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Low Frequency Variability In Globally Integrated Tropical Cyclone Power Dissipation

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[1] Surface wind and temperature records from the European Centre for Medium- Range Weather Forecasts 40 Year Reanalysis (ERA-40) Project are used to estimate low-frequency variations in globally integrated tropical cyclone (TC) intensity from 1958 to 2001. For the first time, the annually integrated power dissipation (PD) is explicitly calculated on a global scale, and results show an upward trend in PD during much of the ERA-40 project period, although we argue this is at least partially due to limitations in cyclone representation in ERA-40. Comparing our estimated trend in PD with Emanuel's (2005) approximation to PD reveals good agreement after 1978, coinciding with the onset of a major satellite observing-system epoch in ERA-40. The low pass (>60 months) filtered PD time series correlates with mean annual tropical temperature, thus this result is consistent with the hypothesis that tropical temperatures may directly regulate the integrated intensity of TCs. **Citation:** Sriver, R., and M. Huber (2006), Low frequency variability in globally integrated tropical cyclone power dissipation, *Geophys. Res. Lett.*, *33*, L11705, doi:10.1029/2006GL026167.

1. Introduction

[2] Tropical Cyclone (TC) intensity and frequency vary on many time scales and due to a variety of forcings. TC distributions are hypothesized to be modulated by a number of natural phenomena, including the Atlantic Multidecadal Oscillation (AMO) [*Goldenberg et al.*, 2001], the Quasi-Biennial zonal wind Oscillation (QBO) [*Landsea et al.*, 1999], the North Atlantic Oscillation (NAO) [*Elsner et al.*, 2000], and the El Nino Southern Oscillation (ENSO) [*Pielke and Landsea*, 1999]. Although controversial, trends in the intensity of TCs have been noted, and linked potentially to changes in tropical sea surface temperatures (SST) associated with anthropogenic global warming. In particular, three recent studies have brought up the issue of the effect of anthropogenic warming on changes in TC frequency and intensity [*Emanuel*, 2005; *Trenberth*, 2005; *Webster et al.*, 2005], but the findings warrant further investigation with independent and objective methods.

[3] While it is well-established that thermodynamic controls on maximum potential TC intensity introduce a dependence of TC intensity on such factors as upper ocean heat content [*Emanuel*, 1999], controls on TC frequency, duration, and integrated intensity are less understood. The complex interaction between natural modes of variability on interannual-to-interdecadal time scales makes progress difficult, especially in the presence of relatively short observational records of varying accuracy and completeness. For example, the AMO, a multi-decadal temperature oscillation in the Atlantic ocean [*Delworth and Mann*, 2000], has been shown to correlate with changes in the numbers of major TCs affecting the eastern United States during the past 100 years [*Goldenberg et al.*, 2001]. The relative lull in Atlantic TC activity from the mid 1960's to the mid 1990's has been linked to the negative phase of the AMO, and the recent upswing in the number of intense TCs in the region has been roughly correlated with entering the AMO's positive phase [*Goldenberg et al.*, 2001]. On shorter time scales, the modes of variability discussed above are important, but the focus of this study is on assessing the long-term trends in TC activity so we do not discuss them further here. The time scale of low frequency fluctuations is comparable to the length of reasonably complete TC records, and this variability makes inferring any trends to global warming difficult [*Henderson-Sellers et al.*, 1998].

[4] Several recent studies have, however, sought to establish a correlation between trends in tropical SST and trends in TC frequency and intensity [*Emanuel*, 2005; *Webster et al.*, 2005]. Results of *Emanuel* [2005] show the potential destructiveness of TCs have increased during the latter half of the 20th century in the Atlantic and northwestern Pacific regions, and this increase appears to be well-correlated to tropical mean SST. Wind data from the early portion of the TC record is suspect, however, and interpretation is subject to arguably *ad hoc* assumptions. *Webster et al.* [2005] conclude that while the total number of TCs occurring globally remains fairly constant, the average number of intense hurricanes (category 4 and 5) occurring annually has increased since 1970 across all basins. *Webster et al.* [2005] avoid using *ad hoc* wind assumptions and adjustments by focusing only on TC activity from 1970 to 2004, corresponding to the satellite era. This choice of a shorter time period may result in less debate over the reliability of the wind data, but the time series may not reflect variability in longer time scale oscillations or provide enough data to establish conclusive evidence for the relationship between TC activity and tropical SST.

