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Is the number of North Atlantic tropical cyclones significantly underestimated prior to the availability of satellite observations?

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[1] The number of North Atlantic tropical cyclones that may have been undetected before satellite observations are available is estimated by passing the cyclone tracks taken from 1976 to 2005 through ship observations from 1900 to 1965. The probability of detection is equated to the probability that the ships would have made wind observations of 18 m/s or higher had the tropical cyclones been present during the earlier years, based on the probability computed from actual wind observations around tropical cyclones during the satellite era. It is estimated that the number of tropical cyclones not making landfall over any continent or the Caribbeans may have been underestimated by up to 2.1 per year during 1904–1913, with this number decreasing to 1.0 per year or less during the 1920s and later decades. Our results suggest that the characteristics of North Atlantic tropical cyclone track statistics might have changed during the 20th century.

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1. Introduction

[2] Tropical cyclones (TCs) represent one of the most destructive types of natural disasters. Hence how tropical cyclone activity has changed in the past, as well as how it may change in the future under global warming, is of great societal concern. Several recent studies have suggested that the destructiveness of TCs has increased over the past 30 years [*Emanuel*, 2005; *Webster et al.*, 2005]. However, one might argue that these "trends" may just be part of multi-decadal variability [e.g., *Chan*, 2006; *Landsea*, 2005]. Unfortunately, global estimates of TC activity can only be done after satellite data are available, and the length of the record makes it difficult to differentiate between a secular trend and multi-decadal cycles. In addition, even during the satellite era, estimates of TC intensity still contain substantial uncertainties such that whether a trend can be found could depend a lot on the data set used [e.g., *Wu et al.*, 2006].

[3] Comparing the different basins, the records over the North Atlantic can be considered to be much more complete than any of the other basins. The HURDAT data set [*Jarvinen et al.*, 1984] contains best track data for North Atlantic TCs since 1851. The records prior to 1910 are probably still quite incomplete [*Landsea et al.*, 2004], hence in this study we will mainly focus on Atlantic TC activity after 1910.

[4] Prior to the satellite era, TCs can be detected only when they hit land or encounter ships in the open ocean [*Jarvinen et al.*, 1984]. Hence it is possible that some TCs that never hit populated areas may have gone undetected. Even for those that were detected, since there were no systematic continuous observations of the storms, intensity (and even track) information can be quite uncertain. Since 1944, organized reconnaissance flights have been conducted to track TCs (mainly west of 50°W) [see *Clark*, 1960]. Since then, intensity and track information over the western part of the North Atlantic have become more reliable, but those over the eastern part of the basin may still be incomplete. Observations from polar orbiters started in 1960, and images from geostationary satellites have become available since December 1966; after that most TCs are expected to be detectable. Hence prior to the 1960s, the number of North Atlantic TCs may have been underestimated. In this study, we will use surface ship observations to assess how severe this underestimation could be. We will focus on the number since TC intensity and duration are very uncertain prior to 1944.

[5] The destructiveness of TCs is a function of the number, duration, and intensity of TCs. Hence even a good handle on the long term trend of the TC count does not directly tell us whether destructiveness due to TCs has increased or not. Nevertheless, the number of TCs in the North Atlantic is still of considerable interest. The total count for each decade since the early 1900s based on the HURDAT data set is shown in the first row of Table 1. Note that the decades are defined so that the two World Wars are excluded. The number of TCs that made landfall over the continental US is listed in the second row. Comparing these two rows, one can see that between 1976 and 2005, when satellite observations are available, 105 TCs made landfall over the US, while 236 didn't. However, for the three decades between 1920 and 1955, 106 TCs hit the US, while only 154 didn't. During the decade prior to World War I, the number of TCs that hit the US actually outnumbered those that didn't. Hence based on the HURDAT data set, there has been an apparent change in the proportion of TCs that made landfall over the US. There are at least two possibilities, the first being that there has indeed been a change in this ratio, which would imply that characteristics of TCs that make landfall over the US is not necessarily representative of those basin wide. Alternatively, one may argue that the number of TCs that didn't make landfall over the US might have been underestimated during the pre-satellite era, giving rise to a spurious trend in the ratio.

