A Technique for Combining Global Tropical Cyclone Best Track Data

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ABSTRACT

Best track data generally consist of the positions and intensities during the life cycle of a tropical cyclone. Despite the widespread interest in the distribution, frequency, and intensity of tropical cyclones worldwide, no publicly available central repository of global best track data from international agencies has been in existence. While there are numerous international centers that forecast tropical cyclones and archive best track data for their defined regions, most researchers traditionally use best track data from a very small subset of centers to construct global datasets and climatologies. This practice results in tropical cyclones that are either missed and/or misrepresented. While the process of combining positions and intensities from disparate data sources can be arduous, it is worthwhile and necessary in light of their importance. The nature of historical best track data is that they are prone to issues with intensity (maximum surface wind and minimum central pressure), especially in the presatellite era. This study is not a reanalysis effort and makes no attempt to correct any longstanding debates about the accuracy of the historical data. Rather, it simply and objectively combines all of the best track data from each of the regional forecast centers that provided best tracks into one single point for distribution, and the methods used to construct the dataset are the focus of this work. Processes are therefore described herein that detail the combining of tropical cyclone best track data with the techniques used to assess the quality of the minimum central pressure and maximum sustained wind speed of each reported tropical cyclone. The result is a comprehensive global best track compilation dataset that contains information on all documented tropical cyclones: the International Best Track Archive for Climate Stewardship (IBTrACS).

1. Introduction

Global tropical cyclone (TC) data have a wide variety of applications, including performing climate change research, determining appropriate building codes for coastal zones, assessing risk for emergency managers, and analyzing potential losses for insurance and business interests (Landsea et al. 2004). TC tracks are used in constructing automated analyses of tropical cyclones, such as performed by Kossin et al. (2007), which used the Hurricane Satellite dataset (Knapp and Kossin 2007). Furthermore, tracks have been used to investigate changes in extreme rainfall from tropical cyclones (Lau et al. 2008). Thus, it is important to understand the global distribution, frequency, and intensity of tropical cyclones.

While numerous studies have investigated the global climatology of tropical cyclones, prior research generally has used a small subset of available best track (BT) data. For example, Emanuel (2005) and Klotzbach (2006) referenced data from two centers: the Joint Typhoon Warning Center (JTWC; Chu et al. 2002) and the Hurricane Database (HURDAT; Jarvinen et al. 1984) of the National Oceanic and Atmospheric Administration (NOAA)/National Hurricane Center (NHC). Although gathering and combining data from these two centers may seem complete for a global analysis, numerous other agencies also compile best track data. Despite the importance and impact that TCs have worldwide, there has been no publicly available nonproprietary dataset that incorporates documented TC best track data for all TC-prone basins from all available agencies.

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The common denominators between agencies providing best track data are the TC's location, maximum sustained wind, and minimum central pressure on a 6-h basis (at 0000, 0600, 1200, and 1800 UTC) during the lifetime of a TC. Best track data are the result of a post-season reanalysis of a storm's position and intensity from all available data—for example, ship, surface and satellite observations—using the latest technology and knowledge at the time of compilation. More recently best track datasets have included additional parameters, but this work concentrates on TC location and intensity. These best track data are compiled and archived by many agencies from around the world, although each one records slightly different TC characteristics in various formats. As such, numerous issues arise when producing a global dataset, such as identifying TCs tracked by multiple centers while reporting vastly different positions and intensities. Furthermore, the reported maximum sustained wind speeds from the various agencies have differing definitions. Despite these issues, the combining of best track data from multiple sources was needed to meet existing needs and fill gaps in the historical global tropical cyclone record.

To address these issues, the NOAA/National Climatic Data Center (NCDC), under the auspices of the World Data Center for Meteorology, Asheville (WDC), has developed a new, homogeneous, and comprehensive global tropical cyclone best track dataset. This new global best track dataset is called the International Best Track Archive for Climate Stewardship (IBTrACS; Kruk et al. 2009; Knapp et al. 2009), and is based on those agencies that archive and maintain publicly available best track data. The IBTrACS dataset utilizes objective techniques to combine best track data that necessarily account for some of the inherent differences between agencies while applying automated quality control procedures to flag potentially erroneous data points. This paper describes the methods used to combine these disparate datasets into a centralized repository of global TC best track data.

It should be noted that although IBTrACS is a logical extension of previous work carried out at NOAA/NCDC (Crutcher and Quayle 1974; Neumann 1999), it is not a reanalysis. That is, the authors did not go back to original land and ship reports, newspaper accounts, satellite pictures, aircraft reconnaissance reports, etc., as is being done for the Atlantic basin reanalysis efforts (Fernandez-Partagas and Diaz 1996; Landsea et al. 2004). Thus, IBTrACS is not a reanalysis; rather, it provides a collation of currently available best track data from agencies worldwide. The IBTrACS developmental effort is the result of a globally coordinated and collaborative project.

In the following sections, we describe the process by which best track data were collected (section 2) and how the TC positions (section 3), maximum sustained winds (section 4), and minimum central pressure (section 5) were combined to derive IBTrACS. A brief overview of tropical cyclone counts from IBTrACS is also provided (section 6), followed by concluding remarks.

2. Sources of best track data

Tropical cyclone best track data are required by the World Meteorological Organization (WMO) to be reported by each of the Regional Specialized Meteorological Centers (RSMC) and Tropical Cyclone Warning Centers (TCWC). In addition, other agencies track TCs in ocean basins where their country has an interest. The following agencies provided BT data for inclusion in a global dataset collection:

- BoM: Australian Bureau of Meteorology
- CPHC: Central Pacific Hurricane Center (as RSMC Honolulu)
- FMS: Fiji Meteorological Service (as RSMC Nadi)
- HKO: Hong Kong Observatory
- IMD: India Meteorological Department (as RSMC New Delhi)
- JMA: Japan Meteorological Agency (as RSMC Tokyo)
- JTWC: U.S. Defense Joint Typhoon Warning Center
- MFLR: MeteoFrance (as RSMC La Reunion)
- MSNZ: Meteorological Service of New Zealand (as TCWC Wellington)
- NHC: NOAA/National Hurricane Center (as RSMC Miami)
- STI: Chinese Meteorological Administration's Shanghai Typhoon Institute

Hereafter, these are collectively referred to as forecast centers. These forecast centers are designed to cover each major ocean basin where tropical cyclones occur: the North Atlantic (NA), eastern Pacific (EP), western North Pacific (WP), north Indian Ocean (NI), south Indian Ocean (SI), and South Pacific (SP). Best track data are generally produced for each tropical cyclone with an intensity of at least 25 kt (WP), 30 kt (NA, EP), and 35 kt (NI, SI, SP). If this is not confusing enough, tropical cyclogenesis and cyclolosis dates as well as reporting times and intensities also often vary by forecast center. This is discussed further in section 3. Ideally, a global BT dataset should integrate information from all available resources to ensure completeness. Additional data for the Southern Hemisphere were obtained from Neumann (1999) and were included because they incorporated data sources not listed above.

