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Global Tropical Cyclone Activity: A Link to the North Atlantic Oscillation

James B. Elsner

Department of Geography, Florida State University, Tallahassee, Florida

Bethany Kocher

Department of Meteorology, Florida State University, Tallahassee, Florida

Abstract.
An index of global tropical cyclone activity (GTCA) is extracted from an interbasin dispersion matrix composed of correlations in the frequency of tropical cyclones among the five principal basins of activity over the period 1966–1998. The extraction is performed using a single-factor common factor analysis model. Factor scores provide the index of GTCA. The time series of factor scores is matched with annual series' of the El Niño-southern oscillation (ENSO) and the North Atlantic oscillation (NAO) revealing a statistical link to the NAO, but not to the ENSO. Results suggest a greater role of high latitude atmospheric and oceanic processes in modulating tropical cyclone climate than previously considered.

1. Introduction

The occurrence of tropical cyclones (TCs) across the globe is well-documented over the past three decades. Satellites allow for comprehensive monitoring and warning, and provide data for climatological studies of global tropical cyclone activity (GTCA). Regional studies of TC activity have produced some understanding of the climate conditions that influence particular basins, but an overall picture has yet to emerge concerning factors that modulate activity globally.

A recent analysis of GTCA [*Lander and Guard*, 1999, 1998] reveals interbasin correlations, but no comprehensive signal between GTCA and either the quasi-biennial oscillation (QBO) or the El Niño-southern oscillation (ENSO). Both the QBO and ENSO are known to have some influence on tropical cyclone occurrence over the North Atlantic [*Hess et al.*, 1995; *Gray*, 1984], the western North Pacific [*Chan*, 1995, 1985], and the South Pacific [*Revell and Goulter*, 1986] basins. The present analysis advances the work of Lander and Guard by demonstrating a statistical link between GTCA and the North Atlantic oscillation (NAO). It does this by first generating a meaningful index of GTCA using a model based on principal components. The GTCA index is subsequently correlated to a leading indicator of the NAO.

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2. Data

Global tropical cyclone data used here consist of the annual number of tropical cyclones in the five main tropical-cyclone basins; including the western North Pacific (WNP), the North Atlantic (NAT), the eastern North Pacific (ENP), the northern Indian Ocean (NIO), and the Southern Hemisphere (SH). The values are taken directly from Table 1 of *Lander and Guard* [1998], which are obtained from the Joint Typhoon Warning Center's (JTWC), and the National Hurricane Center's (NHC) best-track archives. Data for the NIO prior to 1975 and for the SH prior to 1981 were obtained from *Neumann* [1993]. For the WNP, ENP, and the NAT, all TCs that have one-minute sustained near-surface winds of 35 kt or greater are included. For the NIO and SH basins, all TCs for which the JTWC issued TC warnings are counted regardless of intensity. The counting convention is based on a 12-month year. We extend the data to include the basin counts for the years 1996–1998. The number of TCs in the Northern Hemisphere basins (WNP, ENP, NIO, and NAT) are counted over the calendar year. The number of tropical cyclones in the Southern Hemisphere are added over the period from July through the following June and are counted in the year of the last six months (cf. *Lander and Guard* [1999]). The tropical-cyclone data used here covers the period from 1966 through 1998, inclusive (33 years).

The present study concerns the relationship of GTCA to two important climate modes: ENSO and the NAO. The state of the ENSO is examined with values from a multivariate index constructed by the Climate Diagnostic Center [*Wolter and Timlin*, 1998]. The index is computed on a bi-monthly basis and consists of normalized departures using the base period of 1950–1993. Here we use an average of the 12 overlapping bi-monthly values to get an annual index. Data on the state of the NAO are obtained from the Climate Research Unit (CRU) at the University of East Anglia, UK. Values are monthly differences in normalized sea-level pres-

Table 1. Correlation matrix. Values are the Pearson product-moment correlation coefficients for the annual frequency of tropical cyclones between each of the five principal tropical cyclone basins. WNP is the western North Pacific, NAT is the North Atlantic, ENP is the eastern North Pacific, NIO is the northern Indian Ocean, and SH is the Southern Hemisphere.

