instrument conditions, it is quite likely that much stronger winds located just outside the eye were unobservable, although existant'' (Typhoon Post Analysis Board 1st Weather Wing 1954).

In summary, many of the largest increases in lifetime maximum winds based on pressure are supported by historical documentation of the storms. The converse is also true: there is documentation to support that some storms have LMWs that are too high.

2) SOME TYPHOONS WERE LIKELY WEAKER THAN ORIGINALLY THOUGHT

The time series of MSW and MSW_p for the four typhoons with the largest decrease in LMW to LMW_p are shown in Fig. 5. In the postanalysis of Typhoon Patsy (1955), U.S. Fleet Weather Central (1956) noted that based on an MCP of 980 hPa and Fletcher's formula (based on Fletcher 1955) that ''it would appear that the maximum reported surface winds were somewhat over estimated.''

The same appears to be the case with 1965 Typhoon Carla, where the reported wind of 120 kt was from a 1500-ft flight even though the central pressure was estimated at 991 hPa. The MSW was likely much weaker than reported, with an estimated LMW_p of 69 kt.

Typhoon Ruth (1955) had numerous surface ships reporting wind speeds nearby. Postanalysis by U.S. Fleet Weather Central (1956) compared aircraft reconnaissance winds with coincident ship observations and noted that for Typhoon Ruth ''it would appear that the winds are often over estimated by as much as 100 percent.'' In fact, at the supposed peak intensity of 180 kt, the aircraft reconnaissance found a 700-hPa minimum height of 8080 ft, from which a central pressure of 944 hPa was estimated, a pressure more often associated with moderate typhoons with winds nearer 132 kt (cf. Fig. 5).

Finally, for 1964's Typhoon Cora, surface winds were estimated at 175 kt on two consecutive flights at 700 hPa. However, flight-level winds were estimated to be only 70 kt and the central pressure was 970 hPa (which

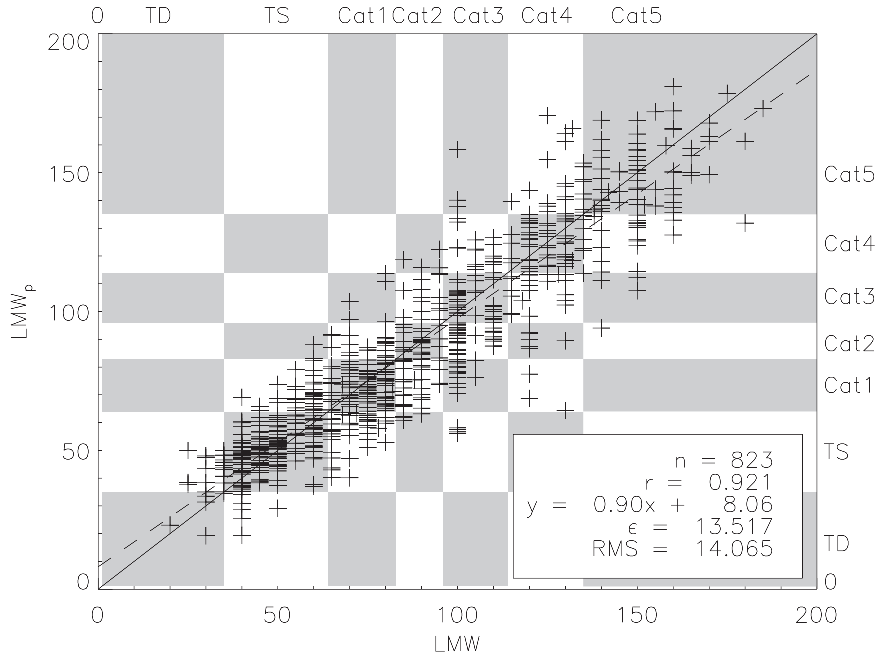

FIG. 6. Changes in LMW as reported from best-track data and as calculated from pressure observations (LMW$_p$) based on the TD-9635 data from 1945 to 1976. The SS hurricane-scale boundaries are provided for reference only (since it is not widely used in the WP basin).

corresponds to an AH77 wind speed of 72 kt). In each case of reported surface winds above 100 kt for Cora, the flight-level winds and central pressures support much lower intensities. In short, there is sufficient evidence that wind reports in these storms were likely overestimated.

3) OTHER CHANGES BASED ON PRESSURE-BASED WIND ESTIMATES

The reported LMW is compared with LMW$_p$ for all storms from 1945 to 1976 in Fig. 6 in terms of the Saffir–Simpson (SS) category (Simpson 1974), used here only for illustrative purposes since the SS categories are not widely used in the WP. In short, 93% of the storms had changes in intensity of one category or less, with more storms increasing in intensity (24%) versus decreasing (14%) when the LMW is derived from the pressure. In fact, eight storms (1% of the total) had increases of three SS categories. In summary, JTWC storms in the early portion of the WP period of record (1945–76) are likely underestimated based on reported MCP, ROCI, and translation speeds.

Another aspect of this analysis provides a history of storm sizes and intensity, based on ROCI available from the TD-9635 dataset. Table 4 shows the 10 largest and smallest typhoons, in terms of ROCI, when considering typhoons that had at least two reports with an estimated intensity (MSW$_p$) greater than 96 kt. First, there is a very large range in sizes of these intense typhoons: from 2.0° (the smallest ROCI values reported in the dataset) to 13.4° latitude, an equivalent range of 220 km to almost 1500 km. Also, the size appears to have a limited impact on MSW. Aside from Typhoon June that peaked at an estimated 172 kt, the ranges for both the largest and smallest systems was from approximately 97 to 137 kt.