Upon receipt of the electronic best track data files, data were converted into a common format. The BT data files arrived in numerous formats: NOAA data tape format (i.e., HURDAT), spreadsheet tables, various ASCII formats, and even photocopied storm reports that were then digitized by NOAA's Climate Database Modernization Program (Dupigny-Giroux et al. 2007). All BT data were converted to Network Common Data Form (netCDF) format (Rew and Davis 1990), since it allows for the storage of many variables along with their descriptions, is supported by Unidata, and has software interfaces for many programming languages.

Finally, a short overview on how the data from these disparate sources are combined is appropriate. First, it should be noted that there are differences (both documented and undocumented) in how each agency determines the best position of the center of circulation and intensity (pressure and/or wind) for each tropical cyclone, which will lead to differences in the combined result. It is outside the scope of this article to define and quantify these differences. Second, given a lack of quantifiable error assessments of each data center, our treatment is that each source dataset is weighted equally when combined with data from other agencies. That is, no agency is weighted more than any other. Last, this combination of data from multiple centers does not constitute a reanalysis of tropical cyclone observations and thus is only a combined collection of multiple best track datasets.

3. Combining tropical cyclone positions

The first step toward a global dataset was identifying large errors in track positions. These often tended to be keying errors when digitizing the track data (e.g., transposing numbers or repeating a position). Next, storm tracks were queried to determine which storms[1] were identified by one or more forecast centers. Finally, the storm positions were averaged to derive a single track.

a. Tropical cyclone position quality assessment

The goal of the position quality assessment was to identify large errors in storm position. The term "large" refers to gross errors that are approximately 111 km (1° latitude) or more. Potential errors in a storm track were assessed based on how well a track followed a "smooth" path. First, track positions were converted from latitude, longitude, and distance from the earth's center to

three-dimensional Cartesian coordinates (x, y, z) to avoid discontinuities at either the date line or prime meridian. The smoothness of any point along a TC track in Cartesian coordinates was assessed using cubic-spline interpolation. That is, for the ith point in the j dimension, there is a point A_i^j where A is one of the Cartesian coordinates $(x, y, $ or $z)$. Then, five TC track subsets S_k, that contain A_i^j are

$$S_k = [A_{i-4+k}^j : A_{i+k}^j], \quad \text{for} \quad k = 0, 1, 2, 3, 4. \quad (1)$$

For each S_k, the point A_i^j is removed while the remaining points are interpolated using cubic splines to create a new estimate at point i, $E_{i,k}^j$. This produces five estimates of A_i^j, one from each of the five time series. The mean and standard deviation of $E_{i,k}^j$, $\overline{E_i^j}$ and $s_{E_i^j}$ (respectively), are used in calculating a z score of A_i^j, Z_i^j, which is a measure of the anomaly of A_i^j from the mean interpolated position via

$$Z_i^j = \frac{A_i^j - \overline{E_i^j}}{s_{E_{i,k}^j}}. \quad (2)$$

When Z_i^j is large the distance between the reported position (A) and the mean estimated position (E) is much larger than the variance of the estimated positions, thus it is likely that the track position is in error. Z scores from all the Cartesian dimensions were combined such that the total deviation of any point in the time series was a combination of the absolute value of z scores from each dimension:

$$Z_i = \sum_j |Z_i^j|. \quad (3)$$

Larger values of Z_i deviate more from a smooth, cubic-spline track, and thus are more likely erroneous. Also, rather than choosing a fixed threshold for Z_i above which points are assumed errant, a point is flagged if Z_i is more than three standard deviations above the mean of all Z_i for an individual storm track. This method allows each track to have its own threshold, thereby enhancing the robustness of the position quality assessment. In general, A_i^j was replaced by E_i^j if it met the following conditions:

- the adjacent points in the five time series appeared smooth, thus not corrupting the estimates $\overline{E_i^j}$;
- the new location was a large distance from the reported position (thus limiting the replacements to large corrections);
- the new location resulted in a set of positions that significantly decreased the total Z score of the storm track.

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[1] Note, the term "storm" refers generically to a tropical cyclone and "track" is the path a particular storm follows, thus, best track data describe the track and intensity during a storm's lifetime.

Finally, the latitude and longitude of each replacement position was determined from the Cartesian coordinates.

Figure 1 depicts the details of this procedure for the 1968 Cyclone Georgette near Madagascar. A portion of the track of Cyclone Georgette is shown in Fig. 1a, where a small discontinuity in the track is present. The Cartesian positions of the 30th–40th points are shown in Figs. 1b–d, where the lines represent A_i^j and the plus signs depict the new positions from the interpolation E_i^j. For the most part, the points are located near the storm track. However, for point $i = 37$, two dimensions show large differences between A_{37}^j and E_{37}^j. This resulted in the point having a large Z_{37} value, as depicted in Fig. 1e. Since the 37th point had a significantly large Z_{37} value the position was replaced with the mean E_{37}^j position. The result was no change in latitude and a change in longitude of 1.3° (asterisk in Fig. 1a). The method was tested against the HURDAT dataset, which arguably has better positional accuracy than other datasets resulting from significant reanalysis efforts (Landsea et al. 2004). For the HURDAT dataset, this algorithm resulted in no corrections to the tracks. Overall, there were only 148 corrections from the 400 000 storm-track positions from all forecast centers.

Another step in the position assessment was to search for tracks that were reported by multiple forecast centers to appear in the wrong hemisphere. For a given point on a track, the distances to concurrent latitudes and longitudes (ϕ, λ) from other tracks were calculated along with their mirror positions: $(-\phi, \lambda)$, $(\phi, -\lambda)$, and $(-\phi, -\lambda)$. When these distances were smaller than 111 km, storm tracks were manually checked and corrected. This technique resulted in finding 15 storms with at least a portion of their track in the wrong hemisphere (in all cases, the error occurred in a wrong notation of longitude resulting in a "mirror" about the date line).

