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An inverse relationship between aggregate northern hemisphere tropical cyclone activity and subsequent winter climate

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[1] Our understanding of the climate role of tropical cyclones (TCs) remains incomplete despite increasing efforts to quantify it. TCs cool the sea surface over a large area, transport heat vertically and meridionally, and dry the tropical atmosphere. Following an anomalous TC season, when TCs have done an anomalous share of energy transport, there may be alterations of other climate mechanisms. Accordingly, a robust inverse relationship between northern hemisphere (NH) TC activity and NH winter climate is explored here. Specifically, aggregate power dissipation index for NH Pacific recurving TCs is the current optimal predictor ($r = -0.57$; $p < 0.01$) of NH winter stationary meridional temperature flux. TC-winter climate causality would not only argue for an elevated climate role of TCs, but would present an autumn predictability barrier given the limited skill in forecasting seasonal TC activity details. A proxy relationship would suggest undiagnosed coupled climate mechanisms that have control over both the tropics and extratropics. **Citation:** Hart, R. E. (2011), An inverse relationship between aggregate northern hemisphere tropical cyclone activity and subsequent winter climate, *Geophys. Res. Lett.*, *38*, L01705, doi:10.1029/2010GL045612.

1. Introduction

[2] Tropical cyclones (TCs) warm the sub-surface ocean [*Shay et al.*, 1989; *Boos et al.*, 2004], cool the sea surface over a large area (Table 1 and Figure S1) [*Hart et al.*, 2007; *Schenkel and Hart*, 2010] through vertical mixing and meridional oceanic transport [*Emanuel*, 2001; *Sriver and Huber*, 2007; *Hu and Meehl*, 2009; *Jansen and Ferrari*, 2009; *Jansen et al.*, 2010], transport atmospheric heat vertically and meridionally [*Sobel and Camargo*, 2005; *McTaggart-Cowan et al.*, 2007], and dry the tropical atmosphere due to increased precipitation efficiency [*Emanuel*, 2008]. Following an anomalous TC season, when TCs have done an anomalous share of transport, there may be subsequent alterations of other climate mechanisms.

[3] Indeed, the perceived climate role of TCs has evolved from passive response to include active forcing as our observations, modeling, and understanding have improved. Considerable prior research has illuminated relationships between TC activity and large scale climate (ENSO [*Gray*, 1984], NAO [*Elsner and Kocher*, 2000], AMM [*Vimont and Kossin*, 2007]), and anthropogenic warming [*Knutson et al.*, 2010]. Reversing the arrow, and asking whether anomalous TC activity precedes anomalous winter climate is equally important, and is explored here. Not only do such relationships beg at the fundamental question of the climate role of TCs, they may influence the ability to predict climate.

2. Methodology

[4] TC data is represented by the official best-track datasets provided by the National Hurricane Center (Atlantic and east Pacific [*Neumann et al.*, 1993]) and the Joint Typhoon Warning Center (Western North Pacific basin [*Chu et al.*, 2002]). TCs from the north Indian Ocean Basin are not included given their far more uncertain historical record [*Landsea et al.*, 2006; *Kossin et al.*, 2007], and their much shorter lifespan and latitudinal expanse. TC activity is quantified from the most simplistic (counts) to more physically meaningful (power dissipation index; PDI). The various metrics and subsets of TC activity are defined in Table S1 of the auxiliary material.[1]

[5] Winter climate is quantified using the NCEP/NCAR (NNR) [*Kalnay et al.*, 1996] and ERA40 reanalyses [*Uppala et al.*, 2005] and among various periods (1960–2008, 1970–2008, 1970–2001, 1980–2008) to quantify the robustness of relationships across an evolving observational network. Winter climate activity is measured by the meridional temperature flux of the stationary eddies (standing waves),