The new storm intensity estimates also provide quite a different ranking of the most intense storms during the TD-9635 period of record. The top 10 storms with the

TABLE 4. List of 10 largest and smallest typhoons from 1945 to 1976 while they had MSW$_p$ ≥ 96 kt (with at least two observations > 96 kt). Here, $\overline{\mathrm{ROCI}}$ is the mean size of the storm when the storm had MSW$_p$ > 96 kt.

	Largest			Smallest		
Rank	Typhoon	$\overline{\mathrm{ROCI}}$ (° lat)	LMW$_p$ (kt)	Typhoon	$\overline{\mathrm{ROCI}}$ (° lat)	LMW$_p$ (kt)
1	1976 Fran	13.4	124	1971 Dinah	2.0	105
2	1975 Nina	12.1	137	1964 Kathy	2.0	106
3	1975 June	11.8	172	1968 Kit	2.0	97
4	1974 Elaine	11.7	103	1973 Ellen	2.2	115
5	1976 Pamela	11.5	126	1953 Judy	2.3	124
6	1974 Gloria	11.2	119	1970 Iris	2.5	107
7	1960 Mamie	10.7	99	1971 Rose	2.6	132
8	1976 Olga	10.5	112	1968 Lucy	2.7	118
9	1976 Billie	10.3	132	1972 Phyllis	2.7	116
10	1974 Irma	10.1	112	1970 Kate	2.7	135

TABLE 5. Table of the 10 typhoons from TD-9635 with the highest LMW values (from 1945 to 1976).

Rank	Rank_p	Typhoons	LMW (kt)	LMW_p (kt)	$\overline{\text{ROCI}}$ (° lat)	LMP (hPa)
1	3	1961 Nancy	185	173	6.2	889
2	111	1955 Ruth	180	132	6.3	926
3	17	1961 Violet	180	161	9.9	886
4	2	1958 Ida	175	178	7.4	875
5	18	1964 Opal	170	161	5.6	905
6	9	1964 Sally	170	168	4.1	898
7	15	1959 Joan	170	163	6.7	894
8	47	1966 Kit	170	149	6.1	907
9	48	1964 Louise	165	149	4.6	917
10	29	1959 Vera	165	156	8.8	896

TABLE 6. Table of the 10 typhoons from TD-9635 with the highest LMW_p values (from 1945 to 1976) (cf. Table 5).

Rank	Rank_p	Typhoons	LMW (kt)	LMW_p (kt)	$\overline{\text{ROCI}}$ (° lat)	LMP (hPa)
16	1	1973 Nora	160	181	5.07	877
4	2	1958 Ida	175	178	7.4	875
1	3	1961 Nancy	185	173	6.2	889
14	4	1975 June	160	172	11.8	874
27	5	1971 Irma	155	172	5.9	884
139	6	1949 Allyn	125	170	7.7	885
70	7	1973 Patsy	140	169	3.7	885
54	8	1954 Ida	150	169	5.9	891
6	9	1964 Sally	170	168	4.1	898
15	10	1957 Lola	160	166	6.4	898

highest LMWs are listed in Table 5 and the top 10 storms with the largest LMW_p's are listed in Table 6. Typhoons Nancy (1961) and Ida (1958) [the latter described by (Jordan 1959)] rank in the top five of each list. This result shows that at times, the wind speed reports are in agreement with what might be estimated from the MCP. Some storms that have very large changes in ranking have been discussed previously (e.g., Typhoons Allyn and Ruth). Overall, there is consistency in the distribution in the top 10 in that the 10th highest intensities are 165 and 166 for LMW and LMW_p, respectively. The primary disagreement is over which storms belong in the top 10.

b. *Analysis of annual activity*

The changes in typhoon activity can be summarized on an annual basis using the accumulated cyclone energy, as shown in Fig. 7. Annual ACE values are calculated as the sum of the square of the MSW over the lifetime of a typhoon, summed for all typhoons in a year,

$$\text{ACE} = \sum_{i=1}^{N_{\text{st}}} \sum_{l=1}^{N_{\text{obs}}} \text{MSW}^2 = N_{\text{st}} L V_{\text{ACE}}^2, \qquad (3)$$

where ACE can also be represented as a three-component term: the number of storms (N_{st}), the mean lifetime of the storms (L) for a given year (N_{obs}), and an ACE-equivalent wind speed (V_{ACE}), which is defined as

$$V_{\text{ACE}} = \sqrt{\frac{\text{ACE}}{N_{\text{st}} L}}. \qquad (4)$$

This represents a mean intensity weighted by the square of MSW. Here, lifetime (L) is the entire period of record for a TC since few agencies report whether the cyclone has tropical characteristics or not.

The time series of these annual values (ACE, N_{st}, L, and V_{ACE}) are provided in Fig. 7. The number of storms does show an increase during the TD-9635 period of record. While significant, it is also likely that short-lived typhoons may have been missed in the presatellite portion of the record, thus contributing to a positive trend. The current best-track winds from JTWC and TD-9635