Last, the time of each reported position was assessed. In some cases, reports from different forecast centers had similar positions for a storm with some offset in time. An algorithm compared the distances between reported positions from different centers. When the algorithm found shorter mean distances between reported positions by shifting (either forward or backward) the time for a center in an increment of 6 h, then the correction was kept in IBTrACS. The time-check algorithm, however, cannot objectively determine which center was reporting the correct time. Out of all 16 539 tracks in IBTrACS, 255 tracks required time adjustments.

b. Identifying unique storms

An automated algorithm was then developed that identified storms reported by multiple forecast centers

by sorting tracks temporally and spatially. Any tracks (from the same or different forecast centers) with at least two concurrent positions within 111 km were identified as one storm. Also, four track positions (equivalent to 1 day) were extrapolated beyond the end of the track to identify storms that were dropped by one center and picked up by another. Storms that crossed a geographic basin were identified as single storms regardless of the intermediate storm intensity as they crossed basin boundaries (though a cross-basin storm flag is provided in the final data).

Each storm position for the entire period of record is then shown in Fig. 2, color-coded by the number of centers tracking the storm. This provides an overview of the number of forecast centers providing information on any one storm. The North Atlantic is the only basin with one source of BT data (i.e., HURDAT). Conversely, storms in the western North Pacific were often tracked by as many as four centers. The Southern Hemisphere storms were less cohesive with any number of centers tracking each storm. Last, the northern Indian Ocean Basin is generally tracked by two centers: JTWC and IMD. Utilizing data through 2007, the result of the technique is that the 16 539 tracks provided by the forecast centers were identified as 7946 individual storms. Of these, 3732 storms were unique in that they were only reported by one center. The remaining 4214 storms were reported by more than one forecast center (Table 1). It is worth noting that differences between forecast centers remain even during a period with global satellite coverage (e.g., west Pacific forecast centers 1980–2005 in Table 1).

All individual storms were assigned a storm serial number that distinctively numbered the storm. This is important since multiple names can occur for any storm because of, for example, storms merging or crossing a basin boundary. The serial number contains information specific to the storm's genesis: calendar year, day of the year, hemisphere (north or south), and latitude and longitude. To help facilitate locating a specific storm in IBTrACS, a lookup table was produced that links the storm serial number to names of the storm from all centers tracking it.

c. Combining storm tracks

Once individual storms were identified, best track data were processed by combining time coordinates and by addressing storm positions and storm intensities via maximum sustained wind (MSW) and minimum central pressure (MCP).

In combining the time coordinate, the longest possible storm track was pieced together by using the first to the last position from all tracks for a storm. Since some BT
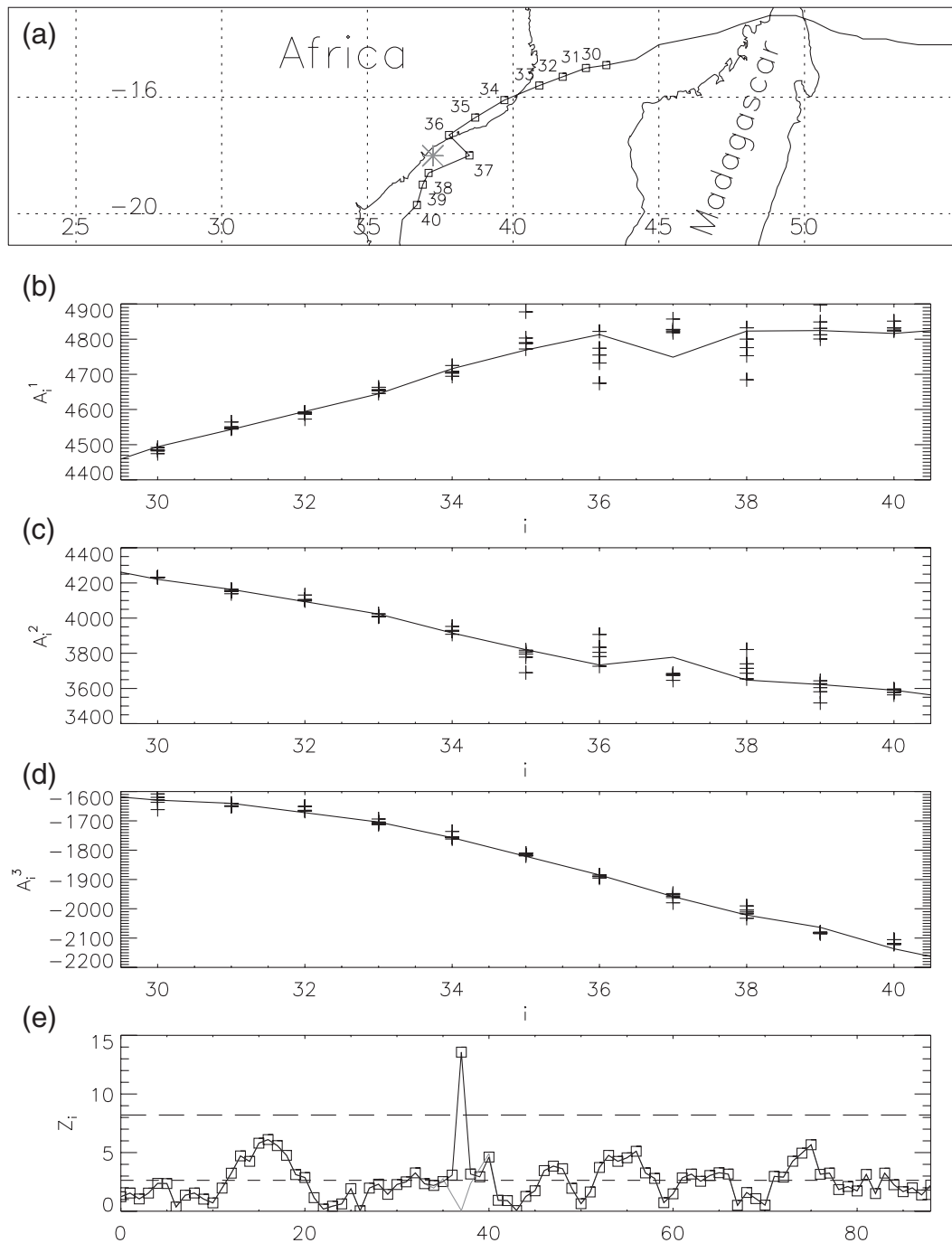
FIG. 1. (a) Track of 1968 Cyclone Georgette where the asterisk represents the replacement storm position at $i = 37$. (b) The A_i^1 (Cartesian coordinate) for the storm track (solid line), the $E_{i,k}^1$ position estimates based on interpolation by splines (plus signs). (c) Same as (b), but for A_i^2. (d) Same as (b), but for A_i^3. (e) The Z_i values for all points in the storm track with the mean Z_i (short dashed line) and three standard deviations above the mean Z_i (long dashed line).

data contained once-daily or 12-h reports, the time coordinates were normalized to 6 h prior to combining by interpolating the position with cubic-splines and holding intensity (MSW or MCP) constant during the time period (such that calculated indices would not vary between the daily and 6-h tracks). The 3732 storms unique to only one forecast center had no further adjustments.