	WNP	NAT	ENP	NIO	SH
WNP	1.000	−0.118	0.373	−0.007	0.175
NAT		1.000	−0.341	−0.047	−0.242
ENP			1.000	0.108	0.361
NIO				1.000	0.111
SH					1.000

sures between Stykkisholmur, Iceland and Ponta Delgada, Azores. We average the differences over the calendar year to obtain an annual index of the NAO for the period 1966–1997 (32 years).

3. An Index of Global Tropical Cyclone Activity

Here factor analysis is used to construct a multi-basin global tropical cyclone index. The analysis begins with the correlation matrix shown in Table 1. The matrix components are the Pearson product-moment correlation coefficients between the number of tropical cyclones in each basin. Values are similar to those obtained by *Lander and Guard* [1999, 1998] who use a rank correlation. That is, negative correlations are noted between TC activity over the North Atlantic and the activity over the four other basins. All other correlations are positive. The values do not exactly match those of *Lander and Guard* [1998] since we use data through 1998 and we do not consider ranks in computing the correlation. Largest correlations occur with activity over the eastern North Pacific. In particular the correlation between the eastern and western North Pacific is +0.373.

Factor analysis is a common statistical tool, and its procedures are explained in detail elsewhere [*Johnson and Wichern*, 1982; *Carter and Elsner*, 1997]. It is similar to an empirical orthogonal function (EOF) analysis except that the model allows each TC basin to have a unique error variance displayed in Table 2. The unique variance values indicate that the tropical cyclone activity over the NIO basin is largely independent of the other five regions. In contrast, the ENP basin has the

Table 2. Unique error variances. Values are the unique variances for the five tropical cyclone basins.

TC Basin	Variance
western North Pacific Ocean (WNP)	0.771
North Atlantic Ocean (NAT)	0.780
eastern North Pacific Ocean (ENP)	0.639
northern Indian Ocean (NIO)	0.882
Southern Hemisphere (SH)	0.762

Table 3. Factor loadings. Values are the common factor loadings for the five tropical cyclone basins from a single common factor model.

TC Basin	Loadings
western North Pacific Ocean (WNP)	0.437
North Atlantic Ocean (NAT)	−0.453
eastern North Pacific Ocean (ENP)	0.674
northern Indian Ocean (NIO)	0.154
Southern Hemisphere (SH)	0.502

smallest unique error variance. However, here we are interested in the dominant *common* factor. Table 3 shows the factor loadings representing the degree of common covariability among the five basins. Note that the NAT basin has a sign opposite to that of the other four basins, indicating the covariability is represented by an inverse relationship between activity over this basin and the rest of the tropics. That is, when TC activity is above average over the NAT it tends to be below average elsewhere and vice versa. The values of the loadings together with the original data matrix are used to compute factor scores that represent a time series of relative covariability. The factor scores are a projection of the tropical cyclone occurrences onto the factor loadings. Missing totals for the NIO and SH during the first three years (1996–1968) are replaced by their respective sample means at this step in the analysis. The values shown in Figure 1 indicate the degree to which the individual year is represented by the dominant common factor.

4. A Link to the North Atlantic Oscillation

In as much as it captures the dominant covariability pattern, the factor-score time series shown in Figure 1

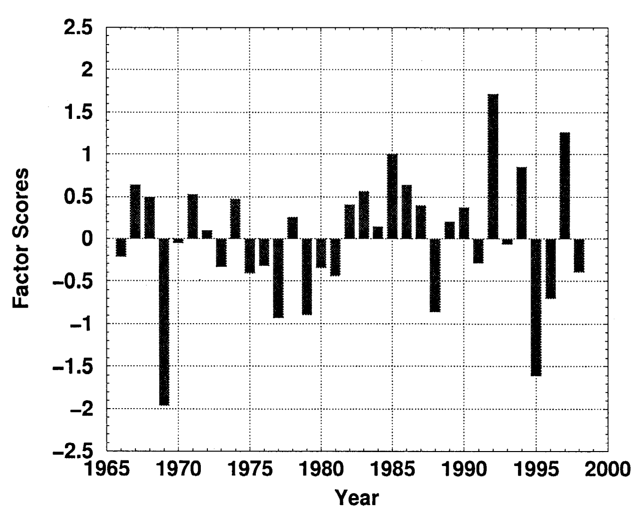

Figure 1. Factor scores of global tropical cyclone activity over the period 1966–1998. Values are the factor scores from a common factor model using one common factor computed from a dispersion matrix of interbasin correlations. The factor scores provide a multi-basin index of global tropical cyclone activity (GTCA).

is considered a robust multi-basin index of global tropical cyclone activity (GTCA). In general, large positive values indicate years of above average GTCA except for the NAT basin and large negative values years of below average activity except again for the NAT. The three years with the largest positive values include 1992, 1985, and 1994 and the three years with the largest negative values include 1969, 1995, and 1988. It should be kept in mind that the common variance is only a portion of the total variation in each basin.

