Tropical cyclone intensification trends during satellite era (1986–2010)

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Received 14 March 2012; revised 17 April 2012; accepted 19 April 2012; published 26 May 2012.

[1] Using International Best Track Archive for Climate Stewardship (IBTrACS, version v03r03) analysis during satellite era (1986–2010) we determined the trends of intensification of tropical cyclones (TC) over all the global basins, except the North Indian Ocean. Over all the basins, the rate of TC intensification from 64 kt to first peak of intensity maxima (global average value = 104 kt) was found to be positive. The above trends were significant for 4 out of 5 basins, except the North West Pacific. The trends indicate that the TCs now intensify from 64 kt to 104 kt nearly 9 hours earlier than they did 25 years back. The maximum reduction in intensification time is noticed over the North Atlantic Ocean where the average time needed for TC to intensify from 64 kt to 112 kt has reduced by nearly 20 hours during the past 25-year period. **Citation:** Kishtawal, C. M., N. Jaiswal, R. Singh, and D. Niyogi (2012), Tropical cyclone intensification trends during satellite era (1986–2010), *Geophys. Res. Lett.*, *39*, L10810, doi:10.1029/2012GL051700.

1. Introduction

[2] It is well established fact that the Sea Surface Temperature (SST) over most of the global basins has increased by about 0.25–0.5°C during the past several decades [*Webster et al.*, 2005; *Santer et al.*, 2006] mainly due to an increase in the concentration of the greenhouse gases. The long term impact of enhanced SST on the number and severity of tropical cyclones has been a highly debated topic of research. *Emanuel* [2005] reported a significant increase in TCs' power dissipation index (PDI) during the past 50 years over the Atlantic and West Pacific basins. *Holland and Webster* [2007] noted substantial century-scale increases in Atlantic tropical cyclone frequency and attributed some of this increase to anthropogenic forcing. *Webster et al.* [2005] also produced evidence that globally the number of most severe cyclones of category 4 and 5 on Saffir Simpson Hurricane Scale nearly doubled between two 15-year epochs (1975–1989) and (1990–2004). However, a number of follow-up studies contradicted these findings and attributed the reported trends to the non-uniformity of observational quality and quantity [*Landsea et al.*, 2006]. Some recent studies [*Elsner et al.*, 2008] based on more recent satellite-era data show an increase globally in the intensities of the strongest tropical cyclones. Theory suggests that a rise of 1°C in SST can indeed result in ~4–5% increase in TC maximum sustained wind speed [*Emanuel*, 2005] but some researchers are skeptical about whether such small trends can be detectable at all [*Landsea et al.*, 2006]. For example, study by *Balling and Cerveny* [2006] showed no significant trends in TC intensification rates over the Atlantic during 1970–2003. Similarly *Klotzbach* [2006] has shown the absence of any linear trend in the cyclonic activity during the recent 20 year (1986–2005) period. The period after 1985 has specific significance in TC research because most of the operational meteorological centers started to use satellite-based observations for TC detection and more importantly the TC intensity analysis based on the Dvorak technique [*Dvorak*, 1984, 1995] that used infrared satellite images [*Knaff et al.*, 2010].

[3] Detection of climatic trend of severe cyclonic activity from such a small record of reliable observations can be done only after successfully addressing issues related to the data quality, statistical validity and significance of the detected trends. On a global and annual scale, category 4–5 cyclones represent only about 10% of the total cyclone population. Also, the seasonal cyclonic activity is believed to be affected by factors other than SST alone, e.g. wind shear [*Gray et al.*, 1994] and solar activity [*Elsner and Jagger*, 2008]. Statistically more robust trends can be identified using a variable that is more continuous in time and space than the number of cyclone events. With the above view, we selected the rate of TC intensification for our present analysis. Increases in TC intensity are expected to result from increases in sea surface temperature and decreases in tropopause-level temperature accompanying greenhouse warming [*Emanuel*, 1987; *Henderson-Sellers et al.*, 1998; *Knutson et al.*, 2006, 2010]. Observations suggest that in contrast to surface and near-surface air temperatures, lower tropospheric temperatures have not increased significantly in past several decades [*Wallace et al.*, 2000; *Karl et al.*, 2006]. This differential warming of the atmosphere could lead to enhancement of atmospheric destabilization and consequently the intensification of convective processes at mesoscale to synoptic scales [*Balling and Cerveny*, 2006]. In the present study, we used a globally homogeneous quality controlled data set containing tropical cyclone best track analysis to analyze the changes in TC intensification during the recent decades for major global basins. In order to ensure that the inferences of the analysis are not impacted by the quality of observations, we used data for the period 1986–2010 during which the estimation of cyclone intensity was carried out using Dvorak's satellite image based technique by almost all the reporting agencies around the world [*Knaff et al.*, 2010]. Not only do the TC intensification processes have a more direct link to the thermodynamic state of the atmosphere

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0094-8276/12/2012GL051700

compared to the number of cyclonic events, the analysis of TC intensification is less sensitive to the missing or unreported events.