For the remaining 4214 storms reported by multiple forecast centers, the IBTrACS position was the average position for each time step. An example of this is shown
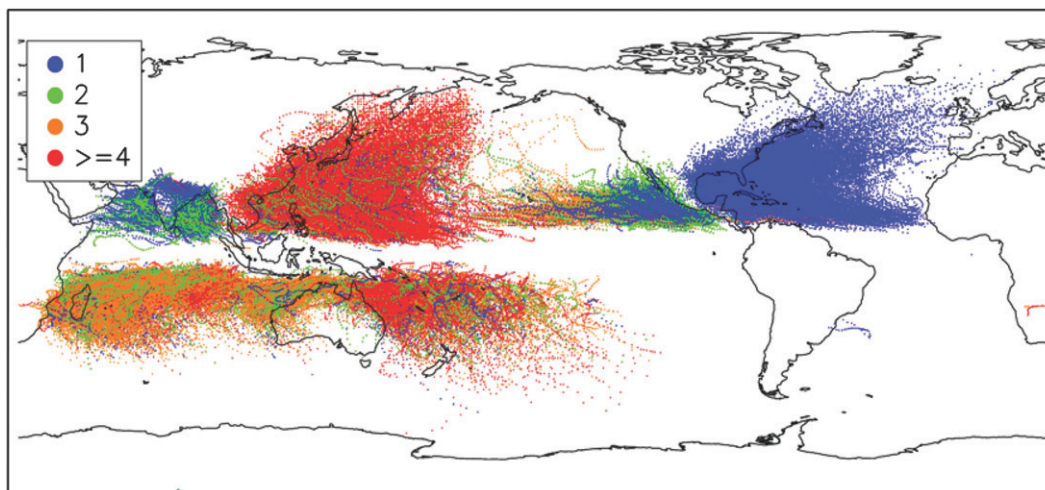
FIG. 2. Positions of all storms within the IBTrACS dataset where shading represents the number of centers providing information for the storm.

in Fig. 3a, where four forecast centers tracked Typhoon Clara in 1961 (HKO, JMA, JTWC, and STI). The first few storm positions are solely from JMA, so the IBTrACS positions in the early portion of the storm track were derived from the JMA data. Thereafter, the IBTrACS positions are the mean positions of the reported latitude and longitude coordinates from the four centers for each time step.

Tracks that merged with or split from the main storm track required special processing. For example, in Fig. 3b where the positions represented two separate storms

(1994 Typhoon Pat and 1994 Typhoon Ruth) prior to their merger, a mean position is not appropriate when the storms are still separate entities. An objective algorithm was developed to determine portions of the tracks that were, in fact, separate storms (e.g., prior to storm merger). In this instance, IBTrACS contains two storms: one track before and after the storm merger, termed the main, and another track that ends at the merge point, termed the spur. Storm splits were handled in a similar way with the spur occurring only after the split. Examples of storms identified as a storm merger and split are shown

TABLE 1. Summary of the BT data acquired from each source.

Center	Period of record[a]	No. of storms[b]	No. of storms 1980–2005	Storms unique to each center
NHC (North Atlantic)	1851–2007	1386	305	1381
NHC (east Pacific)	1949–2007	825	435	95
JTWC (east Pacific)	1949–2000	759	381	72
CPHC	1966–2003	166	121	21
JTWC (central Pacific)	1950–2002	47	28	1
JTWC (west Pacific)	1945–2007	1830	803	161
JMA	1951–2007	1515	686	6
STI	1949–2007	2048	812	304
HKO	1961–2007	1439	770	11
JTWC (Indian Ocean)	1945–2007	635	129	552
IMD	1990–2007	140	125[c]	59
JTWC (SH)	1945–2007	1795	733	196
Neumann	1960–2007	1375	765	9
BoM	1907–2007	864	293	183
FMS	1992–2008	101	86[c]	0
MSNZ	1968–2008	362	254	19
MFLR	1848–2008	1252	273	662

