Northern Hemisphere tropical cyclone activity

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[1] Recent historical Northern Hemisphere (NH) tropical cyclone (TC) inactivity is compared with strikingly large observed variability during the past three decades. Yearly totals of the combined active-basin NH accumulated cyclone energy (ACE) are highly correlated with boreal spring sea-surface temperature (SST) in the North Pacific Ocean and are representative of an evolving dual-gyre, trans-hemispheric correlation pattern throughout the calendar year. The observed offsetting nature of Eastern Pacific and North Atlantic basin ACE during the past three decades and a strong dependence of combined Pacific TC activity upon the El Niño-Southern Oscillation reflect the interrelated modulation of overall NH integrated TC energy by large-scale modes of climate variability. Thus, the quiescent period of overall integrated NH TC ACE continuing throughout 2008 is not unexpected in the context of previous periods of colder Pacific SSTs.
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1. Introduction

[2] During 2007, the major active basins of the Northern Hemisphere (NH) combined for historically low levels of integrated tropical cyclone (TC) energy (Figure 1) as measured by the accumulated cyclone energy index (ACE) [*Bell and Chelliah*, 2006]. This remarkable NH TC inactivity has motivated an investigation into potential explanations for the strikingly large variability observed during the past three decades.

[3] *Emanuel* [2005] utilized the TC power dissipation index (PDI) metric, analogous to ACE, and discovered highly-significant correlations with low-frequency local summer SST during the past 30 years, mainly in the NA. In addition to the potential role of global warming for the observed TC power increases in the NA [e.g., *Emanuel*, 2005], other potential climate factors posited have included the Atlantic Multidecadal Oscillation (AMO) [e.g., *Goldenberg et al.*, 2001], the Atlantic Meridional Mode (AMM) [*Kossin and Vimont*, 2007], which is the leading mode of coupled-ocean atmosphere variability in the Atlantic, as well as the El Niño-Southern Oscillation (ENSO) [e.g., *Gray*, 1984; *Landsea et al.*, 1998; *Bell and Chelliah*, 2006]. In the Western North Pacific (WP) basin, both ENSO and the Pacific Decadal Oscillation (PDO) have been shown to modulate intense typhoon activity on multidecadal time scales [*Chan*, 2007].

[4] Here, the long-term climatology of NH TC activity is examined as a whole and established inter-basin TC relationships [*Frank and Young*, 2007] are incorporated to link NH ACE with large-scale climate variability. Throughout the study, NH ACE is defined as the *combined* total of each individual active basin during the calendar year. It is discovered that NH ACE is closely related to the evolution of SST structure in the Pacific and especially well-correlated with *boreal spring* Gulf of Alaska SST. However, in the NA, a conclusion that changes in North Pacific (NP) climate variability are directly impacting hurricane behavior cannot be firmly established. Nevertheless, there is evidence to suggest that the recent uptick in NA activity primarily since 1995 corresponds with a concomitant decrease in Eastern Pacific (EP) integrated hurricane energy. The downturn in EP and WP ACE is consistent with previous periods of overall colder Pacific SSTs and generally shorter-lived, weaker storms. If combined NH TC ACE variability simply serves as a proxy for NP SST and its attendant large-scale, low-frequency climate variability in a similar way as MDR SST serves as a proxy for NA ACE, then new insight may be gained into the respective role of tropical cyclones in climate.

2. Northern Hemisphere Tropical Cyclone Accumulated Cyclone Energy

[5] The ACE integrated TC activity metric [*Bell and Chelliah*, 2006] convolves frequency, duration, and intensity as provided in the historical best-track datasets (auxiliary material[1]), and all three components co-vary in each basin and are not independent. *Klotzbach* [2006] reported that the record of NH and global ACE during the 20-year period of 1986–2005 failed to exhibit a significant trend with large variability. Yet, the remarkable correlations between ACE and tropical SST [*Emanuel*, 2005] or relative SST [*Swanson*, 2008] in the main development region (MDR) of the NA suggested that ACE (or PDI) reflects a more fundamental metric of global climate than its individual components separately [*Emanuel*, 2007].

