THE INTERNATIONAL BEST TRACK ARCHIVE FOR CLIMATE STEWARDSHIP (IBTrACS)

Unifying Tropical Cyclone Data

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In combining track and intensity estimates from many sources, this centralized collection of tropical cyclone data provides a more complete global climatology and insight into the data uncertainty—a critical consideration for climate trending.

Given the significant impact of tropical cyclones (TCs) on human life, property, and ecology, it is understandable that much research has gone into understanding their distribution, frequency, and intensity around the world and how climate change might affect these parameters (e.g., CCSP 2008; Chan 2006, 2005a; Klotzbach 2006; Landsea 2005; Webster et al. 2005). Many storm characteristics help to define how an individual storm impacts life and property, such as maximum sustained wind (MSW), the distance at which various wind speeds extend outward from the storm center, rainfall patterns, minimum sea level pressure (MSLP), and storm translation speed. Despite the many facets of a storm, much of the tropical cyclone data worldwide consists of the best estimates of storm position and intensity at 6-hourly intervals only, which are termed best-track data.

Optimally, best-track data are the result of postseason reanalysis of a storm's position[1] and intensity from all available data—for example, ship, surface, and satellite observations (although the level of reanalysis will vary by agency). However, with advances in observing system technologies, operational procedures, and scientific knowledge, the historical record of best tracks is inhomogeneous by construction. Despite the obvious need, there has been typically little to no reanalysis of best-track data based on new understanding. However, efforts are underway in the North Atlantic (Landsea et al. 2008) and the South Indian Oceans (Levinson et al. 2010, hereafter LDK) to ▶

[1] From the National Hurricane Center Online Glossary, best-track data are "a subjectively-smoothed representation of a tropical cyclone's location and intensity over its lifetime…" and "… generally will not reflect the erratic motion implied by connecting individual center fix positions." Given this subjectivity, the amount of spatial smoothing will also vary among agencies.

Punch cards were once used to encode the earliest hurricane datasets. See the sidebar "A brief history of global tropical cyclone best-track data" on p. 365 for more information.

do such a reanalysis. Each of the World Meteorological Organization (WMO) Regional Specialized Meteorological Centers (RSMCs) and Tropical Cyclone Warning Centres (TCWCs), as well as other national agencies, compile and archive best-track data. The following datasets are the current sources for International Best Track Archive for Climate Stewardship (IBTrACS) best-track position and intensity:

- Australian Bureau of Meteorology (BOM) (as TCWC Perth, Darwin, Brisbane)
- Fiji Meteorological Service (as RSMC Nadi)
- India Meteorological Department (as RSMC New Delhi)
- Japan Meteorological Agency (as RSMC Tokyo)
- Météo-France (as RSMC La Reunion)
- Meteorological Service of New Zealand, Ltd. (as TCWC Wellington)
- U.S. National Oceanic and Atmospheric Administration's (NOAA's) Central Pacific Hurricane Center (as RSMC Honolulu)
- NOAA's National Hurricane Center (NHC, as RSMC Miami)
- China Meteorological Administration's Shanghai Typhoon Institute (CMA/STI)
- Hong Kong Observatory (HKO)
- U.S. Department of Defense Joint Typhoon Warning Center (JTWC)
- C. Neumann's Southern Hemisphere data (Neumann 1999)[2]

This list is not exhaustive; for example, proprietary best-track collections exist but are not available to the public. Furthermore, other agencies compile best-track data that can be included as their data are made available to the project.

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In recent decades, best-track data were used to assess the interannual and interdecadal variability of tropical cyclones and their relation to global climate change. The sidebar to this article summarizes some historical global best-track data collections, of which only a few are presently maintained and publicly available on a global scale. Given the limited data available, many researchers develop their own global climatology from various sources. A sample of peer-reviewed literature addressing tropical cyclones since 1996 is provided in Table 1. Papers that focus solely on the North Atlantic basin are not included because only one source of best-track data is available: the Atlantic Hurricane Database (HURDAT) from RSMC Miami (Jarvinen et al. 1984). As is evident from Table 1, data from HURDAT and JTWC (Chu et al. 2002) are most often used in constructing a global climatology of tropical cyclones. A handful of papers analyzing the observed variability in the western Pacific include other sources. No papers in the peer-reviewed literature use data from all available RSMCs.

In conjunction with other datasets, global best-track data are crucial for understanding the characteristics and impacts of tropical cyclones. For instance, best-track data have been used to extract tropical cyclone satellite brightness temperatures (Knapp and Kossin 2007) toward reconstructing an objective analysis of historical tropical cyclone activity (Kossin et al. 2007). Similarly, collocation of best-track data with satellite precipitation data have been used to investigate changes in extreme rainfall from tropical cyclones (Lau et al. 2008). Such studies are inherently dependent on the completeness of a global tropical cyclone best-track dataset.

Therefore, NOAA's National Climatic Data Center (NCDC), in concert with the World Data Center for Meteorology—Asheville, has developed a comprehensive dataset through the collection of global tropical cyclone best-track data. The goal was to inventory reported tropical cyclones worldwide and their characteristics and to provide the data as one global dataset: the International Best Track Archive for Climate Stewardship (Knapp et al. 2009).

Although IBTrACS is a logical extension of previous work carried out at NOAA's NCDC (Crutcher and Quayle 1974; Neumann 1999; etc.), we 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 (Fernandez-Partagas and Diaz 1996; Landsea et al.

[2] Data from C. Neumann were included here because he incorporated other data sources not listed above.