[5] Here we further investigate these issues by using near-surface wind data from the European Centre for Medium-Range Weather Forecasts Reanalysis (ERA-40) Project to examine low frequency variability in annual TC power dissipation (PD) [*Bister and Emanuel*, 1998; *Emanuel*, 1998, 2005] globally from 1958 to 2001. This approach complements previous estimates by utilizing a different data source, adopting a more objective analysis approach, and

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making fewer assumptions, although this approach does not come without its own costs. By focusing on low frequency PD variability, we eliminate shorter varying processes such as the QBO and ENSO. This paper is organized as follows: section 2 discusses the background theory of PD, section 3 details the methods used in our study, section 4 contains calculated PD trends and discusses the use of reanalysis data on the PD/SST correlations, and section 5 provides a summary of our conclusions and their implications.

2. Power Dissipation (PD)

[6] Recent studies comment on the observed increase in the occurrence of intense TCs and the possible link that may exist between this increase and changes in tropical SST. Power Dissipation (PD) [*Bister and Emanuel*, 1998; *Emanuel*, 1998, 2005] is an integrated measure of dissipation within TCs and is defined as:

$$PD = 2\pi \int_0^{\tau} \int_0^{r_0} C_D \rho |V|^3 r dr dt$$

where
C_D - surface drag coefficient
ρ - surface air density
$|V|$ - magnitude of the surface wind
and the integral is over the radius to an outer storm limit given by r_o and over τ, the lifetime of the storm. This quantity is a measure of the potential destructiveness of a TC based on surface wind speed and storm duration. Since historical records do not usually include storm dimensions, *Emanuel* [2005] approximates the total PD expression as the Power Dissipation Index (PDI) defined as:

$$PDI \equiv \int_0^{\tau} V_{max}^3 dt$$

where V_{max} is the maximum sustained wind speed at 10 meters. PDI assumes the product $C_D\rho$ is constant and that V over the storm's footprint scales with V_{max}. By calculating PDI for TCs occurring in the Atlantic and northwestern Pacific regions from 1950 to 2003, *Emanuel* [2005] showed the approximate measure of TC dissipation in these regions is highly correlated with tropical SST.

[7] By using the ERA-40 high-resolution wind data, we circumvent the geometric problems faced when using historical winds. Here we introduce our estimation of PD as:

$$PD \cong 2\pi C_D \rho \int_0^{\tau} \int_0^{r_0} |V|^3 r dr dt$$

where C_D and ρ are assumed constant and equal to 0.002 and 1 kg/m^3, respectively. In this expression for PD, we area integrate the ERA-40 wind field over each storm at 6 hour intervals. The inclusion of the area integral allows us to represent more accurately the TC wind profile with respect to PDI, which only includes the maximum sustained winds. By using ERA-40, we avoid making *ad hoc* and subjective adjustments to TC winds. Moreover, whereas the *Emanuel* [2005] study was limited to estimating PDI trends in the Atlantic and northwestern Pacific regions, here we calculate ERA-40-derived PD for all TCs globally. By using unadjusted wind data throughout the ERA-40 project period and including all TC activity globally, we are able to test more robustly the hypothesis that globally integrated TC dissipation is highly correlated with tropical SST.

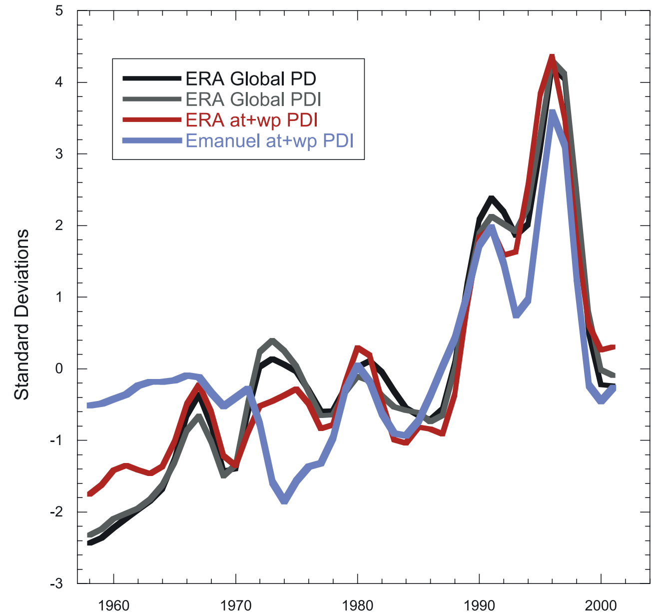

Figure 1. PD quantities for the ERA-40 project period, 1958–2001. ERA-40-derived quantities include global PD (black curve), global PDI (gray curve), and PDI for the Atlantic and northwestern Pacific regions (red curve). Also shown is the Atlantic and northwestern Pacific PDI derived from *Emanuel* [2005] data and filtered using the technique discussed in the methods section (blue curve). All curves are normalized with the respective standard deviations of the detrended time series.