2. Data and Methods

[4] The best track analysis used in the present study is version v03r03 data from IBTrACS Project that was developed by NOAA's National Climatic Data Center under the auspices of the World Data Center for Meteorology, Asheville to collect and disseminate the historical tropical cyclone best track data from all available sources, merging the disparate data into one comprehensive dataset for the user community [*Kruk et al.*, 2009; *Knapp et al.*, 2010]. IBTrACS merging procedure accounts for the inherent differences between best track datasets while applying objective quality control procedures to flag potentially erroneous data points. The complete IBTrACS data (starting from 1900) are available to the public online at "http://www.ncdc.noaa.gov/oa/ibtracs/index.php?name=data-access". Data collection methodologies have changed throughout the period of the IBTrACS data set leading to possible artificial trends and unknown errors. However, during late 1980's almost all the Regional Specialized Meteorological Center's (RSMC) and Tropical Cyclone Warning Centers (TCWC) started using Dvorak's technique for cyclone intensity estimation based on infrared images [*Kossin et al.*, 2007; *Knaff et al.*, 2010]. *Knaff et al.* [2010] pointed out that the Dvorak intensity estimation approach has remained stable, robust and less sensitive to the infrared satellite image resolution. Consequently, we have reason to believe that the best track data for the period 1986 and beyond is globally homogeneous. Hence we used the IBTrACS data collected between the years 1986 and 2010 to ensure the confidence in the results of our analysis. It is to be noted that TC monitoring at the Atlantic and the East Pacific basins was benefited by significant improvements in observational technology during the above period with the deployment of coastal Doppler radars and with the use of advance air-borne sensors like Stepped Frequency Microwave Radiometer, SFMR [*Uhlhorn et al.*, 2007]. The SFMR is considered to be a highly-accurate marine platform for resolving intensity and structure of TC surface winds, but the frequency of these observations is far less (typically one per day or less) compared to satellite observations. The data from the IBTrACS archive used in this study are: storm name, storm serial number, time, latitude and longitude, maximum sustained wind speed (MSW).

[5] To compute the average rate of intensification, we used all the TCs that formed during the period 1986–2010, and attained a peak intensity exceeding 80 kt (10-minute maximum sustained wind speed) over the major global basins. We found statistically sufficient cases over North Atlantic (NA), North West Pacific (WP), North East Pacific (EP), South Indian Ocean (SI), and South Pacific Ocean (SP). Over North Indian Ocean (NI) we found only 19 tropical cyclones satisfying the above criteria; hence we excluded the North Indian Ocean in the present analysis. Under favorable conditions like availability of warm ocean water and a low-shear environment, the intensity of a typical tropical cyclone should grow monotonically until the frictional dissipation forces become large enough to halt the cyclone's intensification beyond a certain limit, defined by SST and atmospheric thermodynamic structure [*Emanuel*, 1987]. However, typically a cyclone, which is a moving vortex, encounters inhibiting factors like interaction with landmasses (coasts or small islands), high shear environment or dry air intrusion, which lead to the reduction of the cyclone's intensity. Once the cyclone moves past these obstacles and finds favorable conditions again, the secondary phase of intensification begins, which in some cases, might be stronger than the primary phase. This process is illustrated by an example in Figure 1. For the present analysis, we used the observations only during the primary intensification phase (between points A and C in Figure 1), in which the cyclonic intensity grows "almost" monotonically until it reaches a maximum (the "primary maxima" or PM) value. We used maximum intensity in a ±24H window to determine PM and to avoid short-term decelerations of TC intensity. We did not use the observations beyond this point, even if the observations in a later phase showed the intensity values larger than the PM. We opted to analyze the intensities prior to the time of the PM because we believe that the first phase of TC intensification is primarily controlled by the oceanic processes and can be better linked to the climatological changes of SST than the secondary intensification that is linked to more complex processes including land-atmosphere interaction.