[a] The first year a storm is observed regardless of the completeness of the archive that particular year.
[b] Total number of storms provided in the best track files. This does not limit storm occurrence to some intensity threshold (e.g., hurricane strength).
[c] Period of record is a subset of the time period in this summary (1980–2005).
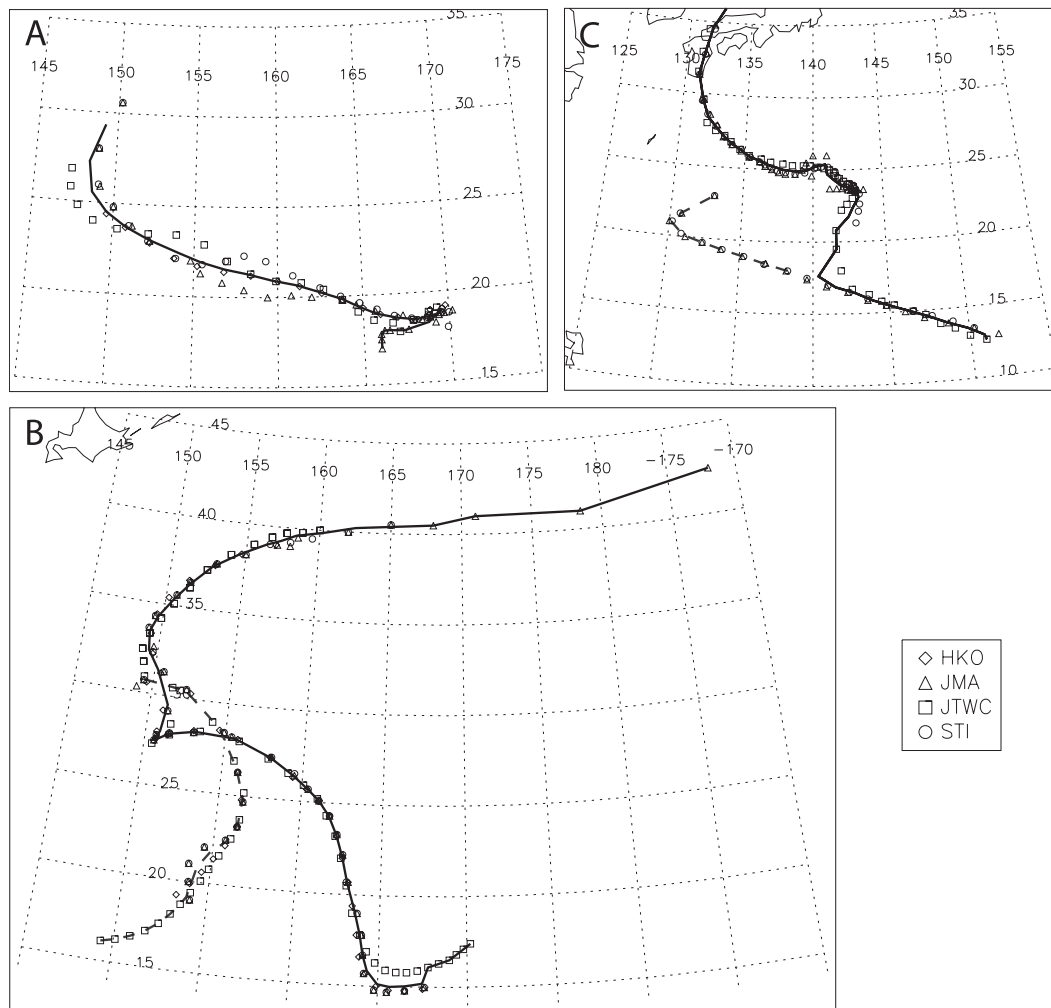
FIG. 3. Result of the IBTrACS algorithm to combine tracks for (a) 1961 Typhoon Clara tracked by four centers; (b) 1994 Typhoon Pat and 1994 Typhoon Ruth, which merged together; and (c) 1954 Typhoon Kathy, which split. Black lines are the main IBTrACS storms and dashed lines are the associated storms.

in Figs. 3b and 3c (respectively) with the main tracks depicted as solid lines and the spurs as dashed lines. In the algorithm, if two storm tracks differed by more than 111 km for five consecutive time steps (i.e., about 1 day), then that portion that differed was considered a separate track. The vast majority of storms consisted of main storm tracks with no separate tracks (94%).

4. Combining storm intensities

Centers report storm intensity differently from each other and many have periodically changed their operating procedures. Based on the data provided, in some instances only MCP was reported while in others only MSW was reported, and sometimes both. MCP data were combined based on the MCP as available from each agency. When multiple agencies report MCP, the MCP provided in IBTrACS is simply the average from each of the reporting agencies. Additionally, IBTrACS also provides the range in the MCP from each of the reporting centers' best track data.

The IBTrACS dataset production does not utilize known wind–pressure relationships (WPR) to fill gaps in MCP or MSW when either is missing. Values of wind and pressure are only provided in IBTrACS if they are reported in the source data. However, a future revision to IBTrACS could make use of WPR to 1) assess quality (i.e., are the winds from one center consistent with the pressure values from another?) and 2) report values when none are available (i.e., if no centers provide central pressure, derive it from the reported wind and WPR).

The process of combining MSW reports was more complex because of differences in wind speed averaging periods in use at each of the forecast centers.

The WMO standard for MSW is a 10-min average (WMO 1983), which is used at many of the forecast centers. Variations from the WMO standard include a 1-min average in use by the United States (JTWC, NHC, and CPHC), a 2-min average used at STI, and a 3-min average used at IMD. Converting between these wind speed periods has historically been done at agencies and must be accounted for prior to comparison, though the appropriateness of this practice has been questioned (Harper et al. 2008). Since a primary goal of the project was to produce a homogeneous best track dataset, all non-10-min winds (V) were normalized to the 10-min average (V_{10}) via

$$V_{10} = 0.88V. \qquad (4)$$

While several conversion factors exist (Harper et al. 2008), the factor 0.88 was chosen since it is the median of the values used by Neumann (1993: 0.87), and that used operationally at JTWC (0.88; Sampson et al. 1995), La Reunion (0.88), and HKO (0.9). The conversion of all basins' MSW to a 10-min average is also consistent with Neumann (1993) and allows for a globally consistent approach to tropical cyclone statistics. In the IBTrACS data, the reported wind is a 10-min sustained wind that is the mean of all available wind reports, although a statistical median, range, and standard deviation of wind speeds are also provided.

The appropriateness of Eq. (4) was assessed through an intercomparison of MSW from the four forecast centers in the western North Pacific: HKO, JMA, JTWC, and STI. The median ratio for 5-yr periods from 1945 through 2007 between STI and JTWC is shown in Fig. 4a, grouped by storm intensity [using the Saffir–Simpson Hurricane Scale (SS)]. The median ratio is similarly plotted for JMA versus JTWC (Fig. 4b) and HKO versus JTWC (Fig. 4c). In doing so, this compares centers using different wind speed averaging periods. It should be noted that complete analysis is not available with JMA since MSW began their BT data in 1977.

Three issues arise from these comparisons. First, the ratio in each comparison (Figs. 4a–c) shows a time dependence for the more intense TCs. The dip in the ratios (Figs. 4a–c) corresponds with the publication of Koba et al. (1990), who argued for a new relationship between satellite convective instability (CI) numbers (Dvorak 1975, 1984) and MSW for typhoons in the WP. There is also evidence of different and inconsistent applications of wind–pressure conversion factors at the JTWC when MCP estimates from aircraft reconnaissance were available prior to 1987 (Knaff and Sampson 2006; Knaff and Zehr 2007).

Second, the ratios are dependent upon the forecast center. Early ratios for HKO were near 0.9 (their reported conversion value from 1 min). Early ratios for STI were much higher and likely represent the unreported conversion used from 1-min Dvorak to 2-min intensities (which was found to be 0.972).