A BRIEF HISTORY OF GLOBAL TROPICAL CYCLONE BEST-TRACK DATA

Over the years, tropical cyclone landfalls have caused government, military, religious, and private groups to study tropical cyclones and to mitigate their effects.[1] In particular, because of the destructive impact of some storms on seafaring and the coastal zone, fragmented records of tropical cyclones extend back thousands of years (e.g., Emanuel 2005a). Tropical cyclone track information in the form of maps was first collected in mariner's logs (e.g., Chin 1972) to aid the understanding of typical tropical cyclone movement. Much like the mariner's logs, records of noteworthy tropical cyclone events are available from a number of sources. Ludlum (1963), for example, discusses early North Atlantic hurricanes, and Shaw (1997) does likewise for the central North Pacific. In 1944 and 1945, during World War II, the U.S. Navy had disastrous encounters with typhoons in the western Pacific (Adamson and Kosco 1967). These events led to the establishment of dedicated U.S. Navy aircraft reconnaissance in 1946 and improved documentation of tropical cyclones.

With the start of the mainframe computer age, NOAA's NCDC used decks of punch cards to store tropical cyclone information for various global basins compiled from storm reports and mariner's logs. Initially, these decks consisted of one tropical cyclone position per card and were difficult to work with (Fig. SB1). Most international agencies provided tropical cyclone intensity data in terms of codes[2] and only once per day. Moreover, India used different wind thresholds for each tropical cyclone stage and sustained wind averaging times were sometimes uncertain. Nevertheless, Crutcher and Quayle (1974) were able to use these decks to produce a global tropical cyclone climatology for the U.S. Navy. The decks were also a precursor to the development of NOAA's NCDC dataset 9636, which has been used by many researchers (e.g., Cooper and Forristall 1997; Hartmann et al. 1992; Walsh and Watterson 1997; Walsh and Katzfey 2000). The dataset, however, is no longer actively maintained.

Early uses of tropical cyclone climatologies included military (e.g., ship routing) and civilian (e.g., engineering design criteria and risk assessment) needs. In the United States, concerns about space launch and recovery led to the development of the Hurricane Analog (HURRAN; Hope and Neumann 1970) prediction system, which used a more efficient punch card format that eventually became the HURDAT format [which should not to be confused with the Atlantic Hurricane Database reanalysis *project*, which is described by Landsea et al. (2004)]. The revised card format stored four records of position and intensity per card (rather than one), allowing one day of data (at 6-h intervals) per card. While 80-column punch cards have become obsolete, the HURDAT format is still in use by many today. For HURRAN, tropical cyclone data were obtained from a number of sources including NCDC, local NHC records, and digitized tracks taken from Cry (1965). Further collaboration with scientists visiting the NHC led to HURDAT-like collections for other ocean basins (e.g., Neumann and Randrianarison 1976; Neumann and Mandal 1978; Xue and Neumann 1984). C. Neumann continues to maintain these global datasets in the HURDAT format. For a number of years, C. Neumann has supplied his global dataset and updates thereto to numerous individuals or groups at their request, who no doubt passed the data on to others. Some of these datasets have become proprietary. Thus, it would appear that global datasets in the HURDAT format originated with C. Neumann. For example, C. Neumann's best-track dataset is a precursor to the University Corporation for Atmospheric Research (UCAR) dataset 824.1, which has been used in modeling studies (e.g., Knutson et al. 1998).

More recently, the Global Tropical and Extratropical Cyclone Climate Atlas (GTECCA) was compiled jointly by the U.S. Navy and NCDC in 1994 using NCDC data as well as HURDAT and JTWC as source data. This was initially available as a computer program on CD-ROM. It also has been used in a variety of climate research (Henderson-Sellers et al. 1998; Lander and Guard 1998; Tonkin et al. 2000; Walsh 1997).

[1] For a discussion of the history of Australian tropical cyclones, see Harper et al. (2008b).

[2] 1 = tropical depression; 2 = tropical storm; 3 = hurricane.

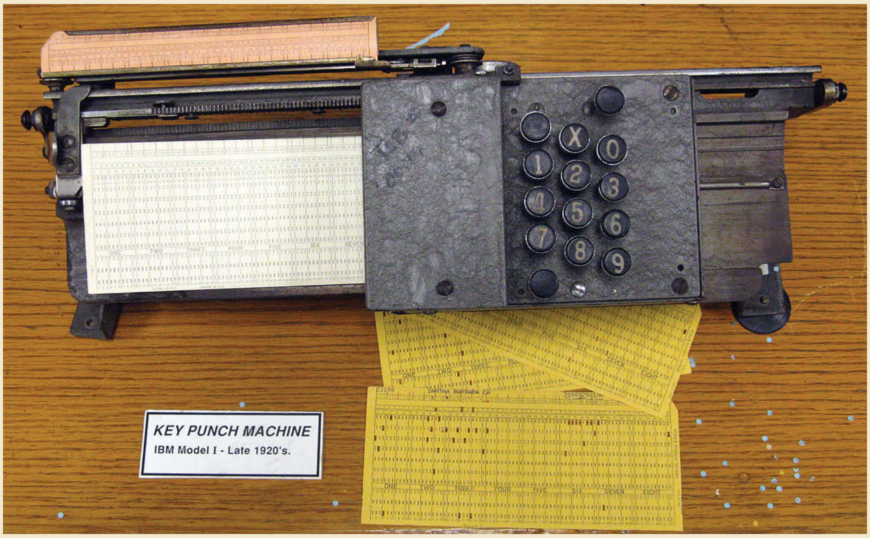

Fig. SB1. Key punch machine (circa 1920) and punch cards similar to those used to encode the earliest hurricane datasets. The NCDC format encoded one report of position, MSW, MSLP, and other information on each card. The more efficient HURDAT format stored four reports (thus, one day of 6-h data) per card. (Photo courtesy of NOAA/NCDC.)

Table 1. Sources of best-track data used in IBTrACS and in recent tropical cyclone climatology research.