[6] Prior to the analysis of the intensification trend, we ensured that each individual TC record in IBTrACS data used for analysis meets the following criteria (a) the intensity at the time of first valid observation should not exceed 40 kt (b) the primary intensity maxima exceeds 80 kt (c) there are no missing observations between the time of first valid observation and the time when TC intensity reached PM, and (d) TC remains over water during this period. Intensification rates were determined for two phases (i) from tropical storm stage to hurricane stage, and (ii) from hurricane stage to PM. Further, using least square regression analysis we tried to evaluate whether linear or exponential growth is a better representative of TC intensification process. We found that the linear fit resulted in smaller estimation errors, and hence we decided to use the linear intensification for further analysis. The two intensification rates for each TC with valid observations were determined as

$$I_1 = [MSW(t_{64}) - MSW(t_{30})]/(t_{64} - t_{30}) \quad (1)$$

$$I_2 = [MSW(t_{PM}) - MSW(t_{64})]/(t_{PM} - t_{64}) \quad (2)$$

where MSW is 10-min maximum sustained wind speed (kt), and t_{30}, t_{64}, and t_{PM} respectively denote the times when the TC crossed (or equaled) the intensities of 30 kt (with condition that $MSW(t_{30}) < 40$ kt), 64 kt, and primary maxima. Linear trends of I_1 and I_2 were determined using least square regression.

2.1. Test of Significance

[7] Availability of fast computing resources makes it easy to test the significance of statistical properties using the approach of permutation resampling or Monte Carlo simulation [*Wilks*, 2011]. The null hypothesis (H_0) that there is no trend in the data can be tested by randomly reshuffling the order of variable sufficiently large number of times (100,000 in the present study), thus creating artificial time series sets of the same size as the original data, and computing the trend for each set. These trends are compared with the observed

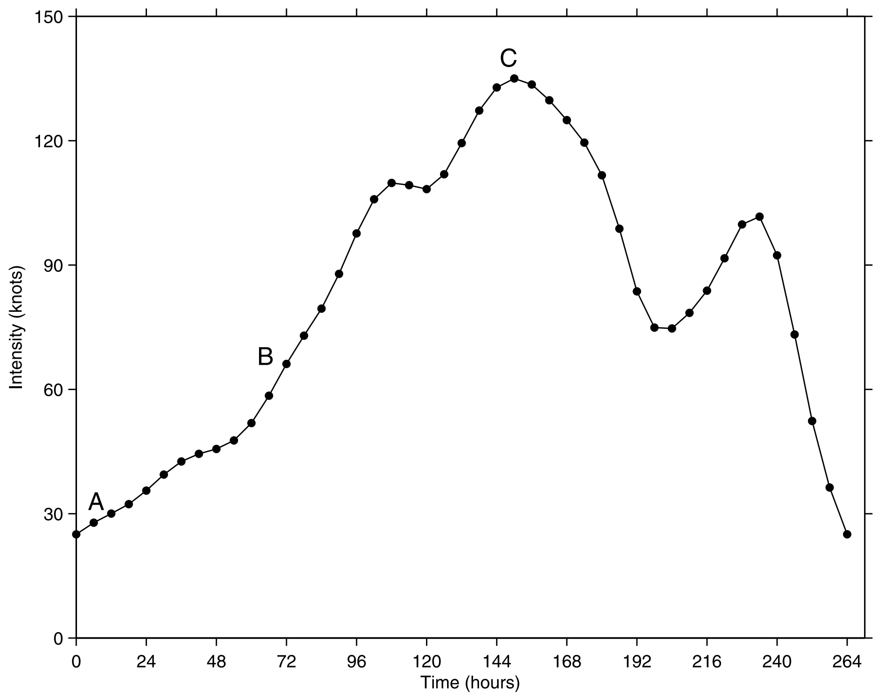

Figure 1. Example of intensification for a typical TC. Intensification rates I_1 and I_2 are determined between the points A-B and B-C respectively.

trend to get the probability of obtaining the observed trend by chance. This approach provides near exact estimate of the significance of the trend of a variable irrespective of its sampling distribution. We described the significance in four broad categories: *not-significant* (significance level < 95.0%), *significant* (95.0%), *very significant* (99%) and *extremely significant* (99.9%). Moreover, we computed the extreme intensification rates (top 5% values) for further discussion, and trends were re-analyzed after removing top 5% extreme intensification cases from the available data for each basin.