Third, the ratio is dependent upon MSW. The weakest storms appeared to be tracked at some minimum intensity (hence near constant ratio of 1.0 for HKO despite the significant change in ratio for stronger storms). Thus, wind speeds for weak systems are thought to represent the minimum reported wind speed to maintain tracking of the TC, rather than the wind speed associated with the actual surface circulation. Such a procedure is evident at other centers as well (Figs. 4a–c).

The time dependence of the ratios was checked by comparing HKO and JMA (Fig. 4d). Both centers use a 10-min period for MSW. The ratios were much closer to 1.0 for most time periods and storm intensities. Therefore, it appears that HKO made the switch in Dvorak analysis from Dvorak (1984) to Koba et al. (1990) coincident with JMA. This is consistent with the findings from Knaff and Zehr (2007).

In summary, the MSW from JMA and HKO were not converted because they are already 10-min winds. This assessment investigated the practicality of using 0.88 to convert 1-min winds at JTWC to 10 min. Similar results were found for the Southern Hemisphere agencies (not shown). Based on these initial conclusions, it is conceivable that the factor in Eq. (4) may not be appropriate for all times and forecast centers, however, until the operating procedures at each forecast center are fully documented, a more accurate conversion cannot be made.

5. Maximum wind speed and minimum central pressure quality assessments

Objective automated quality control algorithms were developed and incorporated for the MSW and MCP for each time step. Values that are caught through the following tests are not removed from the final IBTrACS dataset; rather they are flagged as failing the tests.

For the MSW, the bounds of rapid intensification (Kaplan and DeMaria 2003) were applied. Their bounds were modified to capture the most dramatic wind speed changes between neighboring 6-h time steps within a tropical cyclone, such that a wind speed increase–decrease of 30 kt in a 6-h time step would be flagged as a potentially bad value. For the NA, this test resulted in 16 flagged wind values in the period from 1950 through 2007, and 31 flagged wind values for the WP during the same time period.

The MSW quality assessment also included an upper-bound wind speed of 170 kt, chosen because a value beyond this would correspond to a CI number on the
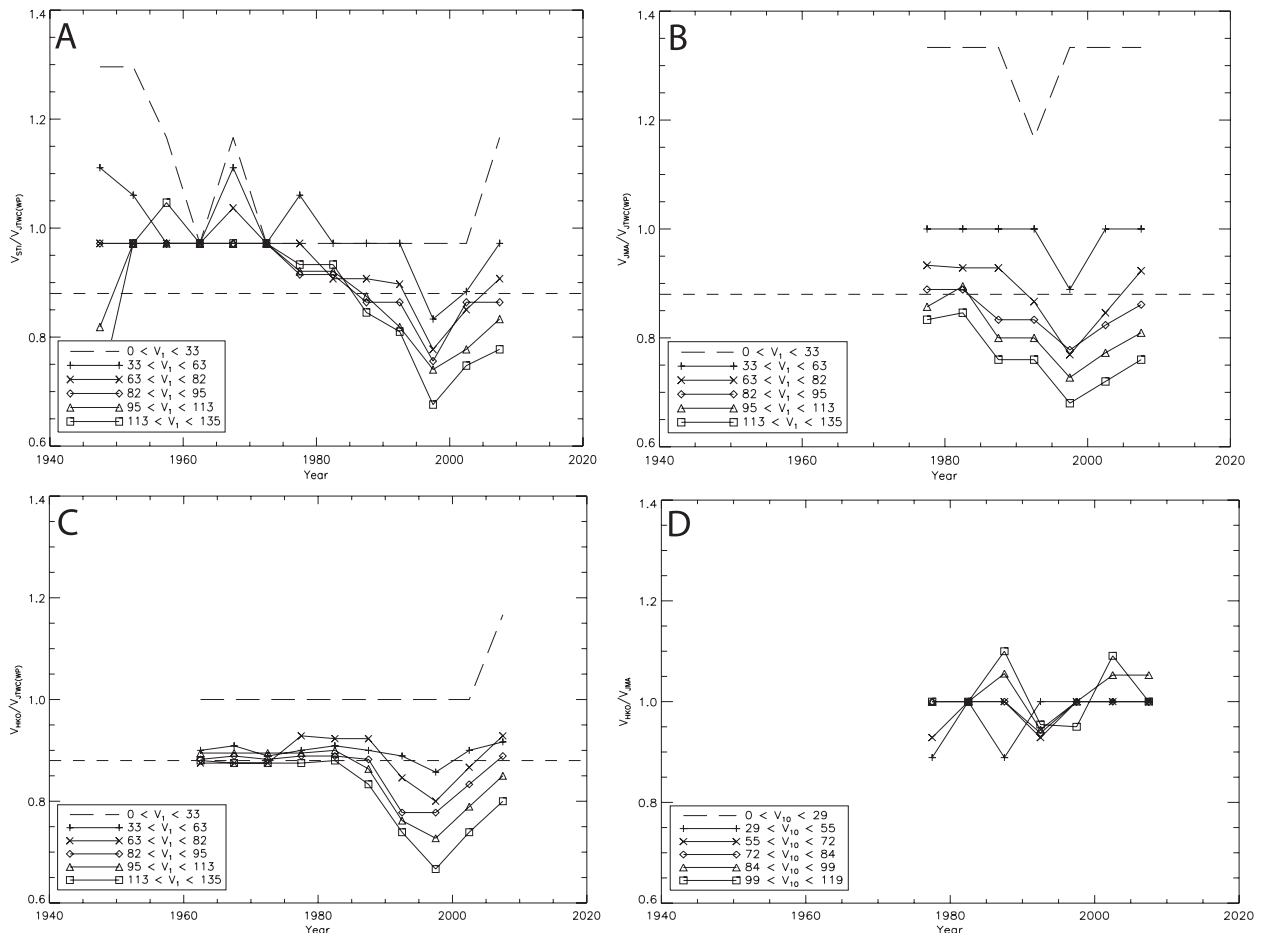
FIG. 4. MSW comparison for storms tracked by multiple centers in the western North Pacific Ocean. Comparisons are performed on the SS 1-min boundaries (kt) and perform in 5-yr increments for (a) STI vs JTWC, (b) JMA vs JTWC, (c) HKO vs JTWC, and (d) HKO vs JMA. The ratio shows large deviations from the nominal 0.88 (short dashed line) conversion value in Eq. (4).