Paper	Target	Source of best tracks											
		RSMC Miami	RSMC Honolulu	JTWC	RSMC Tokyo	CMA/STI	HKO	C. Neumann	BOM	RSMC La Reunion	TCWC Wellington	RSMC Nadi	RSMC New Delhi
(Chan and Shi 1996)	WP			X									
(Henderson-Sellers et al. 1998)	Global	X		X									
(Lander and Guard 1998)	Global	X		X									
(Emanuel 2000)	NA/WP	X		X									
(Emanuel 2005b)	Global	X		X									
(Webster et al. 2005)	Global	X		X				X					
(Chan 2006)	WP			X									
(Wu et al. 2006)	WP			X	X		X						
(Klotzbach 2006)	Global	X		X				X					
(Hui et al. 2007)	WP			X	X	X							
(Knaff and Zehr 2007)	Global	X		X									
(Kossin et al. 2007)	Global	X		X									
(Harper et al. 2008b)	SI							X	X				
(Kuleshov et al. 2008)	SH								X	X	X		
(Lau et al. 2008)	NA/WP	X		X									
(Lowry et al. 2008)	WP			X	X	X	X						
(Wang et al. 2008)	WP			X		X							
IBTrACS	Global	X	X	X	X	X	X	X	X	X	X	X	X

2004). Thus, IBTrACS is not a reanalysis; rather, it provides a collation of currently available best-track data from agencies worldwide.

COMBINING BEST-TRACK DATA. Best-track data from each of the agencies listed above were obtained either directly from agency Web sites or via personal communication. This effort included sending formal letters to each agency seeking their permission to distribute their data as part of IBTrACS, to which all agreed. In addition, consultation with the WMO's Tropical Cyclone Programme was undertaken to ensure that IBTrACS was consistent with their goals, as well as to give each agency some assurance that participating in the IBTrACS effort was a sustainable and worthwhile activity. The result is that numerous agencies supply data and support this effort.

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

When combining data from various agencies, numerous issues arise (see descriptions in Neumann 1993, 1999). The complexity of these issues is likely the primary driver for researchers to limit their dataset sources to the fewest agencies that provide a global picture. While other methods to merge data are conceivable, the development of IBTrACS represents a step toward a homogenized global dataset.

The following is a summary of the techniques used in combining best-track data to derive IBTrACS [a more detailed description of the process can be found in Kruk et al. (2010)].

The first step in combining best-track data is to identify each storm uniquely—that is, which storms reported from one agency were also reported by another. This was done through comparisons of each storm's position in space and time using an algorithm that also accounted for possible errors in longitude (i.e., wrong sign when a storm crossed the dateline) or time (such as when a storm was reported by two agencies with a 1-day offset between their respective times). Identifying unique storms is important even when using data from only one agency; failing to account for unique storms may result in erroneous statistics.

Often, there are large variations in reported positions for weak storms whose centers of circulation were difficult to diagnose. In some cases, the differences in positions were so great (e.g., more than 100 km) that portions of the storm track were denoted in IBTrACS as alternate tracks. Furthermore, issues arise when two storms merge into one circulation, albeit a rare event. In these instances, the IBTrACS path of a single storm ends at the merge point while the other track continues until the storm dissipates.

The next step was to combine intensity estimates. There is a common definition of MSLP among all forecast agencies, which made the combinations straightforward. However, there is an inherent difference in the definition of MSW between various agencies, which complicates a direct comparison. According to the WMO (1983), the maximum sustained wind is a 10-min average wind speed at 10-m height above level ground. In spite of a WMO standard, various agencies use different averaging periods that include 1-, 2-, 3-, and 10-min averages. Conversion to a common averaging period is necessary before the MSW can be compared between agencies. For IBTrACS, MSW values were converted to a 10-min period (V_{10}). While various theoretical conversion factors exist (Harper et al. 2008a), the principal need reduces to converting between 10- and 1-min estimates. The ratio of 10 min to 1 min used by IBTrACS is 0.88, which has also been used operationally (e.g., RSMC La Reunion, JTWC, BOM TCWCs). This assumption is itself a source of some uncertainty given that (historical practice notwithstanding) recent recommendations to WMO suggest a ratio of 0.93 for the storm MSW in open-sea conditions (Harper et al. 2008a).

IBTrACS provides MSW in numerous ways given the complications of combining MSW. First, IBTrACS provides the original MSW and MSLP values as reported by each agency. This allows users to choose their own method of combining MSW or MSLP or to preferentially select one agency and facilitate interagency comparisons. In addition, the mean, maximum, minimum, and standard deviation of MSLP and MSW from all agencies are also provided purely as summary parameters. Providing an average value allows the data to be served in formats already in use by the tropical cyclone community, many of which restrict TC intensity to one value of MSLP and MSW.

It is important to note that the mean MSW as provided in IBTrACS should not be used as the final value, or the "best" of the best-track estimates. First, it is against the consensus of the agencies themselves, who recommended that the mean MSW not be used but stopped short of providing an alternative to the mean (LDK). Second, it combines estimates of MSW based largely on different operational procedures that are yet to be documented (that is, a better correction may be possible once best-tracking procedures are documented). Thus, until a complete reanalysis is made of global tropical cyclones or operating procedures are more completely documented, the IBTrACS project will continue to provide a mean MSW as a summary statistic. In the meantime, the IBTrACS project strongly urges users to examine the raw data from each agency.

To illustrate the complexities associated with combining data from multiple sources, the process is shown for 1992 Typhoon Yvette in Fig. 1, which had four data sources: JTWC, CMA/STI, HKO, and RSMC Tokyo. Yvette is a storm with significant disagreement of intensities among agencies. In Figure 1a, the plus symbols in the inset represent the individual 6-h positions during a portion of the typhoon track and the red dots mark the IBTrACS position. The yellow shading in Fig. 1b shows the range in the MSLP estimates from each agency. The mean MSLP at each time is shown by the red line in Fig. 1b along with the individual agency reports (black lines). Similarly, the mean MSW is shown along with the individual reports in Fig. 1c. The lower (upper) bound of the yellow shading is the minimum (maximum) MSW, MSW_{min} (MSW_{max}), at each time.