Lander and Guard [1998] note that the relationship between the annual frequency of tropical cyclones over the North Atlantic and ENSO does not hold, in general, across the other basins. This is verified by examining Figure 2, which shows a scatterplot of the multivariate ENSO index versus factor scores. The scatter is large and the correlation coefficient is +0.156. Similar small, insignificant relationships are noted if GTCA is correlated with sea-surface temperatures over the central or eastern Pacific Ocean rather than with the multivariate index (not shown). Thus the dominant mode of GTCA is not linearly related to the ENSO, at least over the period of record examined here.

In notable constrast is the linear relationship between the factor scores and the NAO. The NAO is a coherent north-to-south seesaw pattern in sea-level pressures between Iceland and the Azores. When pressures are low over Iceland (Icelandic low) they tend to be high over the Azores (Azores high) and vice versa. The NAO represents a significant regional climate fluctuation [*Lamb and Peppler*, 1987; *Wallace and Gutzler*, 1981; *Bjerknes*, 1964] and appears as an important pattern of global interannual variability [*Hurrell and van Loon*, 1997; *Mann and Park*, 1994]. The intensity of the NAO determines the position and orientation of the midlatitude jetstream through variations in horizontal pressure (geopotential height) gradients.

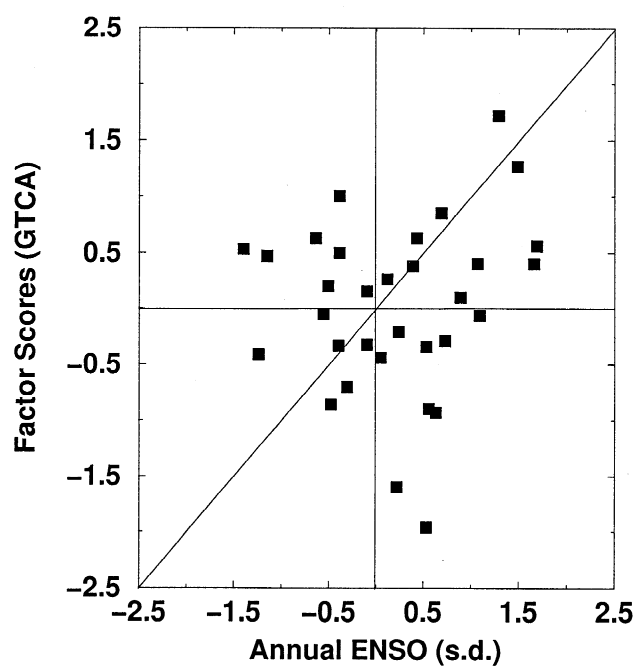

Figure 2. Scatterplot of a multivariate ENSO index (x) and the GTCA factor scores (y). The $y = x$ line is shown. The linear regression equation is $y = 0.149x - 0.011$ over 32 observations (1966–1997).