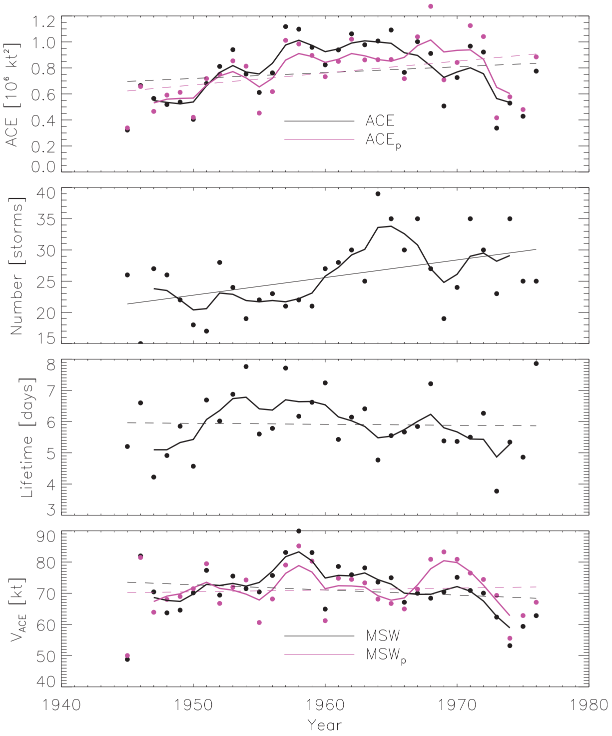

FIG. 7. (top to bottom) Time series of total ACE and ACE_p derived from TD-9635 and parameters that contribute to it [cf. Eq. (3)]: annual number of storms, mean storm lifetime, and V_{ACE}. For each time series, the heavy solid line is the smoothed line (using a 1–4–6–4–1 filter) while the straight line is the linear regression (which is solid if statistically significant). Reported values are from the best-track wind reports (MSW) and winds calculated using KZ07 (MSW_p).

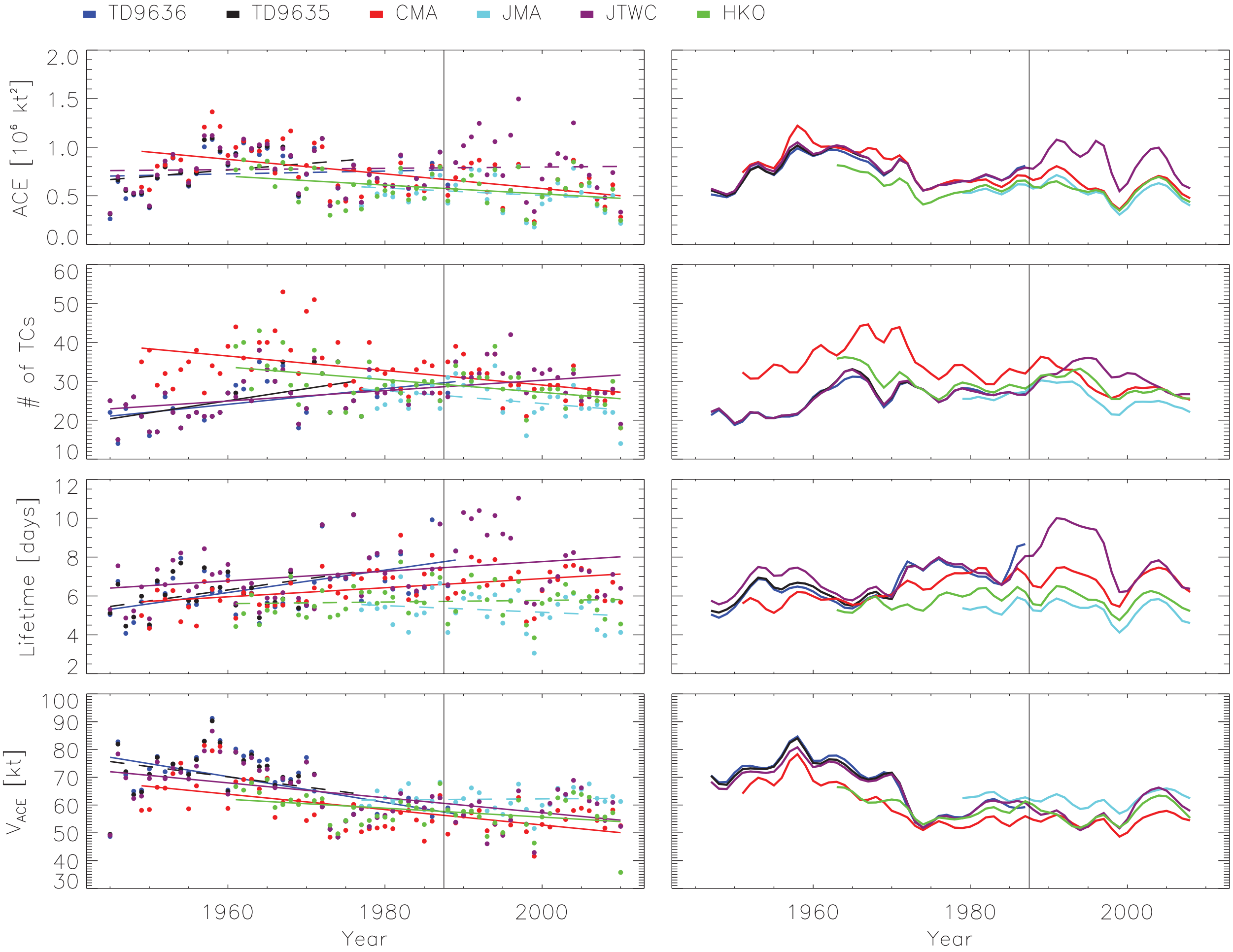

FIG. 8. (top to bottom) Time series of ACE from various agencies, annual number of storms, storm lifetime, and V_{ACE}. (left) Annual values are small circles and straight lines are linear trends of the dataset period of record and are solid if statistically significant. (right) Curves are 1–4–6–4–1 smoothed data.

appear to be too strong in the early period (1950–65) and too weak after. The result is new V_{ACE} estimates that show a decrease relative to the originals in the early period (i.e., during 1950–65) and an increase (i.e., large V_{ACE} values) later. This leads to a change in sign of the linear regression for V_{ACE} during the period of record; however, neither trend is significant at 99%. Further analysis (not shown) using quantile regression (following Elsner et al. 2008) suggests no significant trends at the decile level. Nonetheless, it suggests that procedural changes in the best-track data could impact temporal trends.

