GEOPHYSICAL RESEARCH LETTERS, VOL. 37, L09701, doi:10.1029/2010GL043091, 2010

Daily tropical cyclone intensity response to solar ultraviolet radiation

J. B. Elsner,[1] T. H. Jagger,[1] and R. E. Hodges[1]

Received 2 March 2010; revised 29 March 2010; accepted 31 March 2010; published 4 May 2010.

[1] An inverse relationship between hurricane activity over the Caribbean and the number of sunspots has recently been identified. Here we investigate this relationship using daily observations and find support for the hypothesis that changes in ultraviolet (UV) radiation rather than changes in other concomitant solar and cosmic variations are the cause. The relationship is statistically significant after accounting for annual variation in ocean heat and the El Niño cycle. A warming response in the upper troposphere to increased solar UV forcing as measured by the Mg II index (core-to-wing ratio) decreases the atmosphere's convective available potential energy leading to a weaker cyclone. The response amplitude at a cyclone intensity of 44 m s^{-1} is 6.7 ± 2.56 m s^{-1} per 0.01 Mg II units (s.d.), which compares with 4.6 m s^{-1} estimated from the heat-engine theory using a temperature trend derived from observations. The increasing hurricane response sensitivity with increasing strength is found in the observations and in an application of the theory. **Citation:** Elsner, J. B., T. H. Jagger, and R. E. Hodges (2010), Daily tropical cyclone intensity response to solar ultraviolet radiation, *Geophys. Res. Lett.*, *37*, L09701, doi:10.1029/2010GL043091.

1. Introduction

[2] In accord with the heat-engine theory of tropical cyclone intensity [*Emanuel*, 1991; *Holland*, 1997], the strongest tropical cyclones are getting stronger worldwide with the trend related to increases in oceanic heat content [*Trenberth*, 2005; *Emanuel*, 2005; *Webster et al.*, 2005; *Elsner et al.*, 2008]. Yet according to the theory, tropical cyclone wind speeds are inversely related to the temperature of the air near the top of the cyclone so warming at these upper levels should decrease cyclone intensity. Indeed, a recent study shows fewer strong tropical cyclones over the Gulf of Mexico and the Caribbean Sea when sunspot numbers are high [*Elsner and Jagger*, 2008]. Here we provide new insight into this intriguing relationship by showing the response amplitude of the intensity change is quantitatively consistent with the heat-engine theory, and demonstrating that the relationship is likely the result of changes in UV radiation rather than the result of changes in other physically related variables including total solar irradiance, radio flux, and galactic cosmic rays.

2. Data

[3] Daily Mg II index values as well as the other solar forcing data including total solar irradiance, galactic cosmic rays, and the 10.7 cm radio flux are obtained from the Solar Data Services of the U.S. National Oceanic and Atmospheric Administration (NOAA) National Geophysical Data Center. Tropical cyclone wind speeds are obtained from the U.S. NOAA National Hurricane Center HURDAT and spline interpolated to one-hourly values from their native 6-hourly format [*Jagger and Elsner*, 2006]. The wind speeds represent the best estimate of the highest velocity within the cyclone over a one-minute average at 10 m above the ocean surface. For each tropical cyclone the maximum daily wind speed is used. The day begins at 00 UTC for the wind speed and solar forcing data. Monthly values of the SOI and the NAO are obtained from the U.K. Climatic Research Unit and monthly values of Atlantic SST and weekly values of the MJO are obtained from U.S. NOAA's Climate Diagnostic Center. Daily values of upper-air temperature at 50, 100, 150, and 200 hPa are obtained from U.S. NOAA/National Centers for Environmental Prediction (NCEP)/Environmental Modeling Center (EMC)/NOAA Operational Model Archive Distribution System (NOMADS) development group.

[4] Solar UV radiation at wavelengths less than 240 nm is important for ozone production in the Earth's upper stratosphere. Variation in the amount of this radiation is best measured by the Mg II core-to-wing ratio (Mg II index) [*Heath and Schlesinger*, 1986; *Lean et al.*, 1997; *Viereck and Puga*, 1999; *Viereck et al.*, 2001] shown in Figure 1. The time series reveals the well-known 11-year solar (Schwabe) cycle and short-term fluctuations (near 27 days) caused by the asymmetric distribution of active regions (plages and sunspots) undergoing solar rotation. A change of 0.01 Mg II units corresponds to an approximate change of 1 W m^{-2} in total solar irradiance. The time interval contains 10,578 days, but 1331 (12.6%) of these days have missing Mg II values and are excluded.

3. Quantile Regression of Daily Tropical Cyclone Intensity on Mg II Index

[5] We begin by examining the statistical relationship between the daily Mg II index and daily tropical cyclone intensity maximum over the Caribbean Sea and adjoining Gulf of Mexico. Here tropical cyclone intensity refers to the highest one-minute sustained wind speed somewhere inside the cyclone. The region, which is similar to that used by *Elsner and Jagger* [2008], is bounded by 70° and 97°W longitudes and 8° and 30°N latitudes. From August through October there is sufficient heat in the ocean throughout the

---

[1] Department of Geography, Florida State University, Tallahassee, Florida, USA.