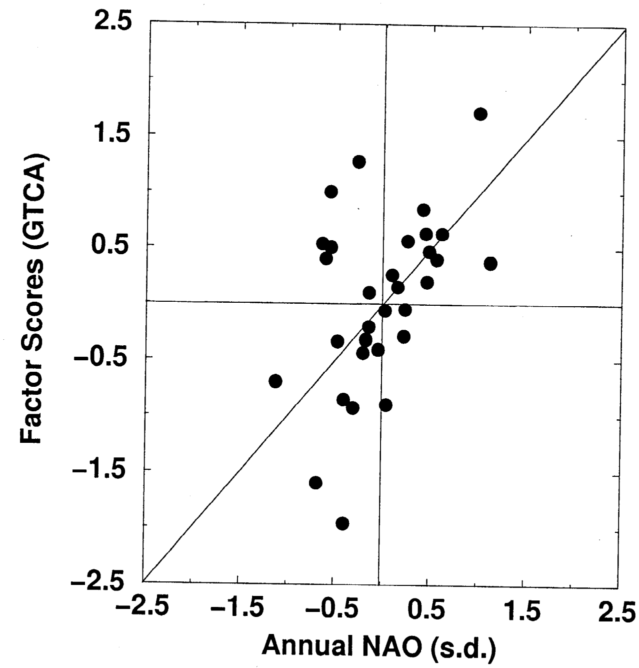

Figure 3. Scatterplot of a NAO index (x) and the GTCA factor scores (y). The $y = x$ line is shown. The linear regression equation is $y = 0.716x + 0.041$ over 32 observations (1966–1997).

Although the NAO is usually largest during the boreal winter, the signal is often robust during spring and summer [*Rogers*, 1990]. *Hurrell and van Loon* [1997] show that the signal-to-noise ratio of the NAO index computed using Stykkisholmur, Iceland and Ponta Delgada, Azores [see *Jones et al.*, 1997] is 1.5 for the 3-month averaged pressure anomalies from July through September.

Figure 3 shows a scatterplot of the NAO index versus the factor scores. The scatter is considerably smaller. The correlation coefficient is +0.465 with a t-value of 2.880 (p-value = 0.0072) guiding us to reject the null hypothesis of no relationship. A coefficient of this magnitude based on 32 pairs of observations would be equalled or exceeded by chance in unrelated data about 7 times in 1000 trials. The average value of the normalized NAO index during the 17 positive factor-score years is +0.161 compared to −0.245 during the 15 negative years. There is a slight trend to the NAO time series, but after removal, the correlation is virtually unchanged [$r(\text{NAO}, \text{GTCA}) - r(\text{NAO}_{detrend}, \text{GTCA}) < 0.03$]. Thus we establish a linear statistical link between the dominant mode of GTCA and the NAO over the time period examined.

5. Concluding Remarks

An index of GTCA is computed from a factor analysis model. The index consists of values of factor scores for each year over the period 1966–1998. The index represents the largest contribution to the common variances among the five principal tropical cyclone basins. The multi-basin index correlates well with an index of the NAO, but not with indices associated with the ENSO.

Speculation as to the physical mechanism behind this surprising finding likely centers on global-atmosphere ocean circulations. The North Atlantic Ocean displays variations across a spectrum of temporal scales. In general, variations in North Atlantic sea-level pressures respond to changes in sea-surface temperature patterns. However, on the interannual to decadal timescales SSTs can respond to sea-level pressures through variations in air-sea fluxes [*Delworth*, 1996]. The NAO is physically linked to changes in sea-ice formation over the Arctic Ocean and to the latitude of the Gulf stream separation, both of which are related to the North Atlantic component of the global thermohaline circulation. In fact, using annual iceberg count data (recorded south of 48°N off the coast of Newfoundland) published in *Marko et al.* [1994], we find a correlation of +0.426 with the factor scores over the period 1969–1991. The iceberg counts are first transformed to fit a normal distribution using a gamma-to-log likelihood transformation.

Recently *Elsner and Kara* [1999] find an inverse relationship in hurricane activity between low and high latitudes. A similar inverse relationship in major hurricane (category 3 or higher on the Saffir-Simpson hurricane disaster potential scale) activity along the U.S. Gulf and east coasts is related to the intensity of the NAO [*Elsner et al.*, 2000]. We hope that these results will lead others to investigate further the role of extratropical forcing, particularly the NAO, in modulating hurricane activity on climate scales.

The important conclusions of this study are:

- Factor analysis provides a useful method for generating an index of GTCA.
- GTCA has a statistically significant link to the NAO over the past 32 years (1966–1997). This finding is entirely new.
- GTCA is not significantly related to ENSO as noted by *Lander and Guard* [1999, 1998].

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J. B. Elsner, Department of Geography, Florida State University, Tallahassee, Florida 32306, USA. (e-mail: jbelsner@elsner.coss.fsu.edu)

B. Kocher, Department of Meteorology, Florida State University, Tallahassee, Florida 32306, USA.

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