[6] The large NH TC ACE variability is a synthesis of the individual basin contributions. Figure 1 demonstrates through stacked bars calendar year sums of WP+Northern Indian Ocean (NIO) (bottom), EP (middle), and NA (top) ACE. NH ACE for the calendar year 2007 amounted to a value of 386 (x10^4 knots^2), less than half of 2004's output when the WP basin itself exceeded 2007's overall total. Preliminary operationally available TC tracks through December 2008 show similar levels of continuing inactivity with NH ACE totals at 400. The specific ACE and hurricane days (HDAYS) breakdown per basin and yearly mean values according to climatology (1981–2006) are highlighted in Table 1. Comparison with the box-and-whisker inset of Figure 1 clearly shows that 2007 and 2008 will reside in the lowest quartile of the NH ACE distribution since 1981. Sharply lower

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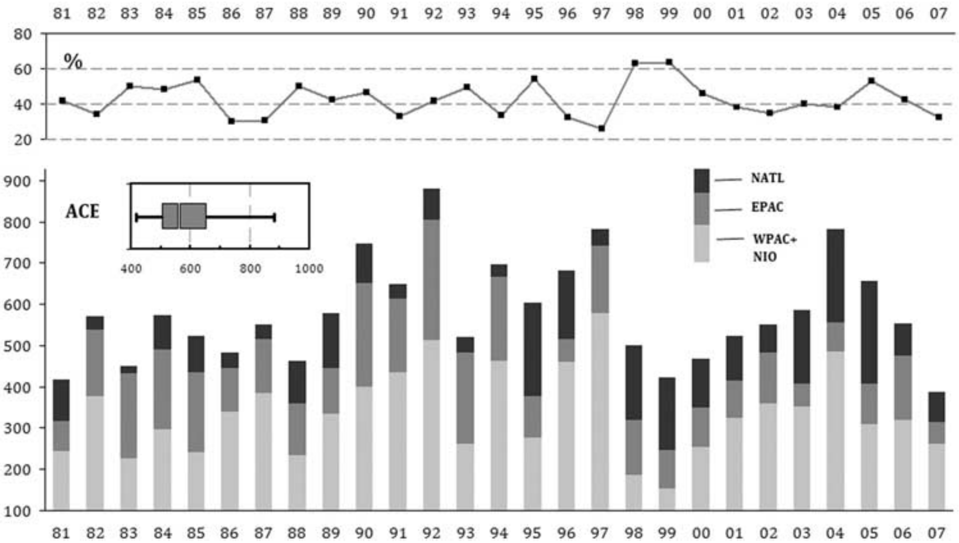

Figure 1. Raw values of Northern Hemisphere and individual basin ACE from 1981–2007 (shaded bar chart). The stacked bars include ACE for the WP+NIO (bottom), EP (middle), and NA (top; darkest) basins. The inset box and whisker plot shows the distribution of NH ACE from 1981–2006 with the median separator between the two rectangles representing the areas encompassed by the first and third quartiles. The total distribution is indicated by the barbed endpoints. Ratio of NH ACE occurring in the EP+NA in percent.

NH ACE was experienced in 1977 (~250), with admittedly more uncertain data prior to the launch of Japan's GMS-1 geostationary satellite in July 1977 (prior temporal sampling was less frequent with only polar orbiters).

[7] Since yearly ACE is the integration of individual storm events and their respective intensity and duration, long-lived (~weeks) major TCs (Category 3+) with trans-basin tracks, while less frequent than weaker storms, contribute disproportionately more to the ACE calculation. Indeed, the distribution of NH ACE per storm in the record examined (1981–2008) clearly shows a long tail toward high-ACE storms (Figure S1). For the 2007–2008 period, the median (75th percentile) ACE per storm was 3.0 (10.5) compared to the climatological value of 5.2 (13.8). Thus, further examination is warranted for understanding not only the evolution of TC maximum winds throughout the data record, but also individual ACE per storm (Figure S1), which can be significantly influenced by ENSO especially in the WP [*Camargo and Sobel*, 2005] and the AMM in the NA [*Kossin and Vimont*, 2007].