Dvorak scale greater than the maximum of 8.0 (Velden et al. 2006). Surprisingly, this test resulted in a flagging of 88 values in the WP between the years of 1953 and 1979 (i.e., there were no reported winds above 170 kt prior to 1953 or after 1979).

Unlike MSW, combining the MCP data was facilitated by common definitions among the forecast centers. A threshold of 50 hPa was chosen to flag potentially large changes in pressure between neighboring 6-h time steps. This threshold generally corresponds to a change of about 2.0 T-numbers on the Dvorak intensity scale. Once again, using the NA and WP basins as examples for the period from 1950 to 2007, the test flagged only three and two values, respectively.

6. Results of combining storm data

The final version of the IBTrACS dataset contains 27 storm attributes and is provided in 7 different user-friendly formats: netCDF, Automated Tropical Cyclone Forecast (ATCF) format, HURDAT, cyclone extended markup language (cXML), WMO revised standard format, and comma separated values (CSV). IBTrACS is also provided via Web Feature Services and is able to be exported to keyhole markup language for use in such software as Google Earth (Knapp et al. 2009). However, not all storm attributes are available in each format because of the restrictive nature of some formats. For example, the 80-column HURDAT format limits 6-h storm attributes to only one position, MCP and MSW. Therefore, it is recommended that the user select a format of IBTrACS that retains all attributes unique to the dataset, including original MSW and MCP reports from each agency (i.e., netCDF or CSV).

Although IBTrACS is not a reanalysis, the inter-agency variability provides measures of the best track uncertainty. For basins with sufficient agency overlap, a summary of the intra-agency differences for position,
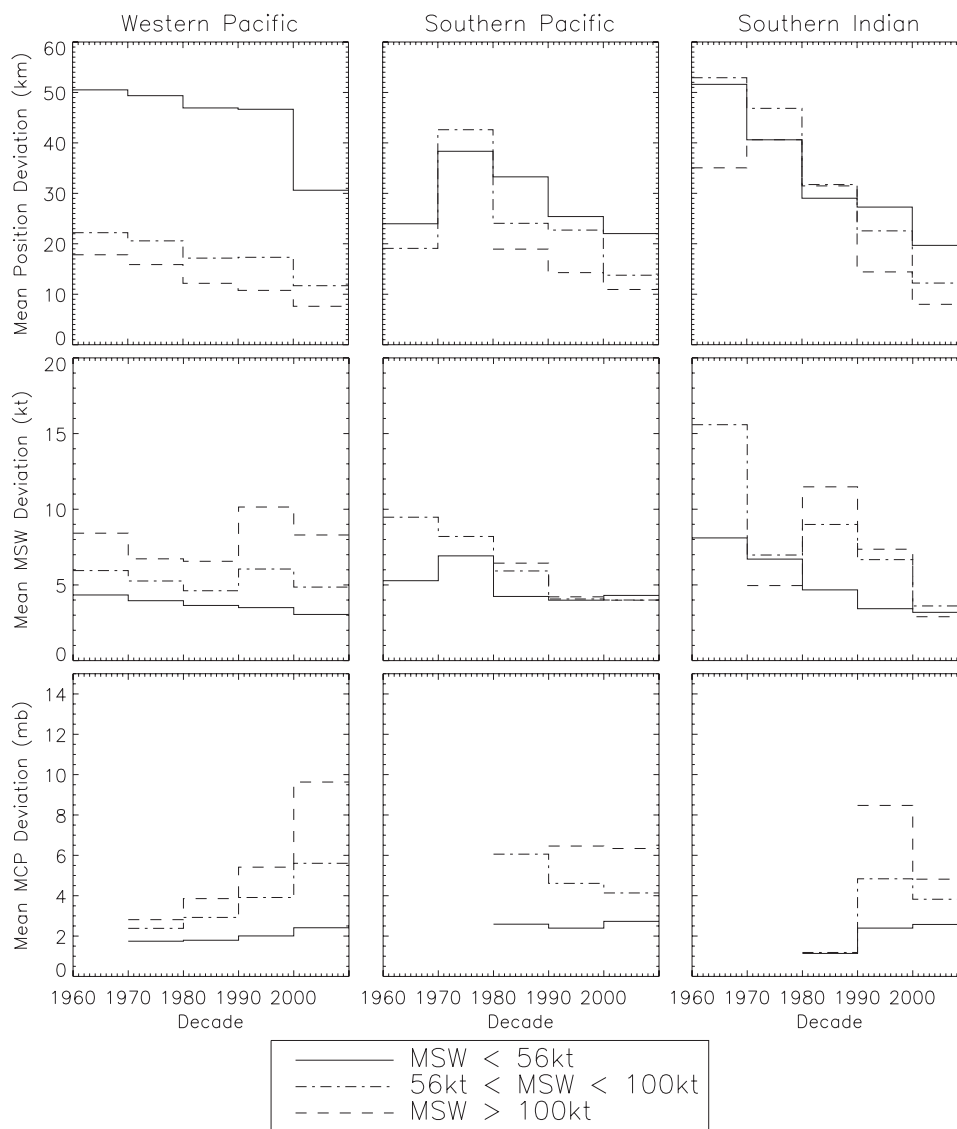
FIG. 5. Summary of mean differences between various data sources as they track the same storm for (top) position, (middle) MSW, and (bottom) MCP for the (left) WP basin, (middle) SP, and (right) SI. Differences are grouped by decade and by SS intensity ranges [where SS intensity winds have been converted to 10 min using Eq. (4)].

MSW, and MCP is shown in Fig. 5 by decade and storm intensity. The values shown are the mean intra-agency deviations for each decade, so they do not represent uncertainty ranges. The degrees of freedom in most cases are too small to construct confidence limits. These plots only show the tendencies of interagency differences in time and space and do not assess the overall quality of the best track data.