$$\left[\overline{v}^{*}\overline{T}^{*}\right] \qquad (1)$$

where v is the meridional wind at a given pressure level, T is the temperature, [] is zonal mean, overbar is a temporal average, and * is anomaly from zonal mean. This measure of winter climate was chosen as it summarizes the hemispheric winter pattern that exists over a considerable time period, is particularly sensitive to the land-ocean (temperature) distribution—both zonally and meridionally—as well as snowcover distribution [*Saito and Cohen*, 2003]. The stationary eddy pattern also largely guides the individual winter storms–as quantified by the transient eddies–through the midlatitudes, further illustrating the fundamental role of the stationary eddies in winter climate. Other components of the total meridional temperature flux decomposition were examined (mean meridional circulation, transient eddies, and total flux). Although not shown here, there is an expected inverse relationship between the anomalous stationary eddy flux and the anomalous transient eddy flux [*Trenberth and Stepaniak*, 2003]. The total flux still showed statistically significant (although weaker) relationships to aggregate TC activity, suggesting that the TC-winter relationship is not simply that of perfectly compensating redistribution of energy among the three flux components.

[6] To refine the TC-winter climate relationship, regression was performed using numerous climate and TC mea-

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Table 1. Annual Area Swept Out by TCs[a]

	Equator to 35°N		Equator to 70°N	
Basin	Ignoring Overlap	Including Overlap	Ignoring Overlap	Including Overlap
N. Atlantic	34.07 ± 1.17%	114.29 ± 6.58%	33.90 ± 1.17%	113.75 ± 6.55%
E. North Pacific	29.17 ± 1.26%	70.25 ± 4.13%	22.84 ± 1.01%	52.27 ± 3.16%
W. North Pacific	60.41 ± 1.80%	175.65 ± 9.02%	52.92 ± 1.81%	144.81 ± 7.81%
Hemisphere Total	40.26 ± 0.91%	97.51 ± 3.52%	34.55 ± 0.87%	78.18 ± 2.85%

[a] 1970–2008 annual average TC footprint area over water by basin, as a percentage of the water area in that basin (± standard error of the mean). The areal footprint is defined as a 500 km swath centered on the track of each TC, as illustrated in Figure S1. The division between east and west Pacific was 180 degrees.

sures among many spatiotemporal subsets (see Table S1 of the auxiliary material), with stringent thresholds for predictor addition ($\alpha < 0.05$) during screening regression. Resulting predictor equations were limited to a maximum of six predictors, and robustness was measured using a one year out-of-sample cross validation, consistent with existing seasonal prediction techniques [*Barnston et al.*, 1994; *Gray et al.*, 1994].

3. Results

[7] The most simplistic measure of TC activity is given by count, and will form the basis for the first relationships explored. For the period 1960 through 2008, the median annual count of TCs in the combined NH Pacific and Atlantic basins is 63 with the 25th (75th) percentile at 57 (68) TCs. Thus, the winters that follow those anomalous TC years are defined as 57 or less TCs (“inactive”) and 68 or more TCs (“active”). As illustrated in Figure 1, there is a moderately strong inverse relationship ($r = -0.55$; $p < 0.05$) between the strength of the NNR winter (JFM) 500 hPa meridional temperature flux and the preceding anomalous TC activity. The analysis was also performed using two different reanalysis datasets and for two different periods of time (Figure 1a vs. Figure 1b) to test sensitivity to reanalysis representation [*Sterl*, 2004]. These preliminary results argue that one significant component of the winter atmospheric thermal transport is inversely related to the hemispheric TC activity preceding it.

[8] However, the relationship shown in Figure 1 demands considerable further refinement and explanation. First, 50% of the years used in the analysis are ignored in Figure 1. Second, TC count is not a physical measure [*Emanuel*, 2005]. A more physically sound metric for quantifying TC energy is the power dissipation (PD) [*Emanuel*, 2005], the time and spatially integrated cube of the wind speed. Power dissipation index (PDI), which removes the spatial component of the integration and uses solely the maximum wind speed, is an approximation to PD given the latter requires reliable and robust two dimensional TC wind fields that are not available over the full periods examined here.

[9] Various spatial subsets of aggregate TC PDI were calculated (Table S1 of the auxiliary material), with the subset poleward of 30°N found to explain the majority of the relationship in Figure 1. Further, the subset of PDI contributed to by the western north Pacific basin (which produces a majority of the hemispheric PDI [*Maue*, 2009]) dominates the relationship. To further account for uncertainty in the reanalyses products themselves, the mean of the fluxes from the two datasets (NNR and ERA40) is used.