[8] While shortcomings in the reliability of ERA-40 wind data exist, especially prior to 1979, we do not attempt to correct them here. Instead, results of this study are presented as an independent, uncorrected, and robust representation of trends in global TC activity as a compliment to the results of previous studies discussed above.

3. Methods

[9] We use 10 meter wind speed, two meter air temperature (2MT), and SST data from ERA-40 to investigate low frequency variability in trends of TC frequency and intensity. These data are analyzed 4 times daily at a spatial resolution of 1.125x1.125 degrees, and we have area weighted all data. The ERA-40 project period begins in September, 1957 and ends in August, 2002, and we use the time period from 1958 to 2001 for our study to achieve a global representation of TC activity.

[10] TCs have not been 'bogussed' into ERA-40 or otherwise adjusted or augmented to match observations beyond the standard process of assimilation [*Fiorino*, 2002] (Uppala, personal communication, 2006), which makes the results presented here truly independent of 'best track' approaches used in previous studies. Despite the lack of bogussing, *Uppala et al.* [2004] found that ERA-40 has a credible representation of aspects of TCs. After 1978,

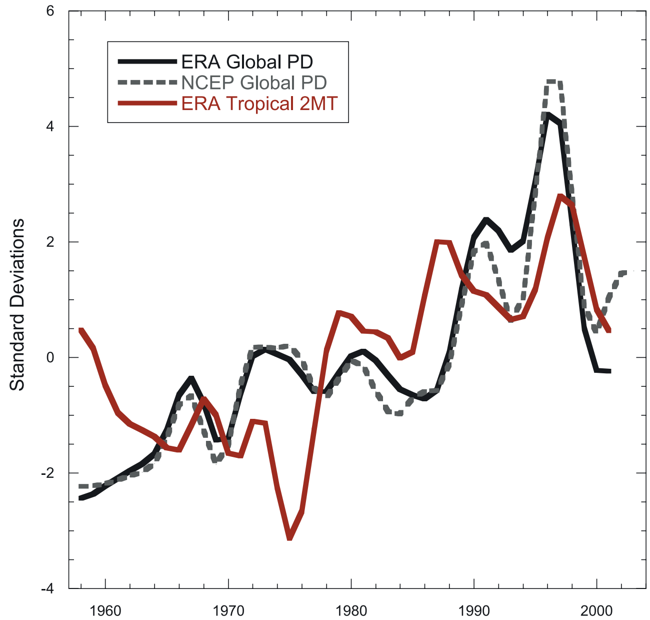

Figure 2. ERA-40-derived global PD (black curve), NCEP-derived global PD (dashed curve) and ERA-40 mean annual tropical 2MT (red curve). Tropical 2MT is averaged annually from 30 degrees north to 30 degrees south globally, and all curves are normalized with the respective standard deviations of the detrended time series. The correlation between ERA-40 PD and ERA-40 2MT is r^2 = 0.34.

consistently more than 90% of southern hemisphere TCs were detected in ERA-40, whereas 90% or more of TCs occurring in the northern hemisphere were detected throughout the entire project period [*Uppala et al.*, 2004]. This success provides an initial basis for our study, indicating that—at least after 1978—ERA-40 might contain useful information about TC activity. Furthermore, an initial analysis of the Accumulated Cyclone Energy (ACE) index [*Trenberth*, 2005] calculated from the maximum sustained 'best track' wind speeds in the Atlantic basin compares favorably with ACE derived from ERA-40 surface winds. Preliminary results yield a correlation of r^2 = 0.86 between the two time series (see auxiliary material[1] Figure S1), supporting the notion that ERA-40 reanalysis correctly distinguishes TC winds from the background wind field.