4. Time series of tropical cyclone data from all agencies

a. Wind-based analysis

The ACE time series based on reported winds is shown for all IBTrACS sources having MSW reports in Fig. 8. The ACE is calculated from MSW without adjustment for wind speed averaging periods; therefore, some offset is expected between agencies based on procedural differences (Knapp and Kruk 2010). Linear trends are calculated for the complete period of record of each agency. The U.S. datasets (TD-9635, TD-9636, and JTWC) are largely consistent and likely are derived from one source. The small interagency variation in ACE before 1960 does not necessarily imply agreement, but rather that few agencies provided MSWs during that period (cf. Table 2). The only significant trends are for HKO and CMA, both showing a decrease in ACE. However, from Fig. 3 we concluded that CMA is likely biased high prior to 1970. Therefore, the decrease in CMA ACE is due in part to the early high bias in MSW. Last, the ACE record appears to bifurcate after the end of aircraft reconnaissance (1987) between JTWC and other agencies (JMA, HKO, and CMA). Nakazawa

FIG. 9. As in Fig. 8, but with ACE$_p$ calculated using KZ07. Gray lines in the top panel are the ACEs from the top panel in Fig. 8 to provide context.

and Hoshino (2009) confirm the differences in T and CI numbers for 1992–97. They attribute the differences to variations in how the Dvorak technique was applied. Furthermore, Lander (2008) studied the 1996 typhoon season (in this period of large differences) and found substantial differences between the JTWC and JMA intensities. These variations in how the Dvorak technique was applied explain at least some of the differences in long-term ACE trends shown in Fig. 8. It is this difference that leads in part to differences in the sign of long-term ACE trends already described.

The contributions to ACE trends among agencies differ. CMA and HKO archives have declining annual storm numbers while other agencies have increases. The storm lifetimes are somewhat more consistent until 1970, when HKO remains short while U.S. agencies have longer lifetimes. Another deviation in lifetime occurs after 1989 where JTWC increases average lifetime to nearly 10 days due to an increased effort to warn on every TC of 25 kt or greater (C. Guard 2012, personal communication). Perhaps the largest consistent change is V_{ACE}, where values were consistently large prior to 1972, after which values are a bit lower.

b. *Pressure-based analysis*

The ACE time series based on MSW$_p$ from KZ07 are shown in Fig. 9. Overall, there is more agreement between agencies for ACE$_p$, particularly prior to the end of aircraft reconnaissance. It should be noted that the JTWC contains pressure estimates starting in 2003. However, between 1987 and 2003, the overwhelming majority of the wind estimates in the WP are derived from satellite. More than likely, what JTWC would have reported for pressure during the period 1988–2002 would derive from the Dvorak relationship. Thus, we reconstruct the JTWC pressure record using the Dvorak WPR, which allows us to still show JTWC when considering a pressure-based analysis [noted JTWC (wind) in