[8] The development of a strong La Niña event during 2007–2008 clearly affected Pacific basin TC activity [*Chan*, 2000]. For example, TC genesis locations in the WP are shifted southeastward towards the dateline during El Niño events which generally portend longer-lived and more intense TCs with some originating in the Central Pacific (i.e., Ioke in 2006). Modified steering currents are also more readily favorable for these lower-latitude storms to recurve into the extratropics and garner considerable ACE during long lifecycles [*Camargo and Sobel*, 2005].

3. Atlantic and Pacific Basin Relationships

[9] Understandably, less attention has been focused upon the dramatic decline in EP hurricane activity and ACE during the past decade [e.g., *Klotzbach*, 2006; *Kossin et al.*, 2007] compared to the NA, which experiences more numerous storms with significant societal impact. Indeed, average combined EP+NA ACE (Figure S2) in two separate 13 years periods (1982–1994) and (1995–2007) is nearly identical and exhibits no significant trend. Figure 1 shows the percentage contribution of EP+NA ACE to the NH total in simple ratio terms without any temporal filtering. It should be noted that there is considerable variability in this quantity and it is a reflection of the WP basin ACE activity since it is the residual of the full NH total. The NIO basin contributes on average 3% of NH ACE but its coastal nations experience a disproportionate frequency of devastating, intense cyclones like Sidr in 2007 and Nargis in 2008.

[10] The relative stability of the EP+NA/NH ratio has not been previously identified and seems hardly a coincidence. Indeed, it appears to be a consequence of well-understood ENSO and slower PDO variability in the Pacific basin and

Table 1. Ratio of Each Basin ACE to the NH Total is Calculated for 1981–2006 Climatology From the Historical Best-Track Data[a]

	2007 Year ACE	1981–2006 Year Mean ACE (% of NH Total)	2007 HDAYS (*0.25)	1981–2006 Mean HDAYS
NH	386	585	327	526
NATL	72	105 (18%)	49	97
WPAC	215	322 (55%)	212	288
EPAC	53	142 (24%)	35	131
NIO	46	16 (3%)	31	10

[a]ACE for NH, Northern Hemisphere; NATL, North Atlantic; WPAC, North Western Pacific; EPAC, North Eastern Pacific; NIO, Northern Indian basins. HDAYS are equivalent to each 6-hourly tropical cyclone observation of maximum sustained winds greater than 64 knots.

the somewhat less understood relationships between quasi-cyclical decadal variability, ENSO, AMM, and other interannual fluctuations in the Atlantic. The offsetting nature of the yearly ACE between the basins reasonably suggests that the recent NA upward trend has not occurred in a vacuum isolated from the rest of the NH and global large-scale climate system but may have significant and as yet poorly understood interplay.

[11] Even though the EP and NA are not physically linked via the ocean, ENSO teleconnections, local coupled meridional modes [e.g., *Chiang and Vimont*, 2004; *Kossin and Vimont*, 2007], and the quasi-monthly Madden Julian Oscillation (MJO) [*Aiyyer and Molinari*, 2008] can impact the geographic distribution of TC genesis locations and the environmental favorability for intensification through the modification of atmospheric vertical shear and steering flow [*Bell and Chelliah*, 2006]. The evolution of upper-level circulation patterns associated with ENSO events directly influences the effects of vertical shear on both the EP and NA basins [*Landsea et al.*, 1998; *Goldenberg et al.*, 2001]. Furthermore, the convective phase of the MJO may enhance the cyclonic shear of the low-level zonal wind aiding in the reversal of the background potential vorticity gradient crucial for instability and wave energy growth [*Molinari et al.*, 1997; *Aiyyer and Molinari*, 2008].