0094-8276/10/2010GL043091

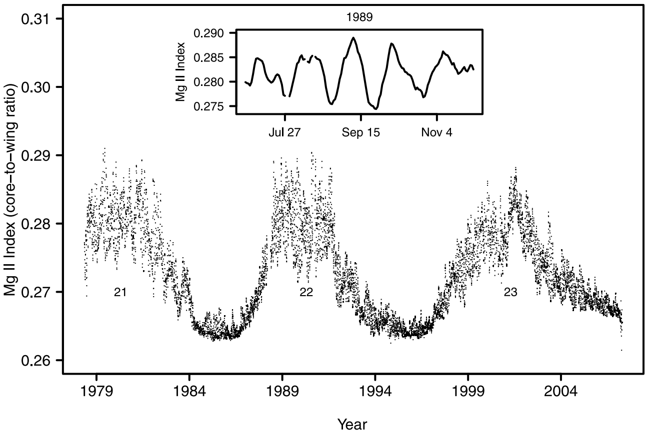

Figure 1. Time series of the daily solar Mg II index. The series begins on 7 November 1978 and ends on 14 October 2007 (10,578 days). Values are plotted as points. Values below the 11-year peaks indicate the solar cycle number. Horizontal axis is labeled on July 1st of the year. The inset graph shows the Mg II index values as a time series over the hurricane season of 1989. Values are connected as a curve. Breaks in the curve indicate missing values. There are 1331 missing values (12.6% of the days).

region for tropical cyclones to intensify, so the limiting thermodynamic constraint on potential intensity is upper troposphere temperature.

[6] There are 387 pairs of daily maximum wind speed and Mg II index values representing samples from 118 different tropical cyclones (wind speeds ≥ 17 m s^{-1}) in this region over the period 1979–2007. The region is vulnerable to very strong cyclones and includes the infamous hurricanes David (1979), Allen (1980), Gilbert (1988), Andrew (1992), and Katrina (2005). Ninety percent of the tropical cyclones spend 5 or fewer days in the region, with most eventually making landfall.

[7] The daily maximum wind speed for each tropical cyclone in the region is regressed onto the daily Mg II index value using quantile regression. Quantile regression extends ordinary least-squares regression to conditional quantiles of the response variable [*Koenker and Bassett*, 1978]. Quantiles taken at regular intervals from the cumulative distribution function mark a set of ordered wind speeds into equal-sized subsets. Downward trends between −1.0 and −2.0 m s^{-1} per 0.01 Mg II units are found for the lowest intensity quantiles but increase to −3.0 m s^{-1} per 0.01 Mg II units at the median. Tropical cyclone intensities above the median indicate statistically significant decreases with increasing Mg II values with the largest at the 80th percentile. The mean trend is −4.3 ± 1.86 m s^{-1} per 0.01 Mg II units (s.d.).

[8] Statistical significance is based on sampling the set of paired daily maximum intensity and Mg II index values randomly choosing one pair per randomly chosen cyclone and then regressing wind speed on the Mg II index for each sample. Since only one daily maximum intensity value is chosen per cyclone for each sample there is no autocorrelation affect on the uncertainty estimates. Trends and uncertainty levels are based on the distribution of quantile regression coefficients generated from 1000 such samples. Predictions of tropical cyclone intensity as a function of Mg II index values using the quantile regression model are listed in Table 1. At the 90th percentile, tropical cyclone intensity decreases from 65.9 m s^{-1} when the Mg II index is 0.264 to 48.1 m s^{-1} when the Mg II index increases to 0.282.

4. Statistical Model Versus Theory

[9] Next we compare the amount of wind speed change we find from our statistical model with the amount of change predicted from the heat-engine theory. Accordingly, the convective available potential energy (CAPE) of the atmosphere is the vertical integral of the local upward buoyancy force arising from the temperature of a theoretical parcel (lifted pseudo-adiabatically) remaining greater than the temperature of its environment. Following *Emanuel* [1994], the theoretical maximum wind speed of a tropical cyclone is proportional to differential CAPE (saturation CAPE minus surface CAPE) computed at the radius of maximum winds. That is

$$v^2 = \frac{c_k}{c_D}\frac{T_s}{T_o}\delta\text{CAPE}, \tag{1}$$

where v is the maximum wind speed (in gradient balance) at the radius of maximum winds, T_s is the ocean temperature, T_o is the mean outflow temperature above the cyclone,

Table 1. Tropical Cyclone Intensity Predictions[a]