[6] *Pielke and Landsea* [1998] and *Landsea* [2005] showed that the destructiveness related to TCs that made

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Table 1. Decadal Averaged TC Counts Based on HURDAT Data Set[a]

Class[b]	04–13	20–29	30–39	46–55	56–65	66–75	76–85	86–95	96–05
All	71	58	98	104	87	103	94	99	148
US	36	25	40	41	30	25	30	25	50
CC (CC/US)	18 (0.50)	15 (0.60)	43 (1.08)	30 (0.73)	21 (0.70)	20 (0.80)	14 (0.47)	26 (1.04)	35 (0.70)
NS (NS/US)	10 (**0.28**)	10 (**0.40**)	8(**0.20**)	16 (**0.39**)	22 (0.73)	36 (1.44)	34 (1.13)	22 (0.88)	33 (0.66)
OO (OO/US)	7 (**0.19**)	8 (**0.32**)	7 (**0.18**)	17 (0.41)	14 (0.47)	22 (0.88)	16 (0.53)	26 (1.04)	30 (0.60)

[a] Underlined numbers are those that are less than half of the 4-decade average from 1966–2005, during which the ratios are: CC/US – 0.73; NS/US – 0.96; OO/US – 0.72.

[b] Class US: Hits continental US. Class CC: Hits any continent (other than US) and any island in the Caribbeans. Class NS: Near shore – hits other islands or within 300 km of land or islands. Class OO: Open ocean.

landfall over the Atlantic coast of the US do not show any significant trends. If US landfall TC statistics is representative of basin wide North Atlantic TC statistics, these results would suggest that the destructiveness related to basin wide North Atlantic TC might not have an upward trend. Based on the hypothesis that the percentage of North Atlantic TCs that struck land should have stayed constant during the 20th century, *Landsea* [2007] suggested that between 1900 and 1965, the number of TCs that did not strike land might have been underestimated by at least 2.2 per year. Hence it is important to clarify whether the trend in the proportion of TCs that make landfall over the US found in the HURDAT data set is spurious or not.

[7] To examine the possibility that the trend may be spurious due to undercounting of TCs that did not hit the US, we have examined all TC tracks and subjectively classified those that did not make landfall over the US into three categories. Class CC contains those that made landfall over any *c*ontinent (mostly North America, except for the US) or any of the *C*aribbean Islands. Class NS (for near shore) represents those that passed within 300 km of any continent and island groups (including the Caribbeans, Bermuda, the Azores, Cape Verde, Canary Islands, and Madeira), including those that hit those islands (apart from the Caribbeans), and class OO (for open ocean) represents those that did not pass within 300 km of any land or islands. The ones that hit the US are classified as Class US. The numbers for each class for each decade are also listed in Table 1. In making these classifications, all times when the TCs are weaker than minimum tropical storm intensity or declared to be "extratropical" in HURDAT are disregarded. But note that a number of TCs that are classified by HURDAT as having made landfall over the US did so during their extratropical stage, and we have kept such designations unchanged. Storms classified as subtropical in HURDAT are included, but removing those storms does not change the ratio between the classes.

[8] Examining Table 1, we can see that while there are decadal variations in the number of TCs classified as Class US or CC, there are no clear trends in these two classes. However, the number of TCs in Classes NS and OO are clearly under-represented prior to the satellite era, especially prior to World War II. These are the categories that did not make landfall, and hence their detection hinges mainly on ship observations prior to the satellite era and thus their numbers might have been underestimated. In this study, we will try to quantify how severe such underestimations might have been.

2. Data and Methodology

[9] The main data sets used in this study are the best track data set for the North Atlantic [*Jarvinen et al.*, 1984] (the HURDAT data set), which contains 6-hourly fixes of tropical cyclone position and intensity (in terms of maximum wind and mean sea level pressure at the storm center), and the International Comprehensive Ocean Atmosphere Dataset (ICOADS) ship observations data set [*Woodruff et al.*, 1987; *Worley et al.*, 2005]. The main idea of the methodology is very simple. In order to estimate whether the number of tropical cyclones during the period before the availability of satellite observations is likely underestimated, we pass the observed set of TC tracks during the satellite era, which is expected to be more or less complete, over the available ship observations during the pre-satellite era. The goal is to investigate whether there are a significant number of tracks that do not pass close to any ship observations (or land) and hence would be undetectable during the pre-satellite era.

[10] However, not all ships close to the center of TCs will observe tropical storm conditions. Since TCs are defined based on maximum wind speed (a tropical storm has maximum wind of over 34 kt or 17.5 m/s), we determine the probability that a particular TC is detectable based on ship observations by estimating the probability that a ship during the pre-satellite era would have reported a wind speed of 18 m/s or higher given its relative distance from a hypothetical TC, whose track and intensity is taken from the TC database during the satellite era.