3. Results and Discussions

3.1. General Trends of Intensification

[8] Table 1 shows the results of the analysis. Except for the trend of I_1 over the north Atlantic and South Pacific basins, the trends of intensification rates I_1 and I_2 were found to be positive during the satellite era, 1986–2010. Over four basins out of five analyzed, the trends of I_2 were significant. Trends of I_1 were significant only over North West Pacific and South Indian Ocean. South Indian Ocean is the only basin where the trends of both I_1 and I_2 were extremely significant. Computation of linear trends is sensitive to extreme values. Rapid intensification (RI) is defined by *Kaplan and DeMaria* [2003] as 95th percentile of all over-water intensity changes of tropical cyclones of tropical depression intensity or greater. Due to large seasonal and climatological variations, RI is more likely to occur during specific months of cyclone season [*Kaplan et al.*, 2010] and also during the El-Nino/La-Nina years over the Pacific ocean [*Wang and Zhou*, 2008]/Atlantic ocean. The present analysis indicates that over the Atlantic basin, all the extreme intensification events for I_2 (top 10%) occurred after the year 2000 (Figure 2), while most extreme events (top 5%) occurred after 2005. Over the East Pacific basin also, the

Table 1. Summary of Results[a]

Basin	N	Trend of I_1[b] (kt/hr/year)	P-Value Significance *After Removing Top 5% Values of I_1*	Trend of I_2[c] (kt/hr/year)	P-Value Significance *After Removing Top 5% Values of I_2*
North Atlantic	89	−0.004	0.1340; Not Significant *0.348; Not Significant*	0.033	0.000; **Extremely Significant** *0.044;* ***Significant***
North West Pacific	148	0.019	0.000; **Extremely Significant** *0.000;* ***Extremely Significant***	0.007	0.185; Not Significant *0.321; Not Significant*
North East Pacific	127	0.008	0.165; Not Significant *0.792; Not Significant*	0.014	0.012; **Very Significant** *0.000;* ***Extremely Significant***
South Indian Ocean	72	0.016	0.001; **Extremely Significant** *0.014;* ***Very Significant***	0.035	0.000; **Extremely Significant** *0.000;* ***Extremely Significant***
South Pacific Ocean	41	−0.001	0.844; Not Significant *0.291; Not Significant*	0.031	0.000; **Extremely Significant** *0.037;* ***Very Significant***

[a]The significant, very significant and extreme significant values are presented by the bold fonts.
[b]30 to 64 kt.
[c]64 kt to peak value.