[11] TC tracks were obtained (Emanuel, personal communication, 2005) and are derived from the 'best track' tropical data sets with positions updated every six hours. Tracks from the North Atlantic and northeastern Pacific basins are originally from the National Oceanographic and Atmospheric Administration's Tropical Prediction Center, and tracks from the northwestern Pacific, northern Indian, and southern hemisphere are originally from the U.S. Navy's Joint Typhoon Warning Center. For wind analysis, TC size is assumed constant for all storms, and winds are integrated over a spatial domain of $7° \times 7°$ for the lifetime of every storm. Sensitivity experiments were carried out using multiple domain spatial scales, and maximum integrated winds were achieved at this resolution (see Figure S2).

[12] In this study we show results that are low pass filtered to minimize short-term variability using a Lanczos filter [*Duchon*, 1979]. This filter is applied once to every time series using 11 weights to filter out variability shorter than 5 years. Greater than 50% of the variance is retained at time scales greater than 60 months, and greater than 90% is retained at time scales greater than 80 months.

4. Results and Discussion

[13] Figure 1 shows the annually integrated, normalized ERA-40-derived global PD, global PDI, Atlantic and northwestern Pacific PDI, and Emanuel's PDI for the Atlantic and northwestern Pacific regions. The quantities derived from ERA-40 all exhibit good agreement with each other, and Figure 1 shows that all series experience an upward shift after 1985. Furthermore, the ERA-40-derived PD and PDI curves are essentially the same, thus, trends in maximum sustained TC winds are nearly identical to trends in the area-integrated storm winds. This result supports the idea that quantities derived from maximum sustained TC winds, such as PDI and ACE, serve as good approximations for area-integrated PD. Consequentially, estimates of integrated PD based on 'best track' winds should be reasonably accurate.

[14] Comparison of ERA-40 PDI and *Emanuel* [2005] PDI data in Figure 1 shows the latter to be over-represented from 1958 to 1966 and under-represented from 1972 to 1978 with respect to ERA-40. Thus, compared to our analysis, *Emanuel* [2005] may underestimate the magnitude of the upward trend in TC activity during the early portion of the record. This early period does, however, contain less reliable surface data in ERA-40. Therefore, the difference in the shape of the curves may also be attributed to shortcomings in ERA-40 [*Fiorino*, 2004].

[15] From Figure 1, ERA-40-derived global PD and PDI exhibit good agreement with *Emanuel*'s [2005] PDI. This agreement suggests *Emanuel's* [2005] PDI calculations confined to the Atlantic and northwestern Pacific regions serve as an adequate approximation for representing trends in global PD and PDI.

[16] The normalized global PD calculations from ERA-40 10 meter wind data is plotted with ERA-40 mean annual tropical 2MT in Figure 2. To further demonstrate the robustness of reanalysis data, PD derived from the National Centers for Environmental Prediction (NCEP) Reanalysis is also plotted in Figure 2. ERA-40 PD correlates with 2MT (r^2 = 0.34) and the correlation improves somewhat (r^2 = 0.40 (see Table 1 and Figure S3)) when PD is compared with mean annual tropical SST. Thus a substantial portion of the low frequency variance in globally integrated PD can be ascribed to changes in mean tropical temperatures. As summarized in Table 1, when correlations are calculated between PD quantities and both mean annual tropical 2MT and SST, better correlations are obtained using SST. Prior to 1982, however, ERA-40 SST is based on monthly Hadley SST climatology, and from 1982 on, SST is from weekly Optimal Interpolation SST (OISST) of NCEP [*Fiorino*, 2004].

[1] Auxiliary material is available in the HTML.

Table 1. Statistical Results for ERA-40-Derived PD Quantities and Mean Annual Tropical SST and 2MT[a]