In light of such caveats, Fig. 5 does provide some insight into interagency differences. First, whether due to increased data availability or interagency communication, the various centers appear to be providing more congruent estimates of cyclone position. Since intense storms generally have an easily identified center of circulation (e.g., an eye), the variance of their position is less than that for weaker storms. The variance does have a lower limit, however, since BT data are reported only to tenths of degrees east or north, which results in a precision limited to ~10 km. Interestingly, all hurricane-strength storms ($V_{10} > 56$ kt) approach this lower limit in the most recent decade. Second, the variation in MSW is slowly decreasing. In general, differences are larger for cyclones with stronger winds. It should again be noted that the values, such as the convergence toward

TABLE 2. The number of tropical cyclones that are either SS category 4 or 5 ($V_{10} \geq 100$ kt) using the minimum and maximum MSW provided in IBTrACS.

| Ocean basin | 1966–86 | | 1987–2007 | |
	IBTrACS min	IBTrACS max	IBTrACS min	IBTrACS max
EP	35	36	57	59
WP	75	135	24	162
NA	16	16	37	37
SP	3	8	13	33
NI*	1	1	6	16
SI	12	26	34	74

* Since IMD digital data begin in 1990, only data from JTWC are available during the early period.

TABLE 3. Number of tropical storm–strength TCs ($V_{10} \geq 30$ kt) using only NHC and JTWC vs IBTrACS. Differences are noted parenthetically.

| Ocean basin | 1966–86 | | 1987–2007 | |
	NHC and JTWC	IBTrACS	NHC and JTWC	IBTrACS
EP	352	353 (+1)	349	349 (+0)
WP	569	607 (+38)	590	602 (+12)
NA	203	203 (+0)	267	267 (+0)
SP	223	258 (+35)	212	235 (+23)
NI*	62	62 (+0)	112	134 (+22)
SI	333	376 (+43)	345	370 (+25)

* Since IMD digital data begin in 1990, only data from JTWC are available during the early period.

5 kt in the South Pacific, do not represent the error of the data, but rather illustrate that the MSW data are becoming more consistent between the centers. Finally, and surprisingly, the MCP values are not generally converging. Instead, the values are diverging, especially in the western North Pacific. It is hypothesized that such a divergence over the last several decades may be linked to the cessation of aircraft reconnaissance in the 1980s. Unlike wind speed, which showed decreasing interagency disparities, the pressure values in Fig. 5 show little to no agreement between the agencies. Clearly, the IBTrACS dataset is useful for position estimation (particularly in later years), but the interagency differences in MSW and MCP warrant further investigation.

The variation of MSW among forecast centers tracking the storm affects basin-wide TC counts. Table 2 demonstrates this by counting the number of Saffir–Simpson category 4 and 5 storms in IBTrACS using the minimum and maximum reported MSW for each storm summed over each basin for two 21-yr periods (1966–86 and 1987–2007). As expected, the EP and NA counts from the IBTrACS dataset for these two periods are nearly identical to those obtained from the HURDAT dataset. However, there are significant differences in the WP where tropical cyclones are frequently tracked by more than one forecast center. It is important to note that the JTWC may have a high bias in their MSW (Wu et al. 2006; Hui et al. 2007). Historically, however, the JTWC may have also biased low in their estimation of MSW during the period 1974–87 (Knaff and Sampson 2006; Knaff and Zehr 2007). Thus, some reanalysis or adjustment to their BT data is likely needed (Hoarau et al. 2006; Lander and Guard 2006). Yet, beyond the availability of a global-scale reanalysis of all tropical cyclone intensities, few options exist outside the utilization of a simple mean of the MSW estimates.

Finally, to verify that the IBTrACS dataset contains all potential named tropical cyclones (i.e., those storms with $V_{10} \geq 30$ kt), tropical cyclone counts were totaled and compared with the more widely used combination of BT data from the NHC and the JTWC (Table 3). In the WP, where most researchers simply use data from the JTWC, the IBTrACS dataset contained 38 additional named storms in the early part of the record (1966–86) and another 12 named storms during the period 1987–2007. In addition, more than 20 named storms were captured, in both periods, in the IBTrACS dataset for the southwest Pacific basin that would have presumably been lost for those exclusively using the JTWC best track data. A substantial increase also holds for the southern Indian Ocean Basin where an additional 43 named storms were captured in the first 21-yr period, and 25 additional storms were identified in the second 21-yr period. In all, nearly 200 storms with winds greater than or equal to 30 kt (10 min), of which 25 were greater than 56 kt, are missed when limiting a global analysis to one data source.

7. Conclusions

The techniques described above represent an initial step toward combining best track data from disparate sources that results in a new global tropical cyclone best track dataset compilation—the International Best Track Archive for Climate Stewardship (IBTrACS). The data provided in IBTrACS are the positions and intensities (via minimum central pressure and/or maximum sustained wind) of each storm available from each of the data sources (see section 2 for a complete list) and were derived using quality assessments. In the process of combining the data from each of the forecast centers, statistics were calculated to provide information on the variations in position and intensities. Also, prior to combining the best track data, quality assessments of the position and intensity were made. While some gross position errors were corrected, all original pressure and

wind values are retained in the final data along with a quality assessment flag. Rather than preferentially selecting data from a single forecast center to define a storm, the IBTrACS positions and intensities are simply the average position and intensity from all available reports. One advantage the IBTrACS dataset has over other available best track data is that it provides the full range of reported values for pressure, intensity, and position, for each 6-h time step from the reporting agencies. In addition, the final dataset is available in seven different formats and users can select either one of the formatted versions or the original unedited data as received from each of the forecast centers including regional RSMCs.

It has been demonstrated herein that limiting tropical cyclone analysis to a subset of the sources will miss some cyclones. Therefore, when creating a comprehensive global tropical cyclone best track dataset, it is imperative that best track data be included from all forecast centers. Future versions of IBTrACS will incorporate other data sources when possible. Also, a global reanalysis, such as has been performed in the North Atlantic to identify previously missed cyclones (Fernandez-Partagas and Diaz 1996), should be conducted to remove ambiguity when centers disagree on cyclone intensities or positions.

There are, however, improvements to the existing IBTrACS best track record that could be made. Presently, the IBTrACS dataset only reports MSW and MCP. However, other parameters are available from some agencies that could be included in IBTrACS, such as the radius of maximum winds (RMW), radius of outermost closed isobar (ROCI), and intensity at landfall. This would presumably be of great value to more users, especially those that require detailed statistics or climatologies on coastal storm surge impacts, near-shore wave modeling, evacuation routes, etc.

Finally, a future version of IBTrACS could explore a more appropriate wind speed conversion factor. The current factor of 0.88 may be suitable, but the operating procedures at each forecast center need to be fully documented to understand what was actually used.

Such enhancements to IBTrACS could set the stage for a more thorough and complete global reanalysis of tropical cyclones.

The freely available dataset can be downloaded online (http://www.ncdc.noaa.gov/oa/ibtracs/).

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