A tropical cyclone is often categorized by its peak intensity. For example, the Saffir–Simpson Hurricane Scale (SSHS; Simpson 1974) is used in the North Atlantic and east Pacific and is used herein merely for illustrative purposes (after converting wind speed thresholds to an equivalent 10-min period). The converted SSHS does not necessarily align with tropical cyclone intensity scales used by other agencies. The

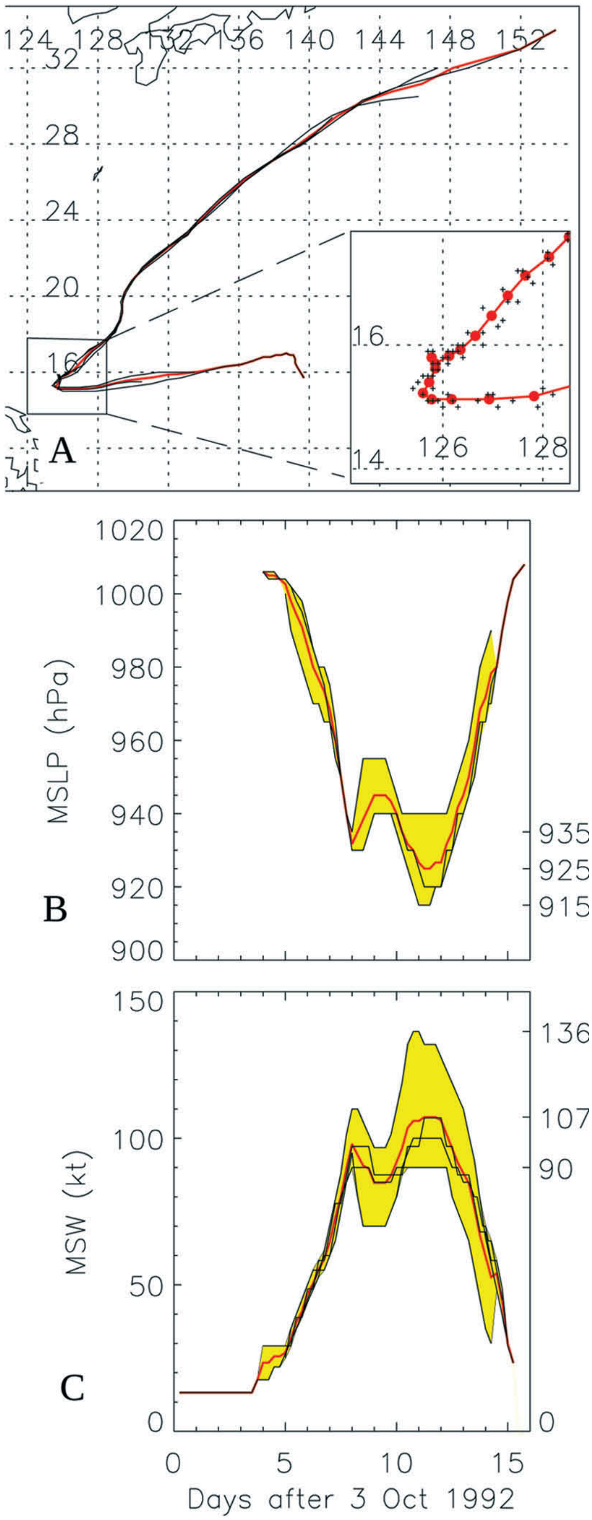

FIG. 1. (a) Tracks of 1992 Typhoon Yvette in the western North Pacific (14°–32°N, 124°–152°W) from various agencies (black) and from IBTrACS (red). Time series of (b) MSLP and (c) MSW for Yvette from various agencies are shown in black with the mean value in red (after converting MSW to 10 min). Shading represents the span of the values from the agencies.

resulting SSHS category of Typhoon Yvette depends on the dataset used. The highest MSW based on the mean of all agencies is 107 kt, which corresponds to a SSHS category 4. Taking into account the full range of MSW_{max} and MSW_{min}, Yvette could have been as weak as an SSHS category 3 (90 kt) or as strong as an SSHS category 5 (136 kt).

IBTRACS DATASET. Table 2 summarizes the various parameters provided in the IBTrACS dataset at 6-h intervals; in all, the IBTrACS dataset contains 27 storm attributes in seven different basins: the North Atlantic (NA), eastern Pacific (EP), western North Pacific (WP), northern Indian Ocean (NI), southern Indian Ocean (SI), South Pacific (SP), and South Atlantic (SA). Furthermore, IBTrACS is provided in several formats: netCDF, Automated Tropical Cyclone Forecast (ATCF), HURDAT, cyclone extended markup language (cXML), the WMO revised standard format, and comma-separated values (CSV). IBTrACS is also provided via Web Feature Services, which allows the import of the data into geospatial software and export 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, MSLP, and MSW. Thus, the remaining parameters listed in Table 2 are not provided in the HURDAT format (or other formats, including ATCF, WMO, and cXML). Therefore, the IBTrACS project strongly urges users to obtain the dataset in netCDF or CSV formats, which retain each agency's original MSW and MSLP reports and other attributes unique to IBTrACS.

The IBTrACS period of record by basin is provided in Fig. 2. Data for some basins are available from as early as 1848. After combining data from available agencies, the resulting IBTrACS dataset can be used to describe the climatology of global tropical cyclones, at least since global records began in 1945. Furthermore, an analysis of interagency variability is possible given the unique aspects of the IBTrACS data.

Global tropical cyclone climatology. All storm tracks for years 1979 through 2007 are shown in Fig. 3a and are color coded by 10-min MSW SSHS category. This shows the global extent of recent tropical cyclones and the portions of the world where they occur.[3] While

[3] The tracks include that of Hurricane Catarina (2004), a rare South Atlantic tropical cyclone (McTaggart-Cowan et al. 2006).