[11] The TC tracks during the years 1979–2002 are first combined with the ICOADS data during the same period to compute a probability distribution function of observed wind speed versus TC intensity and distance of the ship from the center of the TC. At each instance when a TC was present (here we again discarded all fixes that are "extratropical"), we search the ICOADS database to identify ship observations that are located within 500 km of the center of the TC. The actual observed wind speed is then recorded, and a frequency distribution is computed as a function of 3 parameters: the observed wind speed, the intensity of the TC (maximum wind in knots) and the distance of the ship observation from the center of the TC. The ICOADS data is quality controlled (mainly removal of identified duplicates

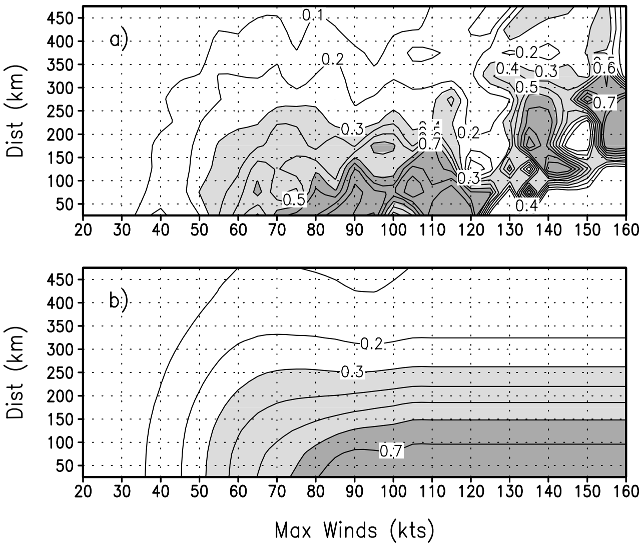

Figure 1. (a) Probability for a ship observation to report a wind speed of 18 m/s or higher, as a function of the intensity (S) of the TC (maximum winds in kts), and the distance of the ship from the center of the TC (d). Contour interval 0.1. (b) Same as Figure 1a, but smoothed by passing a 9-point (3×3) binomial filter over the data 5 times. Shades represent probabilities of over 0.3 and 0.6, respectively.

and observations deemed suspicious) based on the quality control flags used for the ICOADS standard statistics [see *Woodruff et al.*, 1987; see also *Slutz et al.*, 1985, Supplement C], except that the trimming flag is not used, since we expect that observations close to the center of a TC should from time to time report wind speed and/or pressure that differs from the mean at that location by over 3.5 standard deviations.

[12] This frequency distribution is then used to compute the probability that a ship located at a distance d from the center of a TC with a given intensity (S: maximum wind speed of the TC in knots) will report a wind speed of 18 m/s or over. Note that out of all ship observations in the Atlantic between 5 and 45°N during June to October, only 1.2% reported such strong winds, hence we regard the potential presence of such a wind report to provide strong evidence for the detection of a TC.

[13] This probability, as a function of d and S, is shown in Figure 1a. We see that, as expected, the probability is larger when d is small, and generally higher when S increases. The probability is very noisy for $S > 110$ kt, due to the fact that very few ship observations are available close to the center of intense hurricanes. This probability distribution is then smoothed by passing a 9-point (3×3) binomial filter over the data 5 times, and all probabilities for $S > 105$ kt are set to be equal to those for $S = 105$ kt. This smoothed probability is shown in Figure 1b. Both distributions have been used for the calculations described below, and we have found that results are not very sensitive to the applied smoothing.

[14] The TC tracks from the years 1996–2005 are then passed through the historical ship observation records. For each TC during this decade, the time (month, day, and hour), location (latitude and longitude), and intensity (maximum wind speed in kt) of each TC is used, but the year of occurrence is hypothetically changed to a year between 1900 and 1965. Historical ship observations from that year is then taken from the ICOADS data set, and observations (only the time and location of the historical ship observations are used, the actual observed wind speed and pressure are discarded) that are located within 500 km of the center of the (hypothetical) TC is then found. The probability distribution shown in Figure 1b is then used to compute the probability that the ship would have reported a wind speed of 18 m/s or higher had that hypothetical TC been present, and this is taken to be the probability that the TC would have been detected by that ship observation.

[15] Frequently, a single hypothetical TC would encounter multiple ship observations close to its center during its lifetime. The cumulative probability of detection for that hypothetical TC based on observations for each particular year is computed as follows:

$$P_{\mathrm{det}ect} = 1 - (1 - p_1) \times (1 - p_2) \times \cdots \times (1 - p_n). \qquad (1)$$

[16] In (1), p_1, p_2, ..., p_n represents the probability of detection for each individual observation that is close to the center of the hypothetical TC. This cumulative probability of detection is computed for all North Atlantic TCs from each year between 1996 and 2005 using historical ship data from each year between 1900 and 1965.