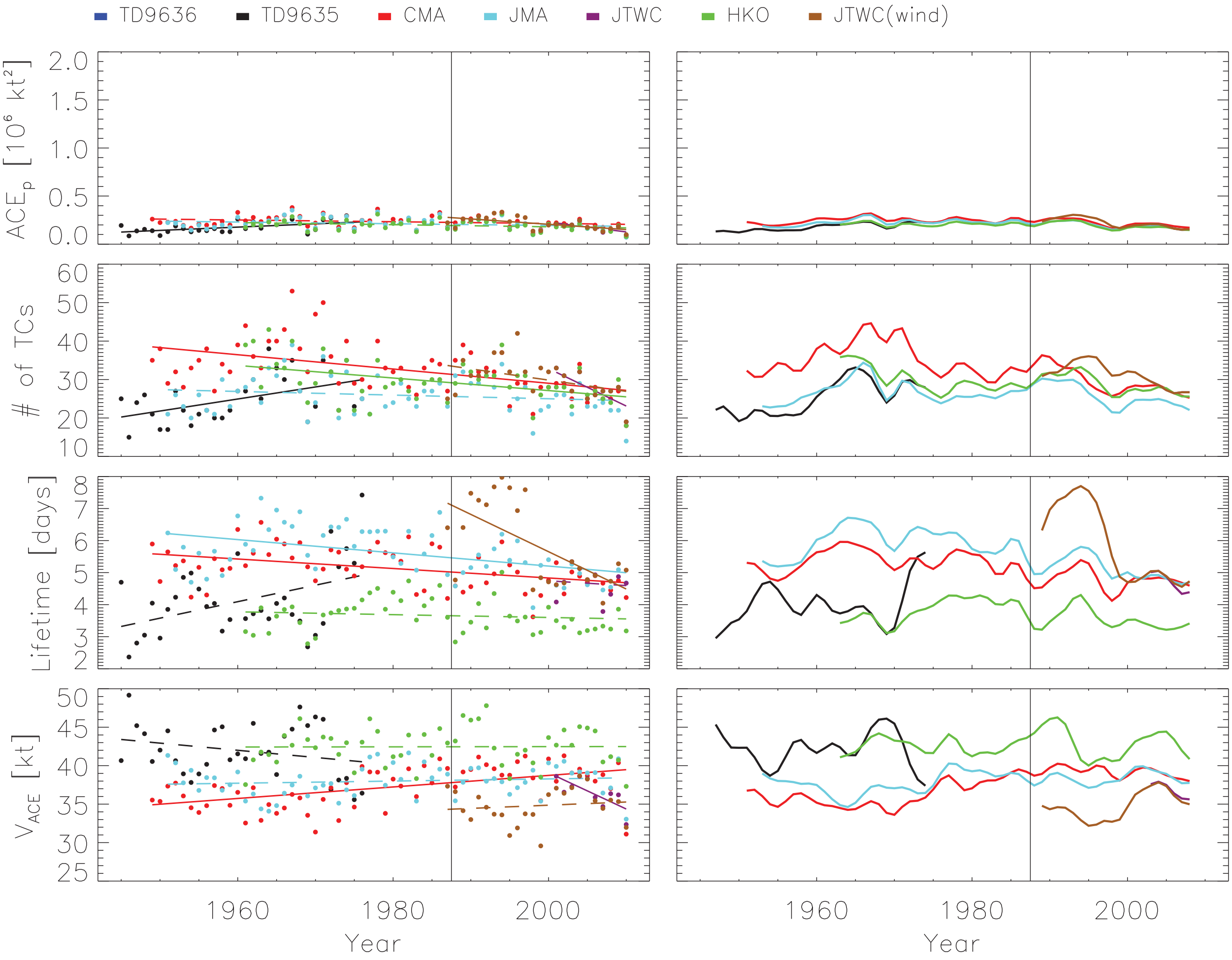

FIG. 10. As in Fig. 9, but for ACE$_p$ with statistics accumulating only while MSW$_p$ < 65 kt (i.e., tropical storm intensity).

Figs. 9–12]. The veracity of this assumption is verified by checking the estimated pressure values for 2003–06, the time period during which JTWC was reporting pressure and used the Dvorak (1984) relationship (i.e., AH77). During this time, the MCP derived from MSW and the reported MCP match within 1.5 hPa for 99% of the reports.

Only two datasets have significant trends: TD-9635 and JTWC. Both have short periods of record and their trends are in agreement with the other records. So the significance we found appears to be an artifact of the shorter periods of record in these datasets.

The interagency agreement prior to 1987 is somewhat surprising given the differences in the ACE$_p$ components. CMA again has more TCs (cf. Fig. 9), and the lifetime trends are consistent among the agencies, with nearly constant offsets between JMA and CMA and then CMA and HKO. A possible change in procedures is implied at JTWC (via TD-9635) near 1970 when the lifetime has an increase from near 6 to closer to 7 days. Here again, we see a significantly large lifetime increase for JTWC in the 1990s. Which leads to the question: Is the large ACE$_p$ from JTWC caused by this increase in typhoon lifetime or something else?

To answer this, we stratify the ACE$_p$ calculations by intensity. Figure 10 shows ACE$_p$ for all tropical cyclones when MSW$_p$ < 65 kt while Fig. 11 shows ACE$_p$ during a storm's lifetime when MSW$_p$ ≥ 65 kt. Comparing these conditions, we confirm that the weaker portions of a storm's lifetime are the cause in the differences in typhoon lifetime. In fact, the interagency differences in the ACE$_p$ components persist in these weak storms (cf. Fig. 9). For example, CMA still has more storms and the variation in lifetime is large. This results in a large variation in V_{ACE}, but the impact on ACE$_p$ is minimal.

Conversely, there is much more interagency agreement for ACE$_p$ and its components when MSW$_p$ ≥ 65 kt (cf. Fig. 11). The number of typhoons is generally within one storm. The lifetime shows agreement before 1987. The large deviation in JTWC is gone. While there is

FIG. 11. As in Fig. 10, but for $MSW_p \geq 65$ kt (i.e., typhoon intensity).

more variation, in particular during the 1990s, it is clear that the lifetime differences of JTWC were for periods when TCs were not yet typhoons, having little impact on the final ACE_p of the weak storms. Therefore, the conclusion is that the deviation in ACE_p in the 1990s is caused by larger intensities at JTWC. In 1990 when only typhoons ($MSW_p \geq 65$ kt) were examined, JTWC has a $V_{ACE} \sim 100$ kt compared to $V_{ACE} \sim 90$ kt from other agencies.

The decrease in interagency ACE variation using pressure is demonstrated in Fig. 12, which shows a time series of ACE from all available agencies using three estimates of MSW as reported in the BT data (top) and from MSW_p using KZ07 (bottom). The black solid line shows the range in ACE values between agencies. It is clear that the variation in ACE is lower in the pre-1987 era and the interagency differences exceed the annual ACE values for some agencies. There is a clear need to understand the differences and decrease the differences where possible. Normalizing winds to a 1-min averaging period following Knapp and Kruk (2010) can decrease some of the interagency ACE variation. However, some differences would remain, particularly after aircraft reconnaissance ended. The interagency variation from ACE_p has smaller differences. However, when considering MSW_p derived from JTWC, the differences between JTWC and other agencies during the 1990s remain large.

In summary, we first investigate the changes in the presatellite record based on the TD-9635 dataset. After investigating the new historical record, we then compare WPR-based ACE from MCP reports from all agencies. MCP is more reliably and consistently reported by early aircraft reconnaissance. In fact, while agencies disagree to a large extent on winds during the early record, the interagency pressure deviations are much smaller and agree in large part with the aircraft reconnaissance. The pressure records from CMA, JMA, and TD-9635 can then be used to derive a pressure-based wind estimate using KZ07 (or other WPRs).