Table 2. Summary of parameters available from the IBTrACS dataset.			
Position (latitude/longitude)	**Wind (MSW)**	**Pressure (MSLP)**	**Other**
Original positions	Original MSW	Original MSLP	Basin
Number of agencies	Number of agencies	Number of agencies	Storm nature
Mean	Mean	Mean	Storm season
Standard deviation	Standard deviation	Standard deviation	
	Maximum	Maximum	
	Minimum	Minimum	
	Median		

Fig. 3a depicts tropical cyclone tracks, it does not describe the observed frequency or mean intensity at any location. Thus, in Fig. 3b, IBTrACS positions were interpolated along where the storm path was and expanded to a width of 1° latitude (111 km), the result of which represents the frequency of a tropical cyclone passing within 55 km of any point (although changing the distance appears to affect the resulting frequencies; cf. Neumann 1993). For consistency between basins, the analysis in Fig. 3b was limited to 1945–2007. The highest concentration of storms exists in the WP basin, where the peak frequency is more than 30 storms occurring per decade (i.e., three storms per year near a grid point). A secondary peak in frequency appears in the EP, where more than 20 storms occur per decade. The NI basin also has a maximum of 20 storms per decade in the Bay of Bengal. The remaining basins have lower frequencies, with the maxima near 10 per decade in the SI and 5 per decade in the NA and SP basins.

Using the agency mean MSW, the maximum MSW of all storms passing near a grid point on the globe is shown in Fig. 4a, whereas the mean MSW is depicted in Fig. 4b. The highest mean MSW is just east of the Asian continent. Although the mean MSW in the NA is not as concentrated as in the WP, its areal extent of mean MSW greater than 45 kt is much larger than any other basin. In the Southern Hemisphere, the winds tend to be strongest near the twentieth parallel in both the SI and SP basins. Although these parameters were derived from IBTrACS, it is important to recognize that the dataset provides many of the same parameters available from other historic best-track compilations (e.g., Neumann 1993).

Given the prevailing tendency of researchers to use a combination of HURDAT and JTWC as a global climatology (cf. Table 1), it is necessary to illustrate how IBTrACS differs. IBTrACS storms that are not in either HURDAT or JTWC are shown in Fig. 5 for 1979–2007. Not surprisingly, IBTrACS has no new storms in the NA or EP basins because the primary data source in those basins is HURDAT. Conversely, numerous storms were reported by other agencies in the WP, SP, and SI basins. For this period, there are 109 named storms that are not provided by either HURDAT or JTWC, 5 of which are typhoon intensity (10-min MSW > 56 kt). This could be due to numerous reasons (e.g., differences in analyzed intensity or operational procedures). Until a global reanalysis of tropical cyclones is made, these candidate storms should be included in studies. Therefore, even in recent decades IBTrACS provides a more complete picture of the number of tropical cyclones worldwide, which could potentially influence the results from some recent climate analyses.

Interagency variability based on IBTrACS. IBTrACS also provides the variability of MSLP and MSW between the available agencies. Rather than preferentially selecting data from a single agency to define a storm, data in IBTrACS are a combination of all available reports. The mean range in MSW shown in Fig. 6a is

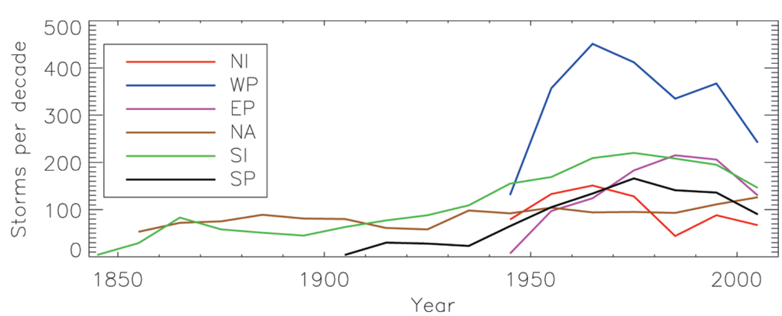

Fig. 2. Inventory of storms per decade sorted by genesis basin: the North Indian (NI), West Pacific (WP), East Pacific (EP), North Atlantic (NA), South Indian (SI) and South Pacific (SP) oceans.