3. Results

[17] The expected value of the number of TCs in each class that might have been undetected for each decade during 1900–1965, assuming the characteristics of TC tracks during that decade is the same as those during the decade of 1996–2005, can be computed based on the average of P_{detect} computed from ship observations from that particular decade. The results for Class OO (those that did not pass close to any land or island) are summarized in row 1 of Table 2. During 1996–2005, the total number of

Table 2. Expected Number of Open Ocean (Class OO) TCs (per Decade) That Could Potentially be Undetected Based on Ship Observations Alone for Each Decade, Estimated Based on the Criteria Described in the Text

	1904–13	1920–29	1930–39	1946–55	1956–65
96–05 (30 TCs)	15.4	10.3	6.9	7.0	2.2
86–95 (26 TCs)	12.7	7.6	5.4	5.2	2.1
76–85 (16 TCs)	6.2	2.4	1.5	1.6	0.4
76–05 mean (24 TCs)	11.4	6.8	4.6	4.6	1.4
Including ET fixes (76–05 mean)	10.2	5.6	3.8	4.0	1.2
More stringent criterion (76–05)	12.2	7.5	5.3	5.2	1.9

Table 3. List of TCs That Contribute Most to Possible Under-Detection During 1920–29

TC (Year, Number, Name, (Max Wind))	TS Fixes	1904–13	1920–29	1930–39	1946–55	1956–65
2000 #3 Chris (35 kts)	1	0.99	0.90	0.72	0.83	0.59
2000 #5 Ernesto (35 kts)	6	0.93	0.86	0.74	0.84	0.46
2003 #16 Peter (60 kts)	11	0.80	0.83	0.65	0.76	0.26
2002 #10 Josephine (35 kts)	5	0.94	0.70	0.46	0.37	0.09
2001 #12 Lorenzo (35 kts)	6	0.84	0.62	0.37	0.25	0.04
1997 #7 Fabian (35 kts)	11	0.95	0.61	0.33	0.31	0.07
1998 #1 Alex (45 kts)	19	0.65	0.60	0.46	0.49	0.22
1996 #7 Gustav (40 kts)	18	0.52	0.59	0.52	0.59	0.30
1999 #5 Emily (40 kts)	16	0.82	0.59	0.40	0.28	0.07
2005 #12 Lee (35 kts)	2	0.83	0.58	0.38	0.32	0.05
Total contributions from all 10		8.27	6.88	5.03	5.04	2.15

TCs classified as Class OO is 30. The expected number that may go undetected by ship observations, based on the objective criteria described in the preceding section, comes out to be 10 or less for all decades except for the earliest one, when the expected number of undetected TCs could have been as high as 15. The years 1914–1919 and 1940–1945 are not included in the table because of reduced number of ship observations during the two World Wars [see *Woodruff et al.*, 1987].

[18] The 10 tracks that contribute most heavily to the possible non-detections during the 1920s are listed in Table 3. The name and year of each storm, as well as the contribution of each storm to each of the decades (note that each storm can contribute up to a maximum of 1.0 to the average number of possible non-detection), are shown. Together, these 10 storms (out of a total of 30 in this class) contribute to 67% of the possible under-detection in the 1920s, and over 70% for 1930s and after, and over 50% for 1904–1913. None of these storms reached hurricane intensity, and more than half are of minimal tropical storm strength (maximum wind of 35 kts). Seven of them had lifetime of less than 3 days (12 6-hourly fixes), the remainder spent most of their lifetimes south of 25°N, between 60 and 30°W, where very few ship observations exist. Details of these tracks can be obtained from the National Hurricane Center historical archives (http://www.nhc.noaa.gov/pastall.shtml). Of the remaining 20 Class OO storms, for the 1920s, only 3 contribute more than 0.5 each to the number of possible non-detection, with the remainder all contributing less than 0.3 each. The total contribution from the second 10 storms equals 3.26, and the last 10 storms together contribute only 0.17.

[19] The expected average number of ship observations (within 500 km of the storm's center) that a typical Class OO TC with a track taken from 1996 to 2005 would have encountered during the 1920s is around 30. Out of these, 4.3 are expected to report winds of 18 m/s or higher. We have examined actual tracks of Class OO TCs during the 1920s and 1930s, and the median number of ship observations in the ICOADS data set found within 500 km of these TCs is 31, with the median TC having 5 observations reporting winds of 18 m/s or higher, suggesting that our detection criterion is reasonable. For the ones listed in Table 3, each of them would have encountered around 15 ships or less during the 1920s (only around 4 for the first 3 in Table 3), making them harder to detect. The weakness of these storms also means that even when there are observations close to their centers, the probability for detection based on each observation is low (Figure 1b).