[12] Through satellite imagery, African easterly wave (AEW) disturbances in the EP have been traced backwards for many TC genesis events to the African coast [*Frank and Roundy*, 2006]. If these TC seedlings developed into NA storms, had their circulation disrupted by vertical shear, or were deflected out of the lower-latitude MDR intensification zone, then the AEWs would be unavailable to the EP basin for development. Even if the waves progress into the EP, there is still no guarantee of development. In addition to in situ environmental conditions, non-local modification of vertical shear and many other aspects of the coupled atmosphere-ocean system by larger-scale climate will also directly impact AEW development [*Goldenberg et al.*, 2001; *Vecchi and Soden*, 2007a].

[13] The compensatory or offsetting nature of ACE during the past three decades between the basins at least suggests a hypothesis that the modulation of AEW activity by large-scale climate variability is critically important in both basins [e.g., *Bell and Chelliah*, 2006; *Kossin and Vimont*, 2007]. However, the exact role of the various mechanisms and inter-basin feedback remains to be quantified.

[14] Additional analysis finds high monthly correlations between 24-month backwards sums of the multivariate ENSO index (MEI) [*Wolter and Timlin*, 1998] and combined EP+WP ACE especially since the late 1980s (Figure S3). As ENSO events are locked to the seasonal cycle, they peak in the winter after the TC active period in autumn. The utilization of 24-month sums allows for integration of TC activity on scales closer to ENSO (2–7 years). This has the distinct advantage of capturing the winter and spring WP activity that is associated with the previous or ongoing ENSO event [*Camargo and Sobel*, 2005]. This robust relationship between monthly ACE and MEI provides further evidence that integrated metrics of TC activity may represent fundamental and important aspects of the climate state, and, in this case, Pacific ACE on ENSO.

4. Relationship With SST

[15] In the NA, filtered seasonal totals of ACE are poorly related with ENSO as shown by weak correlations of August–October Hadley Centre SST [*Rayner et al.*, 2003] in the tropical Pacific with NA ACE (Figure 2 (top)). It is apparent that the global warming trend in low-frequency North Atlantic SSTs is exceptionally well correlated with the upward trending NA ACE from 1981–2007, which has been demonstrated by *Emanuel* [2005] for the NA MDR. However, the similarly high correlations in *austral winter* in the South Pacific demonstrate the difficultly in attributing NA integrated TC metrics to coincident trends in local SST [*Kossin and Vimont*, 2007; *Vecchi and Soden*, 2007b; *Swanson*, 2008].

[16] The entire NH ACE and global SST correlation map (Figure 2 (bottom)) for the period 1981–2007 exhibits a striking trans-hemispheric scale, double gyre structure with very high correlations in the North Pacific during *boreal spring* (April–June). The structure of the correlations evolves throughout the calendar-year with maximum values during boreal spring (Figures S4a–S4j). Remarkably, during the previous three decades, NH TC ACE has reflected Gulf of Alaska SST during April–June to a highly significant degree ($R > 0.95$). It should be noted that the strong correlations remain irrespective of low-frequency filtering procedures, yet the degrees of freedom are still few.

[17] As expected from Figure S3, correlations between WP+EP ACE and SST show strong tropical Pacific sensitivity associated with ENSO (Figure S5). From an evaluation of each individual basin's ACE against SST during April–June (Figures S6a–S6d) and the calendar year (Figures S7a–S7d), only the WP basin (which on average contributes 55% of NH ACE) demonstrates a similar correlation pattern to that of the overall NH ACE (Figure 2 (bottom)). Since the NA and EP ACE time series exemplify strong but opposing trends (Figure S2), relationships with global SST on long time scales will indubitably be dominated by the observed warming trend during the past three decades especially in the tropical North Atlantic [*Emanuel*, 2005].