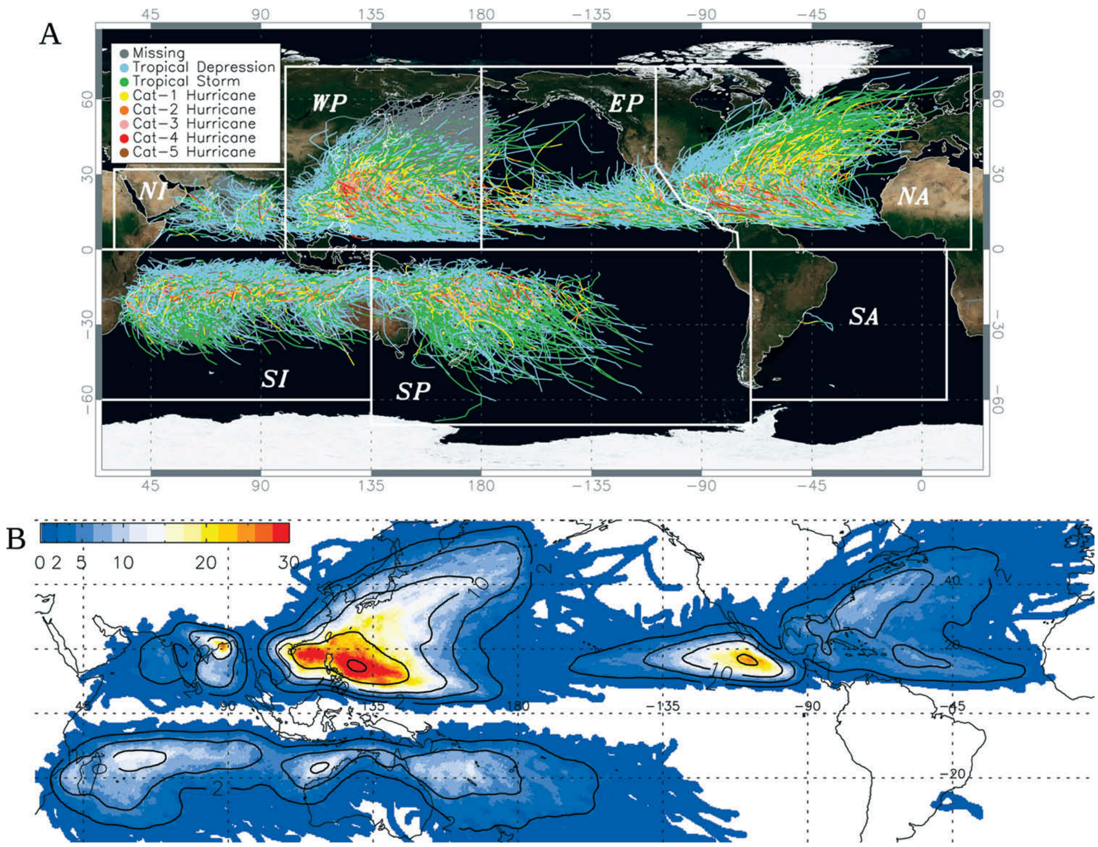

Fig. 3. (a) All IBTrACS storm tracks (1979–2007) colored by their SSHS category (where "missing" indicates MSW was not reported) and (b) frequency of storms within 55 km of any point for 1945–2007 from IBTrACS contoured at 2, 5, 10, 20, and 30 storms per decade.

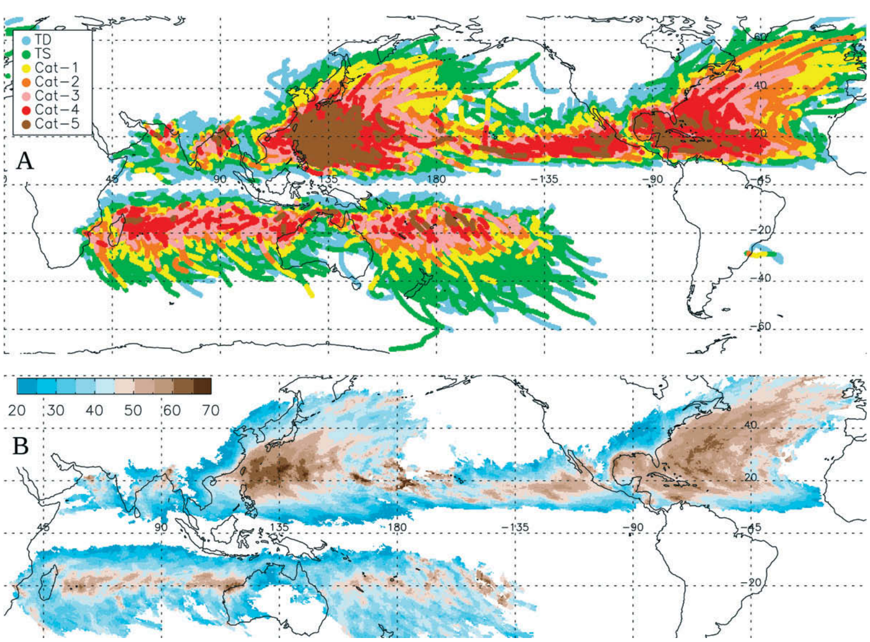

Fig. 4. For storms within 55 km of any point during the IBTrACS period of record (1848–2007), (a) maximum storm intensity during the IBTrACS period of record and (b) the mean MSW (10-min winds in kt) of all storms (for representativeness, the mean is limited to regions with three or more storms).

the spatial mean of $MSW_{max} - MSW_{min}$. This shows that the mean difference in intensity between agencies is quite large, especially over the WP basin. There is also a large difference over the extreme southeastern portion of the SP basin. For the other basins where overlapping reports are available, though differences are smaller, they are still nonzero. This analysis is only appropriate in basins with multiple overlapping reports from two or more agencies. Figure 6b shows the mean range of MSW normalized by the mean MSW (from Fig. 4b). Noise occurs at the edge of the analysis, where outliers are disproportionately emphasized because few storms occur. However, the regions of frequent storms (10 or more per decade) are shown (from Fig. 3b). Much of this region in the WP has relative differences of approximately 15% or more. The largest relative difference occurs near the coast of China, where discrepancies in reported MSW exceed 30%.

Although IBTrACS is not a reanalysis, the interagency variability can be thought of as a proxy for MSW uncertainty that can be used to prioritize cyclones in need of reanalysis. In this article, measures of uncertainty include the following:

- *Storm category differences*: Since their peak MSW often categorizes storms, the difference in using MSW_{min} versus MSW_{max} defines ΔMSW. For 1992 Typhoon Yvette (cf. Fig. 1c), ΔMSW is 46 kt (136–90 kt).
- *Changes in accumulated cyclone energy* (*ACE*): Storm summaries are often made by summing the square of the 6-h MSW over a storm's lifetime to obtain the ACE (Bell et al. 2000). Calculating ACE using MSW_{max} and MSW_{min} defines ΔACE, which integrates the intensity differences over the lifetime of a storm (instead of an instantaneous report, such as ΔMSW). The metric is proportional to the area of the yellow shading in Fig. 1c and tends to give more weight to longer-lived storms.
- *Relative changes in ACE*: Finally, we normalize ΔACE by the ACE calculated from the mean MSW to obtain ΔACE_N for each storm. This provides an estimate of the uncertainty in the intensity record for a particular storm.

These metrics can be used to rank storms from most uncertain to most certain. For illustrative purposes, the three metrics are combined using their mean ranking. The five least certain storms from 1945–2007 for the WP, SI, and SP basins are listed in Table 3. While this treatment may be a worst-case scenario, it represents the storms for which the greatest amount of interagency disagreement exists. Only a global reanalysis of all tropical cyclones can resolve such differences.