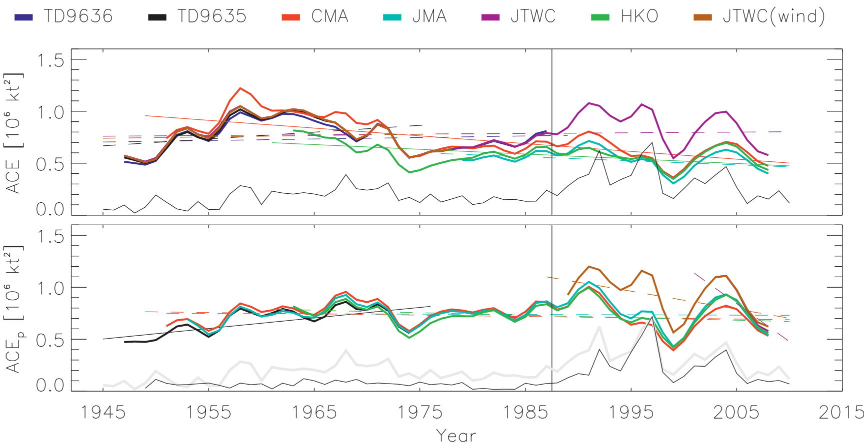

FIG. 12. (top) Time series of smoothed ACE (following Fig. 8) calculated from BT data, where the black line represents the range of ACE values. (bottom) Time series of ACE$_p$ from MSW$_p$ (cf. Fig. 9). Again, the range in ACE values is represented by the black line; the gray line is the original ACE range.

5. Combined pressure-based time series

We derive a combined ACE$_p$ time series on an annual basis, based on the agreement between agencies for 1945–87 (Fig. 13). After 1987, there appear to be two scenarios in the data: a time series that follows JTWC intensities and another that follows other agencies (JMA, CMA, and HKO). Given the lack of aircraft reconnaissance, it is difficult to determine which path is more likely to have occurred. However, an independent estimate is available from an objective satellite-based analysis. The ACE from intensities estimated by Kossin et al. (2007) is shown in Fig. 13 (where the annual ACE has been adjusted to force the 1982–87 mean to match the ACE$_p$ record). It is interesting to note that these objective ACE estimates show better agreement with the JTWC ACE time series. However, more validation of these objective satellite estimates is needed in the WP basin prior to drawing any further conclusions.

When interpreting trends over short periods, the choice of the period of analysis can change the results. The sensitivity of the linear trend in ACE$_p$ to the period of record is shown in Fig. 14, by varying the start date and ending in 2010 (top) or by varying the end data while beginning in 1945 (bottom). The vertical bars represent the linear regression uncertainty associated with the 99% confidence interval. Thus, where the confidence interval crosses the zero line, the trend is not significant. For periods starting in 1945 (Fig. 14, top), a positive trend is apparent until 1970. However, considering the entire period of record, it appears that a significant trend only appears in the JTWC ACE$_p$ record (and appears to be decreasing as years are added to the record). Conversely, when varying the start year, the trends show large variation with few that are significant. Only for a period starting before 1948 does the trend with JTWC become significant. The trends in ACE$_p$ from the other agencies are not significant for any time period.

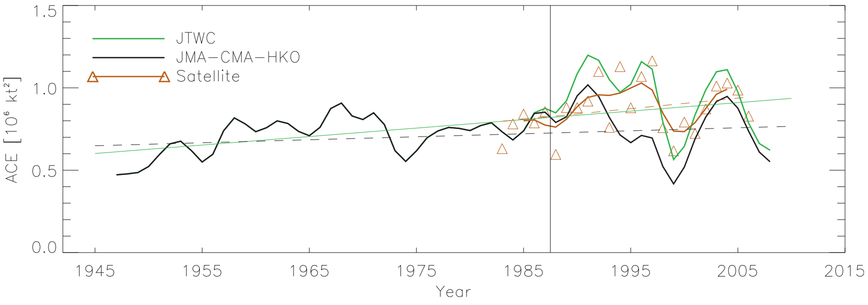

FIG. 13. Time series of smoothed ACE$_p$ derived from a combined pressure dataset. Blue represents the JMA–CMA–HKO pressure values after 1987, green represents the JTWC estimated pressure values after 1987, while brown represents the satellite-based ACE estimates (scaled so that the mean satellite ACE for 1983–87 matches the BT ACE).