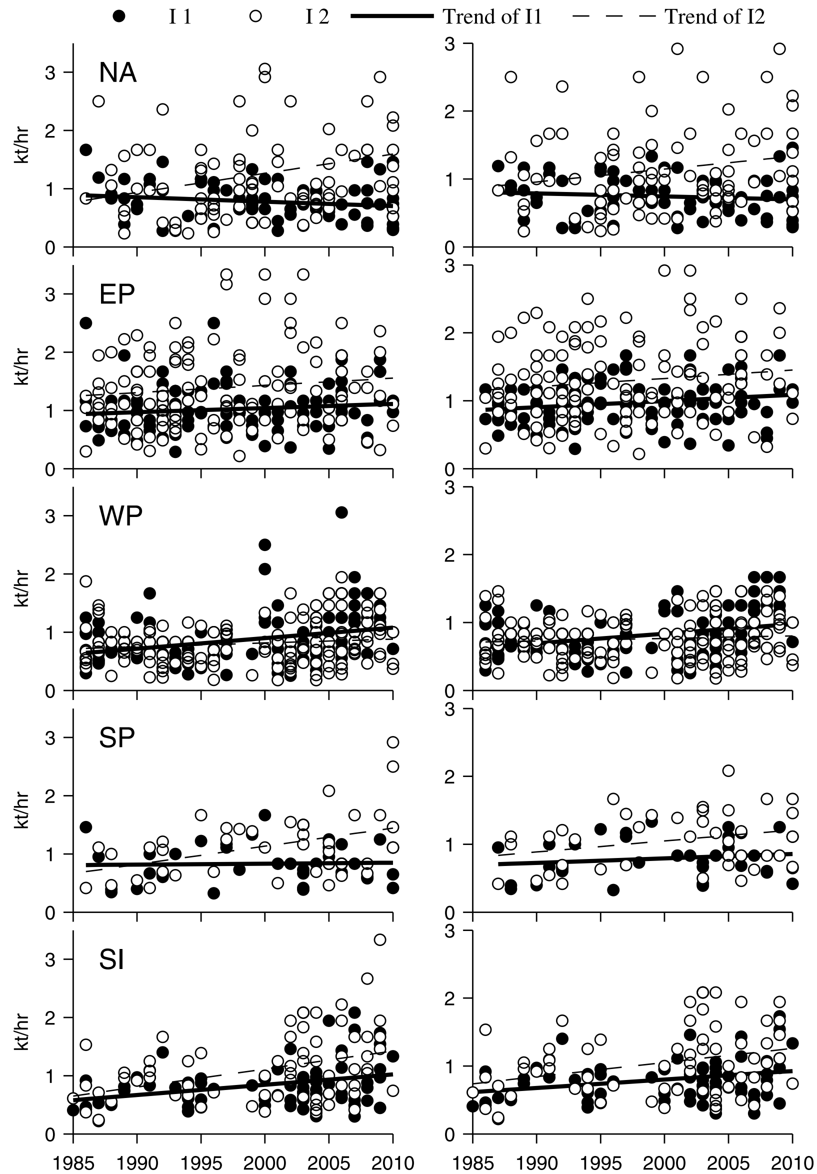

Figure 2. Variation of intensification rates I_1 (dark circles) and I_2 (open circles) with time. (left) All valid observations for five basins, (right) same as left panel but with top 5% values of I_1 and I_2 removed from the data.

present data shows sudden appearance of extreme cases (I_2) between the years 1990 and 2005. A similar trend persisted over the West Pacific basin where almost all the most extreme intensification cases for I_1 occurred after the year 2000. Over South Indian Ocean, the most extreme cases for both I_1 and I_2 occurred after 2002. For South Pacific Ocean, the most extreme cases of I_2 appeared after 2005, while those for I_1 occurred before 2000. The present analysis leads to a general inference that there has been a prominent increase in extreme intensification events during the recent years over all the major basins, except the East Pacific. The extreme intensification was noticed either in tropical storm to hurricane intensity phase, or in hurricane to PM phase (or both), but the uniformity of the timing of the appearance of these events over most of the basins is interesting and appears significant. There is some possibility that the trends noticed in the above analysis are impacted by extreme events and the use of data for TCs that occurred when the conditions for RI were favorable. In order to account for this possibility, we removed the data containing top 5% values of the I_1 and I_2 separately for each basin and carried out a new trend-analysis. Even after removing the extreme events, the nature of the trends did not change much. However, it did change the significance of the results. After extreme event removal, some of the trends became less significant than before, while some became more significant (Table 1).

3.2. Impact of Intensity Bias Corrections

[9] *Knaff et al.* [2010] reported the biases in Dvorak intensity estimates and showed that most of the variance in intensity bias can be explained by maximum sustained wind speeds (MSW). We used the following bias model described in *Knaff et al.* [2010] to correct the intensity estimates uniformly for each basin:

$$\mathrm{Bias(kt)} = 32.174 - 1.99\mathrm{MSW} + (\mathrm{MSW}/5.07)^2 - (\mathrm{MSW}/15.076)^3 + (\mathrm{MSW}/34.351)^4 \quad (3)$$