[20] To test the robustness of the results, we have repeated the calculations for TC tracks taken from the decades 1986–1995 and 1976–1985, and the results are shown in rows 2 and 3 of Table 2. Overall, the results suggest that during 1904–1913, only half of all Class OO TCs might have been detected based on ship observations. However, during the 1920s, about 70% would have been detected, while during the 1930s and thereafter, we expect that 80% or more of these TCs would have been detected.

[21] If we relax the detection criterion by including the "extratropical" fixes (and re- calculating the probabilities shown in Figure 1 by including ship observations close to those fixes), the expected number of undetected TCs (shown in row 5 of Table 2) will come out slightly smaller. We have also tested a more stringent criterion by equating the probability of detection to the probability of observing a wind speed of 19 m/s or higher (row 6, Table 2), and the numbers are only slightly larger. These sensitivity experiments suggest that our results are robust, and that it is very unlikely that the number of Class OO TCs that were undetected by ship observations can be significantly larger than 10 per decade after World War I.

[22] Similar statistics for Class NS TCs are presented in Table 4. During 1976–2005, there are on average more TCs in Class NS than in Class OO, but the expected number of undetected Class NS TCs turns out to be smaller (average of 3 or less since 1920), probably because there is more ship traffic close to land/islands than over parts of the open ocean. Combining the results shown in row 4 of Tables 2 and 4, our analyses suggest that out of the 54 TCs per decade that did not hit land during 1976–2005, the expected number of non-detection could be as high as 21 had the same tracks occurred during 1904–1913, with the number dropping to 10 during the 1920s, and less than

Table 4. Expected Number of Class NS (Near Shore) TCs (per Decade) That Could Potentially be Undetected Based on Ship Observations Alone for Each Decade

	1904–13	1920–29	1930–39	1946–55	1956–65
96–05 (33 TCs)	10.2	3.0	1.8	3.0	0.3
86–95 (22 TCs)	6.5	1.7	1.1	1.9	0.4
76–85 (34 TCs)	11.8	4.5	3.2	4.2	1.2
76–05 mean (29.7 TCs)	9.5	3.1	2.0	3.0	0.6

8 thereafter. During the two World Wars, due to the decline in the number of ship reports, the expected number of non-detection could be as high as 2.3 per year. However, even including these anomalously high periods, when averaged over 1900–65, the expected number of non-detection is estimated to be about 1.2 per year, significantly less than the 2.2 per year suggested by *Landsea* [2007].

4. Concluding Remarks

[23] Our results suggest that prior to the availability of satellite observations, the density of ship observations over the North Atlantic has been high enough since World War I (except during World War II) that it is quite likely for a TC that did not hit land (or islands) to pass close enough to one or more ship observations during its lifetime such that tropical storm like conditions (here defined to be wind speed of 18 m/s or higher) are observed. While a single 18 m/s wind observation may not have been considered a definite detection, TCs that encounter such an observation are likely to have encountered other observations, such as low pressure readings, shifting wind directions, and long period swells, that indicate that a TC is likely to be around. However, since TCs are defined solely based on wind speed, we have not attempted to quantify how these additional observations might affect the probability of detection. Note also that since not all ship observations have been digitized and included in the ICOADS database [see, e.g., *Compo et al.*, 2006], our estimate based on the ICOADS data set may represent an over-estimation of the number of undetected TCs. Moreover, we expect that some of the TCs in Class NS should have impacts on the land/island that they passed close by, and hence might have been detected by other means.

[24] Our results suggest that the expected total number of TCs in Classes NS and OO (i.e., TCs that did not make landfall over any continent or the Caribbeans) that might have gone undetected during the 1920s and 1930s is about 10 per decade or less. Re-examining Table 1, we see that even with the addition of 10 per decade, the total number of Class NS and OO TCs (compared to the number of Class US TCs) during these two decades is still significantly smaller than that expected based on TC statistics during the satellite era, suggesting that the fraction of Class US TCs might have changed during the 20th century. This would imply that the characteristics of North Atlantic TC track statistics have changed during the 20th Century, and that TC statistics derived solely from US landfalling TCs (Class US) may not be representative of those of the entire North Atlantic basin, even on multi-decadal time scales.

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