The most uncertain storms in the WP occurred during the presatellite era when storm observations were few. Notably, the 1951 Typhoon Marge has the largest ΔMSW (which is also the largest in all

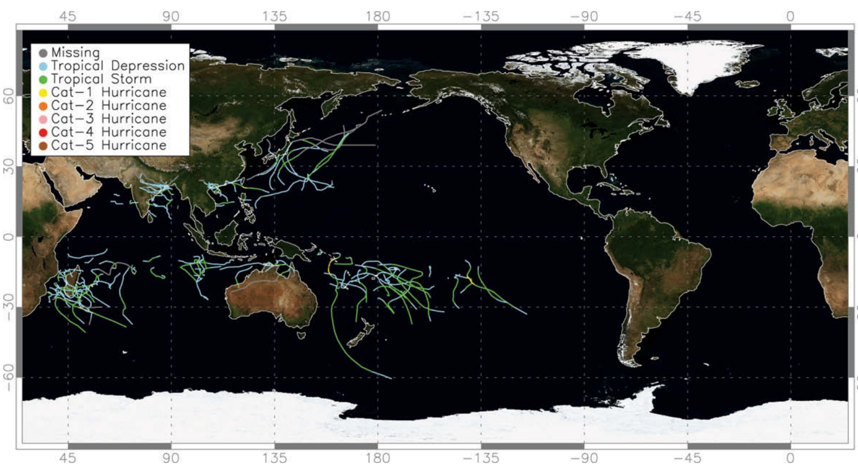

FIG. 5. Storms in IBTrACS but not in HURDAT or JTWC for 1979–2007.

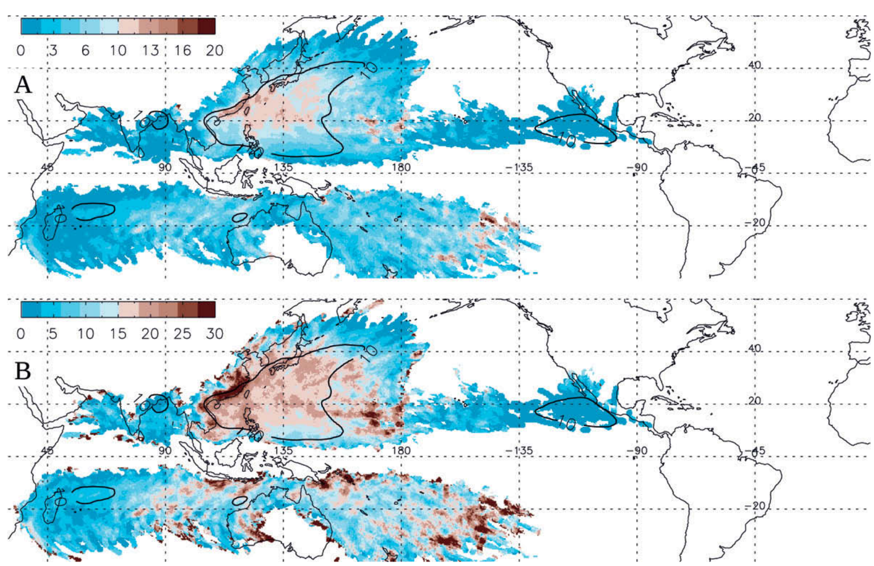

FIG. 6. For all IBTrACS storms during 1848–2007, (a) the mean range of MSW (kt) and (b) the mean range of MSW normalized by the mean MSW (from Fig. 4b) expressed as a percentage. For reference, the contour from Fig. 4a for 10 storms per decade is included.

Table 3a. Five storms with most interagency variability for the western Pacific Ocean. The range of MSW used to calculate ΔMSW is shown parenthetically in knots.

Year	Name	ΔMSW (kt)	ΔACE (10^4 kt^2)	ΔACE_N (%)
1951	Marge	87 (175–88)	40	90
1952	Bess	58 (146–88)	19	105
1969	Ida	56 (156–100)	20	86
1959	Tilda	55 (165–110)	23	76
1954	June	51 (165–114)	24	69

Table 3b. As in Table 3a, but for the southern Indian Ocean.

Year	Name	ΔMSW (kt)	ΔACE (10^4 kt^2)	ΔACE_N (%)
1971	Sally	48 (88–40)	7	170
1985	Isobel	40 (84–44)	9	122
1971	Shelia/Sophia	48 (110–62)	7	126
1992	Irna/Jane	51 (126–75)	17	83
1987	Elsie	44 (97–53)	7	111

Table 3c. As in Table 3a, but for the southern Pacific Ocean.

Year	Name	ΔMSW (kt)	ΔACE (10^4 kt^2)	ΔACE_N (%)
1972	Carlotta	40 (97–57)	26	130
1972	Wendy	36 (106–70)	17	152
1972	Gail	37 (92–55)	11	125
2004	Fay	27 (106–79)	18	100
1972	Emily	35 (92–57)	7	112

IBTrACS). Some of the least certain storms in the SI (Table 3b) occurred more recently, with one as recently as 1992. In addition, the storms in this basin had a significantly higher ΔACE_N, where the range in ACE was often greater than the mean ACE for that storm. Similarly for the SP (Table 3c), there is a recent storm from 2004 with the remaining storms from 1972. Thus, differences between the metrics demonstrate interagency intensity variability, which can be derived from IBTrACS.

Interagency intensity differences based on IBTrACS also affect annual tropical cyclone ACE calculations. In Fig. 7, the time series of annual ACE derived from IBTrACS are shown by basin. The ACE values calculated from MSW_{min} and MSW_{max} are shown via whisker points. For the WP, large differences exist in any given year. The normalized difference (ΔACE_N) shows no temporal trend, suggesting that intensity estimates from various agencies in the WP are just as different today as in the 1970s. The SI has a shorter period of record with multiple agencies reporting. None of the linear regression trends for WP and SI are statistically significant at the 95% confidence interval. For the SP, the trend in ACE is not significant but the ΔACE_N is significant. The trend remains significant even after removing the high values from 1970–72.