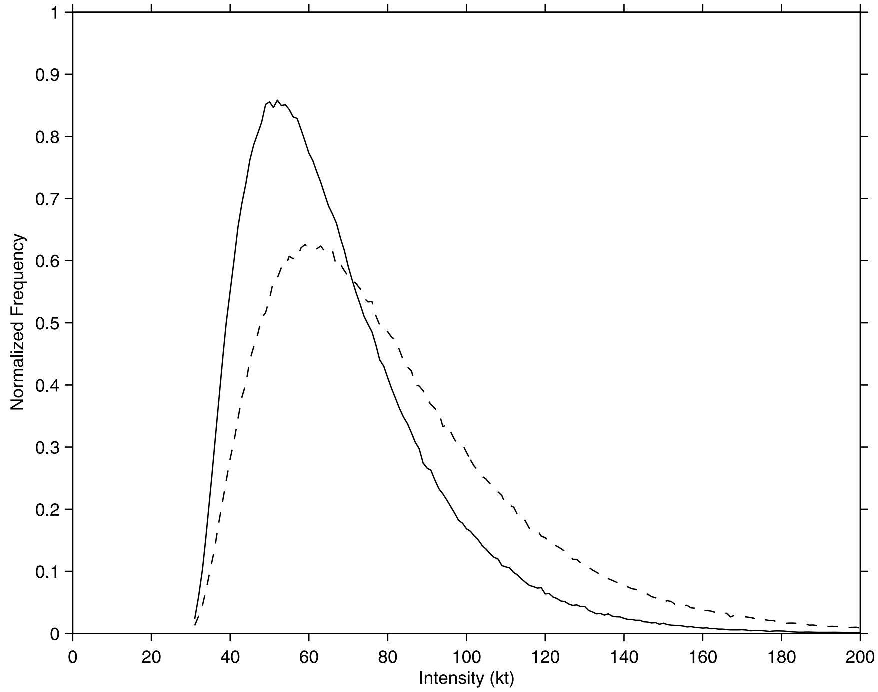

Figure 3. Simulated intensity distribution of global cyclones (solid line), and the same with 30% increase in average intensification rate (dashed line).

The corrected intensity estimates were obtained by subtracting the bias from the IBTrACS intensity data. This correction had very little impact on the trend estimates. For example, the trends of I_1 changed from 0.019 to 0.020 (WP), and 0.016 to 0.017 (SI). For NA, EP, and SP the trends remained the same. Similarly the trends of I_2 changed from 0.033 to 0.035 (NA), 0.031 to 0.032 (SP) and 0.031 to 0.030 (SI). Thus the corrections did not have much impact on the magnitude and significance of the trends in TC intensification.

3.3. Trends in TC Maturity Time

[10] Knowing that the TC intensification rates, particularly from 64 kt to PM, are positive for all five basins, it would be interesting to compute the trends in time-duration ($t_{PM} - t_{64}$), of TC maturity for I_2 phase. The global average value of intensity at primary maxima (MSW_{PM}) was found to be 104 kt in the present analysis. On global scale the trend of ($t_{PM} - t_{64}$) was found to be −0.351 h/yr, which is significant at 95% level (one tailed p-value = 0.022). To put it simply, the average time taken by a TC to mature from 64 kt to 104 kt has reduced by about 9 hours during past 25 years. For individual basins, trend in ($t_{PM} - t_{64}$) was significant at 90% level only over the North Atlantic Ocean (trend = −0.781 h/yr, p-value = 0.078), indicating that on average, the cyclones over the North Atlantic mature from 64 kt to 112 kt (mean of MSW_{PM} for North Atlantic), nearly 20 hours earlier now than they did 25 years back (maturity time reduced to ∼40 hour from ∼60 hours). Increasing TC intensification may partly be attributed to the rate of ocean warming at different basins. North Atlantic basin shows strongest warming trends of 0.264°C/decade compared to a global average of 0.0948°C/decade during the period of study, which is consistent with the fact that the NA basin has second largest trend in intensification and the largest trend in the time of maturity.

3.4. Impact of Intensification Rate on TC Intensity Distribution

[11] How do the changes in intensification rates affect the TC intensity distribution? To answer this question we performed Monte-Carlo simulation of the evolution of an average TC from 30 kt to maximum intensity. TC track length was assumed to have a Gaussian distribution with mean of 10 days and standard deviation of 3 days. From IBTrACS data, linear intensification rates were found to have a Gamma distribution with shape parameter $\theta = 3.437$, and this was used for simulation. Assuming that the number of annual TCs and their average life span will remain unchanged and only intensification rates will increase by ∼30% (which is consistent with the results of our analysis), a large number (10^5) of TCs were simulated. Figure 3 shows that just by changing intensification rates, the TC intensity distribution changes significantly. The peak of histogram shifts from 50 kt to 60 kt, the number of Cat-1, 2 storms reduce while Cat 4,5 storms increase significantly. We did not consider the limiting factors like increased frictional dissipation with increasing intensity and this might have resulted in unexpectedly higher counts towards the right side tail of the distribution. The results of the simulation are consistent with the observational findings [*Webster et al.*, 2005] and projections by climate models [*Oouchi et al.*, 2006; *Bengtsson et al.*, 2007; *Vecchi and Soden*, 2007; *Bender et al.*, 2010], suggesting that the enhanced TC intensification is probably linked to an increase (reduction) of high(low) intensity cyclones on the global scale.