[10] Temporally, the TC-winter climate relationship was found to exist from December to March ($r \approx 0.35$; $p \approx 0.05$) and is gone by April ($r \approx 0$), although peaks in January and February (discussed next). December flux is ignored to avoid conflating predictor and predictand. Further, the analysis is limited to the more reliable [*Landsea*, 2007] satellite era available in both datasets: 1970–2001. Finally, the winter flux is summarized as the areal mean between 35° and 70°N in Figure 1, as that latitude range showed the greatest significance ($p = 0.02$). Thus, when the relationship shown in Figure 1 is refined as described above, and examined over 32 years of the satellite era, a highly statistically significant

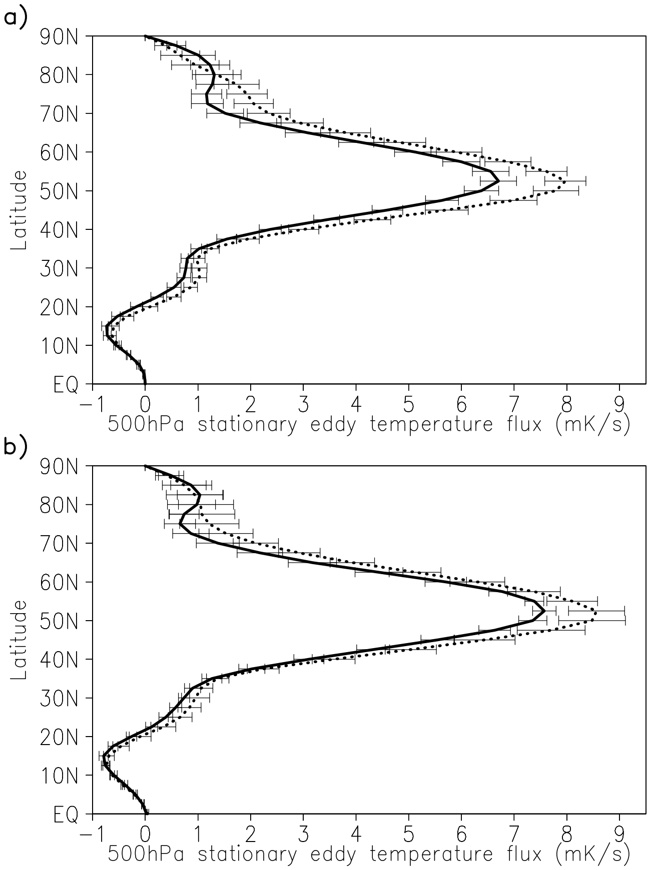

Figure 1. An analysis of the relationship between anomalous TC activity and winter climate. JFM 500 hPa zonal mean meridional temperature flux (mK/s) of the stationary eddies. The dotted (solid) curve represents the composite mean of the winters following inactive (active) NH TC seasons as defined in the text. Error bars represent the standard error of the mean for datasets of size varying from n = 9 to 13. (a) Flux calculated using NNR for the period 1960–2008. (b) Flux calculated using 1970–2001 ERA40.

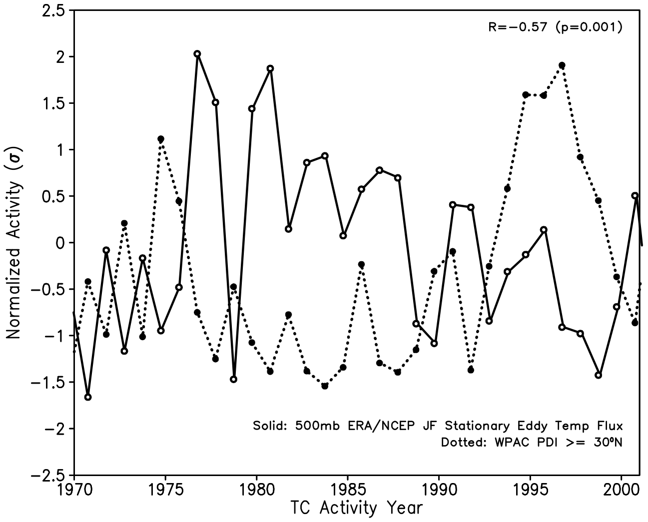

Figure 2. Narrowing and refining the TC-winter climate relationship over time. Normalized activity for 35°–70°N areal average JF 500 hPa stationary eddy temperature flux for the mean of NNR and ERA40 (solid) and western Pacific TC PDI poleward of 30° (dotted). The normalization is with respect to the 1970–2001 mean for each respective timeseries and each dataset is unsmoothed in time.