Finally, the annual ACE was summed to determine the impact of the interagency variability on decadal statistics. ACE values computed from IBTrACS are provided in Table 4 for two decades (1986–95 and 1996–2005) following Klotzbach (2006). Between these decades, the ACE decreases, increases, and hardly changes for the WP, SI, and SP, respectively. However, since the range of ACE_{min} and ACE_{max} overlap for each decade, the significance of the interdecadal changes in the WP and SI are questionable. Furthermore, since winds are squared in calculating ACE, the differences between MSW_{min} and MSW_{max} are disproportionately emphasized. Thus, great care is needed when gleaning trends or changes (or lack thereof) from annual or decadal data.

SUMMARY. The IBTrACS dataset is the result of a globally coordinated and collaborative project. IBTrACS provides the first publicly available centralized

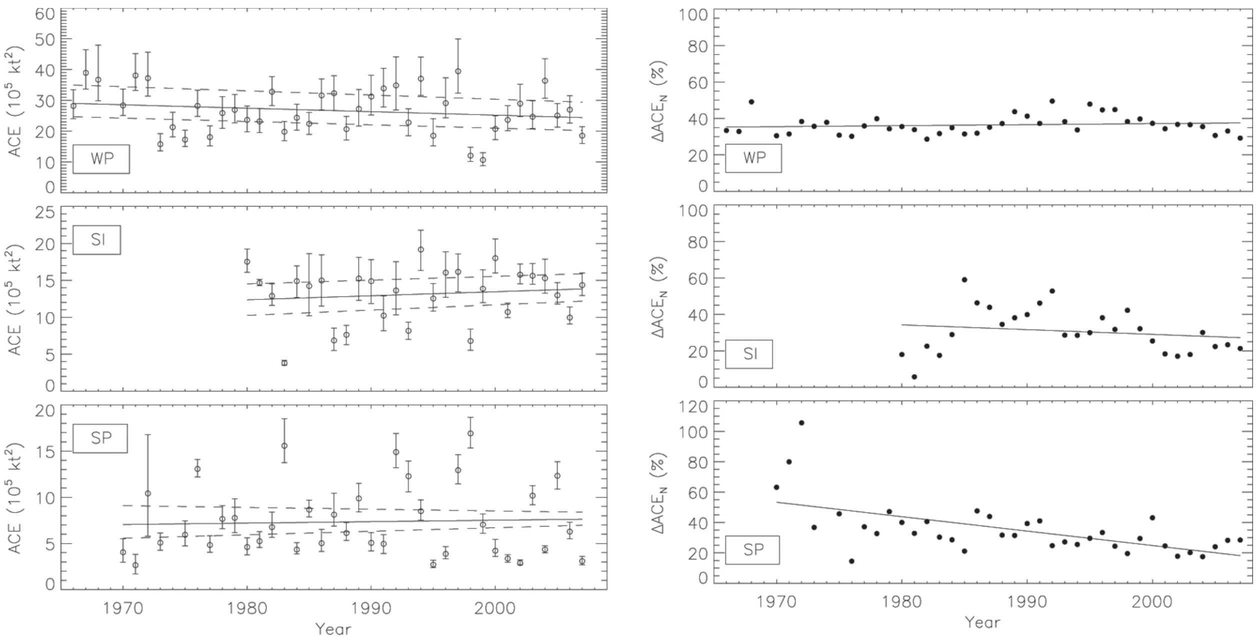

Fig. 7. (left) ACE and (right) ΔACE$_N$ calculated from IBTrACS MSW for (top) WP, (middle) SI, and (bottom) SP basins. Range in ACE shows extent of ACE from maximum and minimum MSW. Solid lines show linear regression; dashed lines show linear regression of minimum and maximum ACE.

Table 4. ACE calculated from mean MSW, MSW$_{min}$ (ACE$_{min}$), and MSW$_{max}$ (ACE$_{max}$) for the period 1986–95 and 1996–2005. ACE (10^4 kt^2) is calculated only when storms were not identified as extratropical and the mean MSW > 30 kt.

Basin	1986–95				1996–2005			
	ACE	ACE$_{min}$	ACE$_{max}$	ΔACE$_N$ (%)	ACE	ACE$_{min}$	ACE$_{max}$	ΔACE$_N$ (%)
WP	3335	2592	4152	47	2899	2334	3645	45
SI	1384	1065	1734	48	1536	1304	1839	35
SP	914	770	1124	39	908	792	1067	30

repository of global tropical cyclone best-track data from the RSMCs and other agencies. In combining the disparate datasets, IBTrACS uses objective techniques that necessarily account for the inherent differences between international agencies. Unlike any other global tropical cyclone best-track dataset, IBTrACS provides a measure of the interagency variability, which helps to identify uncertainty in the tropical cyclone record. While IBTrACS is not a reanalysis (e.g., Fernandez-Partagas and Diaz 1996; Harper et al. 2008b; Landsea et al. 2004), the derived uncertainty metrics can serve as a stepping stone in identifying those tropical cyclones that are in most need of reanalysis.

As IBTrACS data stand, numerous inhomogeneities exist in the intensity record due to interagency differences in available technologies, observations, and procedures over time. For example, inhomogeneities were introduced when various satellite data became available at an agency or when forecasters were trained in different analysis techniques. As discussed in LDK, efforts are underway at NCDC to document the operating procedures at the various RSMC and forecast offices, with an emphasis on changes in processes or capabilities that affect dataset homogeneity.

Finally, IBTrACS is expandable to allow for inclusion of other best-track datasets that may become available. This allows input from individuals and/or agencies that have yet to make best-track data available. IBTrACS could become even more useful by including other information on global tropical cyclones. For example, nondeveloping storm tracks could be included for the tropical cyclone forecasting community in a future version. Such data are necessary to compile statistical tropical cyclone intensity prediction models (e.g., DeMaria and Kaplan 1999). Furthermore, some agencies provide non-6-h analyses and other storm parameters (such as radius of maximum winds, storm size, eye diameter, and radius of the outermost closed isobar), which could be incorporated into IBTrACS, making it more useful to surge and wave modelers, emergency managers, and reinsurance groups. (To download the freely available IBTrACS dataset, visit www.ncdc.noaa.gov/oa/ibtracs/.)

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