4. Conclusions

[12] Relative warming of oceans with respect to lower troposphere and resulting reduction in atmospheric stability can be considered to be more directly linked to TC

intensification than the seasonal TC activity. However, non-uniformity of TC intensity observations in available best track records has been a major concern for the detection of long-term trends in TC intensification rates. During satellite era (1986–2010), TC intensity analysis by operational weather centers worldwide relied on a common method, the Dvorak technique based on satellite infrared images, providing higher confidence about the uniformity of TC intensity observations during this period, at least on basin scales. In the present study, satellite era observations of tropical cyclone intensity from IBTrACS data are analyzed to study the trends of TC intensification during 1986–2010. The analysis indicates that over most of the basins, the TC intensification trends are positive and significant. The nature of these trends and their statistical significance does not change appreciably even if top 5% extreme values of intensification are removed from the data for each basin, or the TC intensities are corrected for biases. On global average sense, the time required by a TC to mature from 64 kt to 104 kt has reduced by ∼9 hours during past 25 years. Over the North Atlantic basin, where the trends of intensification are among the largest, the TCs now mature from CAT-1 to CAT-3 stage (∼112 kt) in ∼40 hours compared to ∼60 hours in late 1980s. Statistical simulations indicate that increased TC intensification rates can drastically alter the TC intensity distribution with significant reduction (increase) in low/medium (high/very high) intensity TCs.

[13] **Acknowledgments.** We sincerely acknowledge the National Oceanic and Atmospheric Administration (NOAA) of the United States for providing free access to the valuable IBTrACS data. The authors are grateful to both the reviewers for their valuable comments and to Kaushik Gopalan for editorial help.

[14] The Editor thanks Greg Holland and an anonymous reviewer.

References

Balling, R. C., Jr., and R. S. Cerveny (2006), Analysis of tropical cyclone intensification trends and variability in the North Atlantic Basin over the period 1970–2003, *Meteorol. Atmos. Phys.*, *93*, 45–51, doi:10.1007/s00703-006-0196-5.

Bender, M. A., T. R. Knutson, R. E. Tuleya, J. J. Sirutis, G. A. Vecchi, S. T. Barner, and I. M. Held (2010), Modeled impact of anthropogenic warning on the frequency of intense Atlantic hurricanes, *Science*, *327*, 454–458, doi:10.1126/science.1180568.

Bengtsson, L., et al. (2007), How may tropical cyclones change in a warmer climate, *Tellus, Ser. A*, *59*, 539–561.

Dvorak, V. F. (1984), Tropical cyclone intensity analysis using satellite data, *NOAA Tech. Rep. 11*, 45 pp.

Dvorak, V. F. (1995), The Dvorak tropical cyclone intensity estimation technique, *Rep. 1195*, Am. Meteorol. Soc., Boston.

Elsner, J. B., and T. H. Jagger (2008), United States and Caribbean tropical cyclone activity related to the solar cycle, *Geophys. Res. Lett.*, *35*, L18705, doi:10.1029/2008GL034431.

Elsner, J. B., J. P. Kossin, and T. H. Jagger (2008), The increasing intensity of the strongest tropical cyclones, *Nature*, *455*, 92–95, doi:10.1038/nature07234.

Emanuel, K. A. (1987), The dependence of hurricane intensity on climate, *Nature*, *326*, 483–485, doi:10.1038/326483a0.

Emanuel, K. A. (2005), Increasing destructiveness of tropical cyclones over the past 30 years, *Nature*, *436*, 686–688, doi:10.1038/nature03906.

Gray, W. M., C. W. Landsea, P. W. Miekle Jr., and K. J. Berry (1994), Predicting Atlantic basin seasonal tropical cyclone activity by 1 June, *Weather Forecast.*, *9*, 103–115, doi:10.1175/1520-0434(1994)009<0103:PABSTC>2.0.CO;2.

Henderson-Sellers, A., et al. (1998), Tropical cyclones and global climate change: A post-IPCC assessment, *Bull. Am. Meteorol. Soc.*, *79*, 19–38, doi:10.1175/1520-0477(1998)079<0019:TCAGCC>2.0.CO;2.

Holland, G. J., and P. J. Webster (2007), Heightened tropical cyclone activity in the North Atlantic: Natural variability or climate trend? *Philos. Trans. R. Soc. A.*, *365*, 2695–2716, doi:10.1098/rsta.2007.2083.

Kaplan, J., and M. DeMaria (2003), Large-scale characteristics of rapidly intensifying tropical cyclones in the North Atlantic basin, *Weather Forecast.*, *18*, 1093–1108, doi:10.1175/1520-0434(2003)018<1093:LCORIT>2.0.CO;2.