($r = -0.57$; $p < 0.01$) relationship exists between one physical measure of TC activity and one physical measure of winter climate (Figure 2).

[11] It is noteworthy that TC count and PDI are poorly correlated [*Maue and Hart*, 2007]. Further, additional research [*Frank and Young*, 2007; *Maue*, 2009] has shown that the magnitude of intra-basin compensation of TC activity varies depending upon metric used. It is thus not surprising that the temporally consistent relationship over the entire period noted in Figure 2 is weakened considerably during and after the 1990s when count is used instead of PDI (not shown). These important caveats are possibly a result of evolving observational tools used to classify TCs [*Landsea*, 2007]. Specifically, an increase in recorded short-lived TCs [*Landsea et al.*, 2010] would impact TC count more than PDI given the dominance of the time integral in PDI [*Maue and Hart*, 2007]. Moreover, short-lived TCs are typically weaker than average, further limiting their contribution to aggregate seasonal PDI.

[12] That the relationship in Figure 2 emphasizes a latitudinal subset of TC activity is also supported by recent GCM research [*Jansen and Ferrari*, 2009]. In that study, TCs originating deep in the tropics and moving out of the tropics (which are also those most likely to become the intense, high-latitude recurving TCs in Figure 2 based on *Hart and Evans* [2001]) maximize the oceanic meridional transport out of the tropics.

[13] That the TC-winter climate relationship carries over from count to PDI argues that the relationship is more than likely not a spurious one. Nonetheless, the results thus far do not preclude the possibility that the TCs are acting as proxies or even integrators of other large scale forcing mechanisms. Indeed, recent work has shown that hemispheric potential energy is modulated by tropical-extratropical interactions that include TCs [*Cordeira et al.*, 2010], further stressing the need to search for proxy relationships.

[14] Accordingly, numerous global and regional teleconnection indices on one, two, and three month averages for each of the twelve months leading up to winter (JFM) were examined for predictive power exceeding that of the TCs. Further, numerous areal measures of SST across many spatiotemporal averages in the preceding year were included given the strong relationship between regional SST and seasonal and hemispheric TC activity [*Maue*, 2009]. Table S1 of the auxiliary material lists a sample of climate and TC metrics that were examined (values largely obtained from http://www.cpc.noaa.gov). While no such table could be complete, it is insightful that the ten leading unrotated EOFs—all of which are in Table S1—explain a great majority (50–85%) of the variance of monthly NH climate [*Barnston and Livezey*, 1987] (http://www.cpc.noaa.gov/data/teledoc/exp_var_timeseries.shtml) with additional variance explained by the remainder of Table S1, leaving relatively little unexplained variance that would support an unknown proxy of the magnitude in Figures 1 and 2.

[15] As the regressions in Tables 2 and 3 show, the top predictor for the midlatitude winter activity was an integrated TC activity measure. Although not shown, this TC-winter relationship extended from 700 to 400 hPa, and thus is not limited to the 500 hPa shown here. Although the ordering (and to a lesser degree the selection) of the 2nd–6th predictors changed in the regression depending on pressure level, an aggregate TC metric remained the most explanatory predictor throughout by a significant margin.