				Correlation, R^2		Linear Regression		Correlation Prob., T-Test	
		Mean	Standard Deviation	ERA-40 2MT	ERA-40 SST	ERA-40 2MT	ERA-40 SST	ERA-40 2MT	ERA-40 SST
ERA global PD	1958–1978	2.81 e19 J	2.26 e18	0.33	0.32	−0.57	−0.57	0.0063	0.0080
ERA global PD	1979–2001	3.81 e19 J	6.53 e18	0.31	0.40	1.11	1.11	0.0060	0.0012
ERA global PD	Total	3.33 e19 J	4.93 e18	0.34	0.40	0.67	0.65	<0.0001	<0.0001
ERA global PDI	1958–1978	1.65 e8 J/m^2	1.26 e7	0.33	0.33	−0.57	−0.59	0.0067	0.0063
ERA global PDI	1979–2001	2.19 e8 J/m^2	3.54 e7	0.33	0.44	1.18	1.2	0.0045	0.00057
ERA global PDI	Total	1.94 e8 J/m^2	2.69 e7	0.33	0.39	0.66	0.65	<0.0001	<0.0001
ERA at+wp PDI	1958–1978	9.52 e7 J/m^2	6.60 e6	0.32	0.25	−0.32	−0.28	0.0070	0.020
ERA at+wp PDI	1979–2001	1.27 e8 J/m^2	2.34 e7	0.24	0.36	1.01	1.1	0.019	0.0024
ERA at+wp PDI	Total	1.12 e8 J/m^2	1.74 e7	0.35	0.43	0.63	0.63	<0.0001	<0.0001
Emanuel at+wp PDI	1958–1978	1.67 e9 J/m^2	3.00 e8	0.15	0.13	0.25	0.24	0.084	0.11
Emanuel at+wp PDI	1979–2001	2.14 e9 J/m^2	4.39 e8	0.40	0.42	1.05	0.95	0.0013	0.00078
Emanuel at+wp PDI	Total	1.92 e9 J/m^2	3.76 e8	0.47	0.48	0.57	0.52	<0.0001	<0.0001
ERA tropical 2MT	1958–1978	297.67 K	0.106	-	0.95	-	0.99	-	<0.0001
ERA tropical 2MT	1979–2001	297.88 K	0.063	-	0.83	-	0.80	-	<0.0001
ERA tropical 2MT	Total	297.78 K	0.089	-	0.96	-	0.98	-	<0.0001
ERA tropical SST	1958–1978	298.94 K	0.104	0.95	-	0.99	-	<0.0001	-
ERA tropical SST	1979–2001	299.15 K	0.049	0.83	-	0.80	-	<0.0001	-
ERA tropical SST	Total	299.05 K	0.082	0.96	-	0.98	-	<0.0001	-

[a]We also include PDI for the Atlantic and northwestern Pacific regions based on *Emanuel* [2005] data for comparison. Only data overlapping with the ERA-40 project period is used, and the *Emanuel* [2005] data is filtered in the same manner as the ERA-40-derived quantities. The table displays statistics for three different time intervals: 1958–1978, 1979–2001, and 1958–2001. Correlation and linear regression coefficients are calculated along with significance levels. The early series represents the time frame prior to the inclusion of reliable satellite data into ERA-40.

[17] To further investigate an empirical relationship between SST and PD, a regression fit is calculated between these two variables and shows that a 0.25 °C increase in mean annual tropical SST corresponds roughly to a 60% increase in global PD (see Figure S4).

5. Conclusions and Implications

[18] Annually integrated global PD is calculated for the first time using ERA-40 winds, and resulting trends from 1958–2001 are analyzed against trends in mean annual tropical temperatures. We find that ERA-40 estimates of TC trends are consistent with independent analyses by *Emanuel* [2005], *Webster et al.* [2005], and *Trenberth* [2005]—ERA-40 may be a useful tool for analyzing TC variability. Furthermore, agreement with NCEP Reanalysis suggests these reanalysis products are faithfully and robustly reproducing important elements of TC climatology. Given the lack of spatio-temporal resolution in reanalysis data, the ability to reproduce trends in TC activity with respect to 'best track' wind records serves as support for the robustness of this data.

[19] We find that global mean PD exhibits a 25% increase between the periods 1958–1978 and 1979–2001. This increase suggests the recent observed increase in TC activity may be related to observed trends in tropical temperatures, though ERA-40 surface data prior to 1979 exhibits some deficiencies in detecting the extent of TC activity, especially in the southern hemisphere. The PD trend agrees with tropical temperature records, exhibiting a correlation of $r^2 = 0.34$ for tropical 2MT and $r^2 = 0.40$ for tropical SST. Thus, PD is an important quantity that appears to correlate with trends in tropical temperatures and may be an important feature for understanding the long-term evolution of integrated TC intensity.

[20] Our analysis of ERA-40 data indicates that trends in the maximum sustained TC winds are essentially identical to trends in integrated storm winds. This result indicates that derived quantities based only on maximum winds, such as PDI and ACE, serve as reasonable approximations for area-integrated PD. Consequentially, estimates of PDI and ACE based on 'best track' winds should be reasonable indicators of global TC activity.

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