Kaplan, J., M. DeMaria, and J. A. Knaff (2010), A revised tropical cyclone rapid intensification index for the Atlantic and eastern North Pacific basins, *Weather Forecast.*, *25*, 220–241.

Karl, T. R., S. J. Hassol, C. D. Miller, and W. L. Murray (2006), Temperature trends in the lower atmosphere: Steps for understanding and reconciling differences, report, Clim. Change Sc. Program and the Subcomm. on Global Change Res., Washington, D. C.

Klotzbach, P. J. (2006), Trends in global tropical cyclone activity over the past twenty years (1986–2005), *Geophys. Res. Lett.*, *33*, L10805, doi:10.1029/2006GL025881.

Knaff, J. A., D. P. Brown, J. Courtney, G. M. Gallina, and J. L. Beven II (2010), An evaluation of Dvorak technique-based tropical cyclone intensity estimates, *Weather Forecast.*, *25*, 1362–1379, doi:10.1175/2010WAF2222375.1.

Knapp, K. R., M. C. Kruk, D. H. Levinson, H. J. Diamond, and C. J. Neumann (2010), The International Best Track Archive for Climate Stewardship (IBTrACS): Unifying tropical cyclone best track data, *Bull. Am. Meteorol. Soc.*, *91*, 363–376, doi:10.1175/2009BAMS2755.1.

Knutson, T. R., et al. (2006), Possible relationships between climate change and tropical cyclone activity, *Rep. 72*, Tropical Meteorol. Res. Programme, World Meteorol. Org., Geneva.

Knutson, T. R., et al. (2010), Tropical cyclones and climate change, *Nat. Geosci.*, *3*(3), 157–163, doi:10.1038/ngeo779.

Kossin, J. P., K. R. Knapp, D. J. Vimont, R. J. Murnane, and B. A. Harper (2007), A globally consistent reanalysis of hurricane variability and trends, *Geophys. Res. Lett.*, *34*, L04815, doi:10.1029/2006GL028836.

Kruk, M. C., K. R. Knapp, D. H. Levinson, H. J. Diamond, and J. P. Kossin (2009), An overview of the International Best Track Archive for Climate Stewardship, paper presented at 89th Annual Meeting, Am. Meteorol. Soc., Phoenix, Ariz.

Landsea, C. W., B. A. Harper, K. Hoarau, and J. A. Knaff (2006), Can we detect trends in extreme tropical cyclones?, *Science*, *313*, 452–454, doi:10.1126/science.1128448.

Oouchi, K., J. Yosimura, R. Mizuta, S. Kusonoki, and A. Noda (2006), Tropical cyclone climatology in a global-warming climate as simukated in a 20 kmmesh global atmospheric model: Frequency and wind intensity analyses, *J. Meteorol. Soc. Jpn.*, *84*, 259–276, doi:10.2151/jmsj.84.259.

Santer, B. D., et al. (2006), Forced and unforced ocean temperature changes in Atlantic and Pacific tropical cyclogenesis regions, *Proc. Natl. Acad. Sci. U. S. A.*, *103*, 13,905–13,910.

Uhlhorn, E. W., P. G. Black, J. L. Franklin, M. Goodberlet, J. Carswell, and A. S. Goldstein (2007), Hurricane surface wind measurements from an operational stepped frequency microwave radiometer, *Mon. Weather Rev.*, *135*, 3070–3085, doi:10.1175/MWR3454.1.

Vecchi, G. A., and B. J. Soden (2007), Increased tropical Atlantic wind shear in model projections of global warming, *Geophys. Res. Lett.*, *34*, L08702, doi:10.1029/2006GL028905.

Wallace, J. M., et al. (2000), *Reconciling Observations of Global Temperature Change*, Natl. Acad. Press, Washington, D. C.

Wang, B., and X. Zhou (2008), Climate variation and prediction of rapid intensification in tropical cyclone in the western North Pacific, *Meteorol. Atmos. Phys.*, *99*, 1–16, doi:10.1007/s00703-006-0238-z.

Webster, P. J., G. J. Holland, J. A. Curry, and H.-R. Chang (2005), Changes in tropical cyclone number and intensity in a warming environment, *Science*, *309*, 1844–1846, doi:10.1126/science.1116448.

Wilks, D. S. (2011), *Statistical Methods in the Atmospheric Sciences*, pp. 168–172, Academic Press, New York.