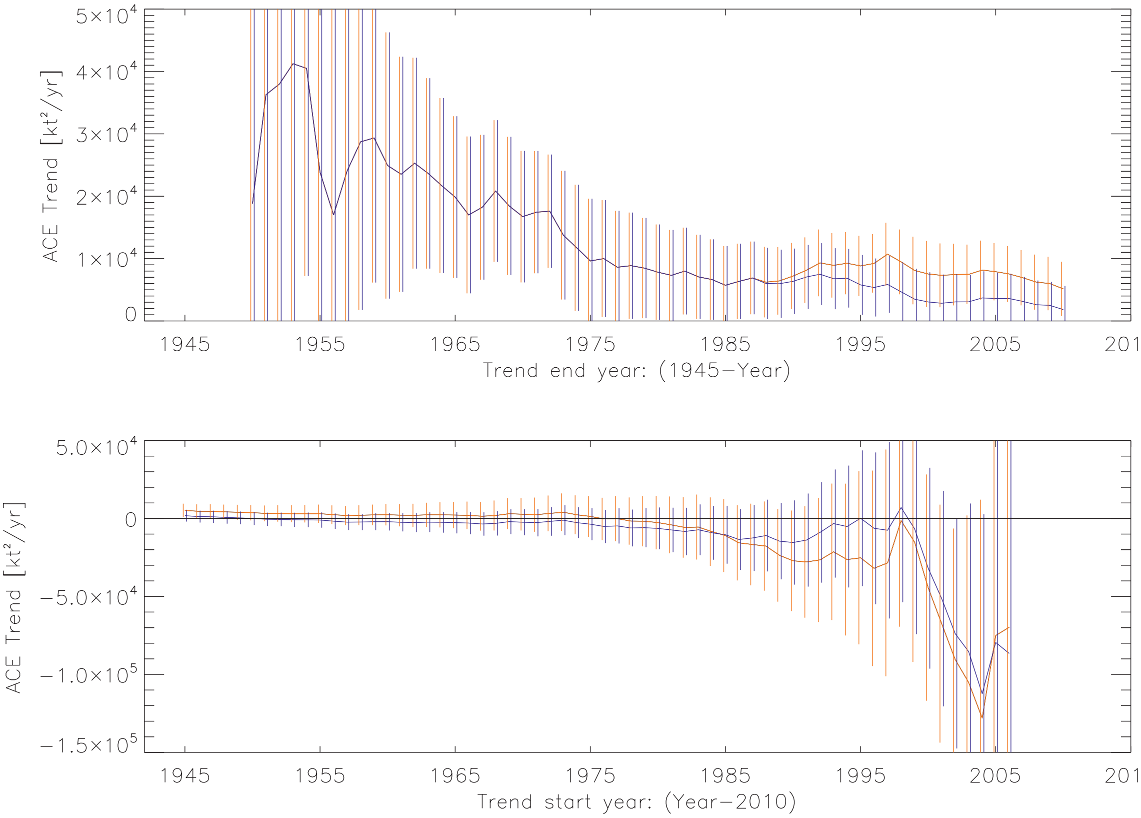

FIG. 14. (top) Trend in ACE for periods beginning in 1945 with a varying end year. Blue represents trends following the JMA–CMA–HKO results in the 1990s while the orange line follows JTWC. Vertical hatching represents the 99% confidence interval of the slope. (bottom) As in the top panel, but the period of trend has a varying start year and end in 2010.

6. Discussion

At this point, it seems appropriate to summarize the findings of analyzing storms with the largest MSW_p versus MSW changes using historical documentation. Comments in annual typhoon reports and poststorm analyses suggest wind reports were in error. However, these same wind estimates with significant errors appear in the best-track data of some agencies, which makes it clear that some early best-track data were derived from warning bulletins by some agencies and from aircraft reconnaissance by others. Following our analysis of changing WPRs (cf. Fig. 3) in the early period for all agencies, this analysis is appropriate for all agencies, not any particular one. Based on this analysis and that of others (e.g., Mien-Tze 2012), we recommend that a complete reanalysis of historical typhoon MSWs be performed to provide users with the highest quality climate data for TC impact studies, analyses, and applications.

Consistent with Chu et al. (2002), we recommend not using wind data for typhoons early in the record, given the dependence on aircraft reconnaissance wind speeds, changing practices at an agency, and the potential lack of quality control in the wind data. Furthermore, pressure data in the recent JTWC record also need to be used with care given their change in WPR. Nevertheless, it appears that the historical pressure-based record of typhoon activity is more consistent between agencies than the wind-based reports.

Therefore, to reconcile these past MSW differences, the community should conduct a reanalysis of the intensity records with a consistent methodology and dataset. Objective techniques could be applied using the position and storm duration information from the various agencies. Results could be used to create both an intensity estimate and a measure of uncertainty. Another more labor-intensive, but potentially more accurate, option is to conduct a subjective reanalysis using homogeneous techniques (e.g., a consistently derived intensity using a Dvorak technique) and multiple experienced analysts. This option would also be able to include information from all available surface observations. This type of labor-intensive method is currently being conducted by Météo-France in the southwest Indian Ocean (T. Dupont 2011, personal communication) and by NOAA to the eastern Pacific Ocean (Kimberlain 2012), if applied to the WP, could also provide a homogeneous measure of TC activity in the post-AR time period. Such activities will help to improve the historical MSW record.

However, new in situ observations need to be made to decrease the likelihood of differences in the future. One of the findings of this and other studies is that once routine aircraft reconnaissance was discontinued in the WP, interagency intensity differences became apparent. The largest differences in this basin occur during the 1990s, just a few years after AR ended. Which of the several records available is more correct is debatable, and the existence of these divergent intensity records prohibits definitive conclusions on important topics such as climatic changes in TCs from being drawn. It is likely that intensity differences are due to drifting methodology and changes in input at the various agencies. Furthermore, as more remote sensing methods for intensity estimation become available and operational procedures evolve further, there is a possibility that the intensity records will diverge even more. An international effort to provide ground truth via low-level AR or other platform [e.g., the Aeroclipper discussed in Duvel et al. (2009)] for an adequate period of time to calibrate the agency intensity estimates could be fruitful. Large international efforts to observe TCs have been conducted in the WP before, but these campaigns typically collect more comprehensive datasets for a shorter period of time than would be optimal for calibrating intensity estimates. A tropical cyclone intensity intercomparison field project would probably need to focus on routine MCP and MSW observations for a significant portion of one or more seasons to be effectively used for calibrating the agency estimates.

Finally, our approach does not take into consideration the possibility of missed typhoons. These are typhoons that may have occurred but were not recorded by the observation network of the time, also referred to as undersampling. Several studies consider the changing observational procedures in the North Atlantic Ocean, quantifying the probability of missed tropical storms (Landsea et al. 2010; Vecchi and Knutson 2008, 2011). However, a similar study for missed typhoons in the Pacific is lacking.

7. Summary

This study finds that the historical best-track records (1945–76) demonstrate inconsistency between pressure and wind reports. This suggests that the operational procedures of reporting MSW and/or MCP have changed. We also confirm that MCP is more consistently observed and reported during 1945–76 than MSW. Additionally, in cases where the LMW significantly differs between MSW- and MCP-derived reports, the published typhoon reports often support the MCP-derived wind. Thus, it appears that an MCP-based wind is more temporally homogeneous than the actual best-track wind reports for these earlier records, and that MCP-based analyses of typhoon intensities are more homogeneous during 1945–87 than MSW-based analyses. MCP is also more consistent between agencies than MSW, but only during the period of aircraft reconnaissance (1945–87).