5. North Pacific SST Variability

[18] The striking relationship between NH TC ACE and extratropical NP SST appeals to an inherent and overarching mechanism of climate variability linking the tropics and extratropics on seasonal and longer time scales. The leading tropical mode of variability is well-established to be ENSO, but how it manifests itself spatiotemporally with respect to North Pacific climate is still the subject of considerable research [e.g., *Newman*, 2007]. Thus, it is hypothesized that the correlation pattern between NH ACE and boreal spring NP SST arises from the slow evolution of the large-scale modes of interannual climate variability. While the TCs themselves directly influence in situ SST anomaly patterns, there is currently little evidence to suggest that TCs represent a causal mechanism for non-local, extratropical Pacific SST variability.

[19] Previous studies have elucidated upon the dominant modes of North Pacific climate variability including the PDO [*Mantua et al.*, 1997], interdecadal Pacific signal (IPS) [*Frauenfeld et al.*, 2005], North Pacific Oscillation (NPO) [*Rogers*, 1981; *Linkin and Nigam*, 2008], and its oceanic

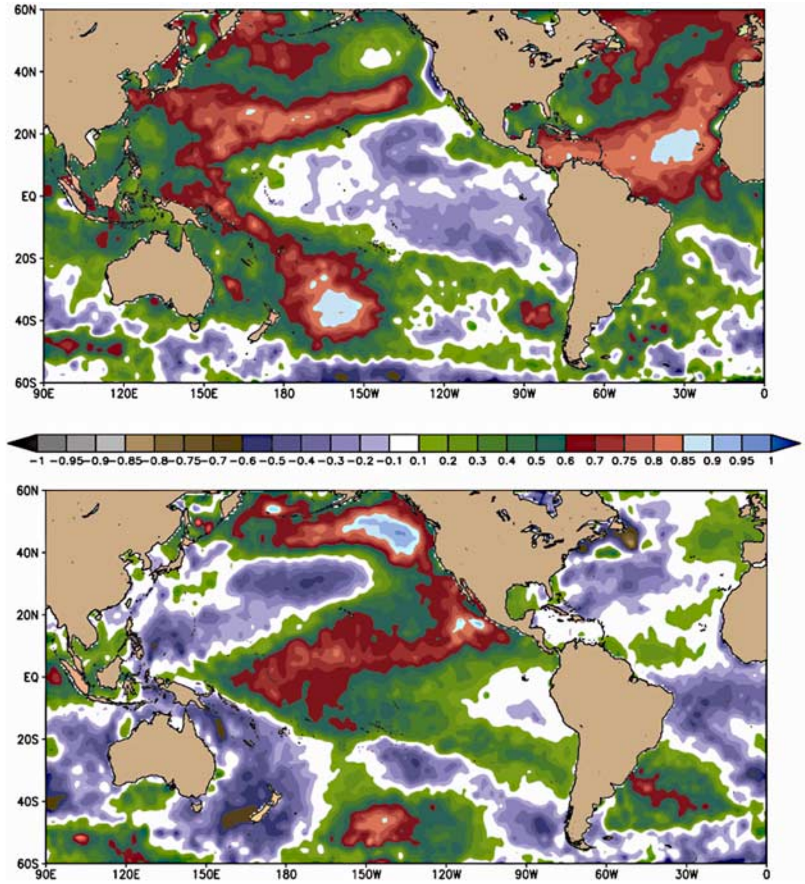

Figure 2. (top) Correlation map between NA ACE and August–October monthly mean SST for 1981–2007 with a 1-2-1 filter applied once. (bottom) Correlation map between NH ACE and April–June SST (1981–2007).

expression, the recently observed North Pacific Gyre Oscillation (NPGO) [*Di Lorenzo et al.*, 2008]. The latter NPO/NPGO was posited as a quasi-decadal coupled oscillation which is significantly correlated with fluctuations of salinity, nutrients, and fish stocks in the Northeast Pacific. Initially identified as the Victoria Mode [*Bond et al.*, 2003], the NPGO is the second EOF of North Pacific climate variability (PDO is first EOF). Indeed, the correlation pattern between the NPGO and SST anomaly map [*Di Lorenzo et al.*, 2008, Figure 4b] closely resembles the structure of Figure 2 (bottom), which implicated tropical coupled dynamics in the forcing of the NPGO and associated ecosystem changes.