4. Concluding Discussion

[16] If the TC-winter relationship is direct, a key task is to completely quantify the mechanisms underlying the causation. Such examination is well beyond the scope of this study and perhaps currently beyond our resources. Further, one must answer the question of why the SST areal composites did not explain significantly more winter variance than the TC activity, given the inherent relationship between hemispheric SST distribution and the strength of the stationary waves. While TCs do cool the SST over a large area that varies considerably from year to year (Table 1 and Figure S1), such cooling is only one feedback of TCs. The TCs also dry and warm the tropical atmosphere [*Emanuel*, 2008] and, through movement outside the Hadley Cell,

Table 2. Predicting Winter Activity Using Counts[a]

Predictor Step and Name	Description	t	p
(1) TotalTotal	Annual count of Atlantic and Pacific TCs	−7.10	<0.001
(2) PDO0910	September–October mean PDO	5.39	<0.001
(3) Epac-NonTropCount	Count of eastern Pacific TCs that move north of 30°N	−4.23	<0.001
(4) PNA07	July PNA	−4.48	<0.001
(5) NAO0708	July–August NAO	3.58	0.001
(6) SST-NH-0102	January–February mean NH SST	3.18	0.003

[a] 1960-2008 (n = 49) forward screening regression to predict the strength of the winter stationary eddies. Predictand is the areal-mean stationary eddy meridional temperature flux at 500 hPa between 35°N and 70°N for JFM as represented by the NNR. The resulting six-predictor regression equation has an out of sample r2 of 0.56. The t- and p- values listed are the relevant values for significance resulting from the stepwise regression, with t as the normalized location on the t distribution and p the two-tailed significance for hypothesis testing based upon the values of t and n.

Table 3. Predicting Winter Activity Using Satellite Era PDI[a]

Predictor Step and Name	Description	t	p
(1) WPACRSPDI	W. Pacific TC PDI between 30°N and 40°N.	−9.62	<0.001
(2) NAO05	May NAO	−8.14	<0.001
(3) SST-Atl-Mid-Trop-01	January midlatitude-tropical SST difference	5.87	<0.001
(4) SST-TropEPac-Wpac-0910	Difference between eastern and western Pacific Tropical SST during September and October	4.16	<0.001
(5) TotalRAce	ACE for TCs that begin south of 30°N and reach at least 40°N	3.38	0.002

[a] As in Table 2, except for the period 1970–2001 (n = 32) and for January and February only. Resulting five-predictor regression equation has an out of sample r2 of 0.79.

transport significant amounts of angular momentum, moist static energy, kinetic energy, and accordingly change the available potential energy of the hemisphere as a whole [*Palmen and Riehl*, 1957; *Anthes and Johnson*, 1968; *Kornegay and Vincent*, 1976; *Pauluis*, 2006; *Kelsey and Bosart*, 2006], all of which are factors that modulate the stationary wave pattern in addition to SST. Combined with the oceanic results of *Sriver and Huber* [2007], *Jansen and Ferrari* [2009], and *Jansen et al.* [2010], the results shown here argue that measures of SST incompletely capture the full impact of the TC activity on climate. Further, there are other mechanisms changing SST (such as ENSO) that may obfuscate any potential TC-winter climate relationship. Indeed, when the analyses in Figure 1 exclude years of major ENSO events (not shown), the curves in Figure 1 further spread apart. TCs themselves–as climate integrators–may explain more winter variance as proxies than SST alone. In the event that the relationship is proxy, there would be remarkable coupling between TC and winter climate activity driven by unknown forcing(s). For example, additional research should examine the potential relationship between TC activity and anomalous snowcover, given the latter's significance for NH winter modes and its ability to extend climate memory [*Saito and Cohen*, 2003].

[17] Should further research support a causal relationship, it does not bode well for our ability to forecast winter in advance. Causality implies that it would be necessary to accurately forecast not only the total count of TCs before winter forecasts can be issued, but also their full lifecycles. While considerable recent progress has been made on dynamic predictions of TC seasonal activity [*Vitart and Stockdale*, 2001; *LaRow et al.*, 2008], forecasting seasonal spatiotemporal TC distribution remains a great challenge. Nonetheless, more recent higher resolution coupled GCM and observational studies have further supported the hypothesis of a more active TC role in climate [*Hu and Meehl*, 2009; *Hsu et al.*, 2008].

[18] Regardless of whether the nature of the relationship is decided to be proxy or direct through much-needed additional research, these results may help to partially close a long-standing gap in a previously open loop among pre-TC season conditions, TC seasonal activity itself, and the post-TC (winter) season that then may help precondition the next cycle.

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