During the aircraft reconnaissance era, we found that pressure-based winds are sometimes significantly different from reported winds and appear to have a time-dependent difference (in terms of annual statistics). Plots of individual storms suggest that in many cases, MSW_p provides a more realistic measure of intensity than MSW, especially for storms that appear to be artificially capped. Finally, JTWC storms in the early portion of the WP period of record (1945–76) are likely underestimated based on reported MCP, ROCI, and translations speeds.

The dearth of WP aircraft reconnaissance since 1987 has hampered efforts to reconcile MSW/MCP reports between agencies. In the 1990s and 2000s, particularly, wind and pressure-based winds both show a divergent measure of activity. This highlights how, without ground truth, satellite-based intensity records can drift as methods and data availability at different agencies diverge. Best tracks also show evidence of procedural changes, such as when JTWC changed pressure estimation procedures in 2007, which produced a step change in the pressure record. The CMA winds appear to be too large in the early portion of the record (prior to 1970), possibly due to procedural changes. Results also suggest that MSW from TD-9635—and, thus, JTWC—are generally too high during 1950–65. After 1987, all agencies were more dependent upon satellite-based methods that primarily estimate wind speeds to estimate intensity. However, changes to operational procedures and satellite-based intensity estimates were not comprehensively documented, which complicates intercomparisons between agencies. The use of pressure as an intensity metric does allow us to more confidently use the earlier TC records in the WP. Examining the MCP-based ACE values, we find that the post-1987 records are different for each agency and that there is a range of ACE trends that can be derived by varying both the start date and the agency. The value of ACE_p appears to be consistent between agencies until reconnaissance ended in 1987.

The largest variation in ACE$_p$ is found in the 1990s, which includes a year identified by Lander (2008) to have irreconcilable differences. The ACE$_p$ differences in the 1990s have been shown to be mostly independent of deliberate procedural changes at JTWC to expand the tracking of TCs < 35 kt, and appear to be related to differences in intensity estimation for stronger TCs. The various agencies largely agree on the number and lifetime of strong storms. However, they differ, sometimes greatly, on the intensity of the stronger storms during this period, leading to differences in ACE. It is worth noting that CMA has consistently larger ACE$_p$ and ACE values in the era before 1970. This is likely caused by the CMA MSW values that are too large. Finally, if JTWC intensity estimates are correct in the 1990s, then overall ACE$_p$ is likely increasing at a nonzero rate. The satellite-based ACE appears to support the larger JTWC ACE$_p$ values in the 1990s, so further analysis and validation of these satellite objective estimates in the western Pacific is desired to investigate this possibility.

Finally, analyzing TC intensity in terms of pressure leads us to believe that reconnaissance-based pressure estimates can help reconcile many of the differences between the best-track datasets for the period 1950–87. However, we have less confidence that we can quickly reconcile intensity records for years after the end of the reconnaissance era. Since 1987, intensity estimation techniques and operational procedures have evolved at each agency such that the records have drifted apart.

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APPENDIX

Digitized WP Aircraft Reconnaissance Data

Digitized aircraft reconnaissance data for the western Pacific Ocean are available in the form of Automated Tropical Cyclone Forecast (ATCF) F-deck data from 1966 through 1987 (except for a missing year of 1978). Yet, aircraft reconnaissance began in the 1950s with summaries of flights provided in various forms [e.g., in annual typhoon reports (ATRs) produced by the JTWC], some of which are available online as PDFs back through 1959. Thus, there was a need to digitize reconnaissance data contained in the ATRs for 1959–65 and find and key data prior to 1959. NCDC archives of paper and microfilm records were scoured for additional aircraft reconnaissance information on WP typhoons. It was found that archived data for most of 1946–58 exists in microfilm and paper format.

Western Pacific typhoon aircraft reconnaissance data from the years 1946–65 and 1978, excluding 1952, were transcribed from original documents, or copies of original documents, into a spreadsheet. Microfilm and paper documents were inspected for reconnaissance aircraft fixes and other data collected during flight. Data were collected from reports such as tropical cyclone consolidated reports, annual typhoon reports, storm summary and life history of the typhoon reports, and aircraft weather code charts. Unfortunately, data for 1952 could not be found, 1955 data were very limited, and 1978 data were incomplete in its digitized format.

In total, there were 5085 center fixes keyed during this project. The most frequently reported parameters include flight level (76% of observations), minimum central surface pressure (58%), minimum 700-hPa height (56%), maximum surface winds (60%), flight-level winds (43%), location method (58%), fix accuracy (63%), eye diameter and shape (55%), and eye temperature (41%). However, many of the early reports present incomplete periods of reconnaissance. Limitations like instrument malfunctions and aircraft safety (such as engine loss) contributed to incomplete or aborted missions. Also, missing values were often found for data related to the minimum 700-hPa height. It is important to note that all available remarks were keyed (41% of flights). These remarks are extremely useful in understanding the data, or lack thereof. Remarks also often address inconsistencies in the data. For example, they often indicate aborted missions, instrument failure, or that an observation was made at the 500-hPa level instead of at 700 hPa.

The types of inflight observations of typhoons varied each year. Observations in the initial years (1945–49) were sparse; however, observations become more consistent starting in 1950. More parameters were recorded with greater detail. In early recordings the heights were measured in feet while the recording of the temperature and dewpoint temperature were made in degrees celsius. In addition, different observers had different descriptions for similar typhoons. For example, a ‘‘semi-circled eye shape’’ in one observer’s eyes is a ‘‘horse shoe’’ in another’s.

Transcription of western Pacific typhoon aircraft reconnaissance data from the years 1946 to 1965 and 1978 (excluding 1952) from paper and microfilm format into a digital spreadsheet will ensure the preservation of the data for future generations, as well as easier data analysis. The transcription of the data may also supplement data already available from the Joint Typhoon Warning Center and other agencies across the globe, as well as provide a resource for more detailed studies.

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