[20] The NPO [*Rogers*, 1981; *Linkin and Nigam*, 2008] is primarily driven by internal, stochastic dynamics during boreal winter that affect the intensity of the subtropical high and therefore modulate the strength of prevailing trade winds. In the NP, the peak variability of the atmospheric NPO mode occurs in boreal winter through an accumulation of storm tracks and the modulation of the semi-permanent Aleutian Low.

[21] If the NP acts as a climate integrator [*Newman et al.*, 2003; *Newman*, 2007] of previous ENSO phases, then it follows that some manifestation of the integrated TC memory is retained in the NP SST in a proxy sense. That is to say the atmosphere-ocean conditions which favor enhanced or decreased TC activity are retained in patterns of SST variability. Obviously the TCs themselves are not responsible for the patterns of SST on large-scales, especially in the extratropics during winter.

6. Discussion

[22] 1. NH ACE (Figure 1) continues through 2008 at low-levels reminiscent of other cold periods of Pacific climate including the late-1990s and the so-called climate shift of 1977: the previous lowest ACE year prior to 2007.

[23] 2. EP+NA ACE has largely compensated during the past three decades and exhibits no significant trend (Figure S2). The increase in NA TC frequency and intensity mainly since 1995 has corresponded to a concomitant downturn in the EP. The overall ratio of EP+NA ACE has remained stable throughout the period examined.

[24] 3. Running sums of 24-month of ENSO and Pacific basin ACE correspond very closely especially during the past 20-years (Figure S3).

[25] 4. Combined NH basin ACE is highly correlated with SST across the Pacific (Figure 2 (bottom)). Individually, only WP ACE is well-correlated with NH ACE. The NA and EP ACE correlations with SST are dominated (inversely so) by regions of coincident long-term warming trends in SST (Figures S5 and S6).

[26] It is not clear why the number of global cyclones each year (80–90) has remained a long-term constant of nature. Previous analysis showed that the interannual variability in

large-scale climate patterns affected TC formation regions and intensity in different ways [*Frank and Young*, 2007]; this conclusion is clearly in accord with previous TC climatology studies including the results presented here. Global and NH ACE are not a constant of nature [*Klotzbach*, 2006], and undergo significant variability as exemplified by the tepid totals of 2007 and 2008. Thus, the enhanced longevity and proclivity of intense TCs dominate in so-called active years, which contribute considerable ACE, are the result of genesis location shifts and the beneficial prevailing environmental conditions such as weakened vertical shear modulated by large-scale climate variability.

[27] The structure of the Pacific correlation pattern of SST with NH ACE suggests that considerable predictive information for the upcoming NH TC year is present in boreal spring. Furthermore, when acknowledging the role of ENSO in modulating WP+EP TC ACE, winter midlatitude storm activity imprinting upon boreal spring NP SST, and the interrelated basin climatology described above, NA ACE activity falls out as a *residual* of the NH minus WP+EP ACE total. This suggests an additional null hypothesis to the NA global warming and hurricanes puzzle: the NA increase in activity since 1995 is part of large-scale hemispheric climate variability with clear association to the EP *against* a backdrop of local and relative NA tropical SST increases.

[28] To understand the evolution of TCs in a future climate, an adequate understanding of the mechanisms controlling current and past TC activity is critical to identifying exactly what features of climate will indeed change, especially in the Pacific basin [*Vecchi and Soden*, 2007a; *Vecchi et al.*, 2008]. The evolution of NP SST signals may provide a fruitful area for further research into climate modulation of global TC variability.

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