	Mg II Index				
P	0.264	0.267	0.272	0.276	0.283
10	19.7 (18.0, 21.2)	19.3 (18.0, 20.5)	18.8 (17.9, 19.5)	18.4 (17.5, 18.9)	17.8 (16.5, 18.5)
20	21.9 (20.1, 23.8)	21.5 (20.0, 22.8)	20.8 (19.6, 21.5)	20.2 (19.0, 21.2)	19.4 (17.9, 21.2)
30	24.2 (22.1, 25.8)	23.7 (22.1, 25.0)	23.0 (21.9, 24.1)	22.4 (21.3, 23.7)	21.7 (20.0, 23.4)
40	27.1 (24.3, 29.7)	26.4 (24.2, 28.5)	25.4 (23.9, 26.9)	24.5 (23.2, 25.9)	23.4 (21.5, 25.3)
50	30.4 (26.0, 34.0)	29.3 (25.9, 32.1)	27.9 (25.6, 29.8)	26.6 (24.7, 28.2)	25.1 (22.5, 27.2)
60	36.6 (31.1, 42.1)	34.8 (30.5, 39.1)	32.3 (29.5, 35.3)	30.1 (27.9, 32.6)	27.4 (23.6, 30.2)
70	43.1 (34.5, 49.8)	40.4 (33.9, 45.5)	36.6 (32.4, 39.9)	33.5 (29.9, 36.2)	29.5 (24.4, 33.4)
80	56.5 (48.3, 66.3)	52.7 (46.6, 60.5)	47.2 (42.7, 52.8)	42.7 (37.8, 47.5)	36.9 (30.0, 43.2)
90	65.9 (58.9, 73.0)	62.4 (57.3, 67.6)	57.4 (53.1, 61.5)	53.3 (47.4, 58.4)	48.1 (38.8, 56.3)

[a] Predictions are made at values of the Mg II index (core-to-wing ratio) as a measure of solar UV radiation for different wind speed percentiles (P). The value outside the parentheses is the wind speed (m s^{-1}) predicted at the percentile for a Mg II index value listed in the column. The values inside the parentheses are the lower and upper 5% confidence limits on the predicted value based on a bootstrap resampling of the daily data. The model predicts decreasing intensity with increasing core-to-wing ratios (read across columns in each row) for all wind speed percentiles.

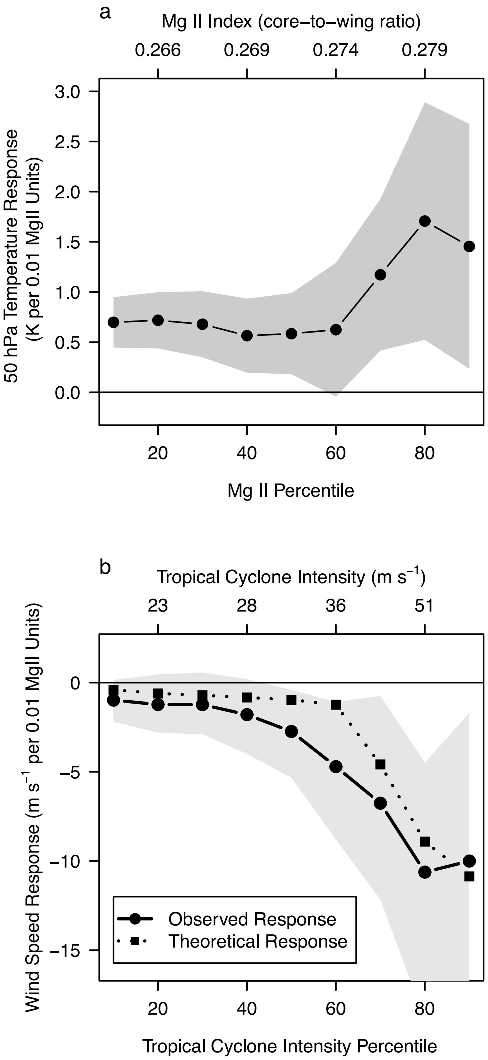

Figure 2. Upper air temperature and tropical cyclone intensity response to variations in solar UV radiation. (a) Change in 50 hPa temperature for a change in Mg II index given the Mg II index exceeds the given percentile. The first point to the left is the ordinary least squares regression coefficient of temperature on Mg II index using all but the lowest 10% of the Mg II values. The next point is the regression coefficient after removing the lowest 20% of the values, and so on. The point-wise one standard-error band is shown in grey and is computed using a sandwich estimator to account for the autocorrelation in the daily values. (b) Observed and theoretical response of tropical cyclone intensity to variations in solar UV radiation (Mg II index). The observed response is a change in a percentile of tropical cyclone wind speed for all values of Mg II index. The theoretical response is the change in a percentile of wind speed for a set of temperature responses to Mg II index values exceeding a given Mg II index percentile. The solid curve (circles) and the 90% confidence band is based on a bootstrap resampling of the daily data. The dotted curve (squares) is based on equation (2) with the temperature response estimated from NCEP reanalysis data.

δCAPE is differential CAPE, c_k is the exchange coefficient for enthalpy, and c_D is the drag coefficient. Here we are interested in the relative difference in wind speed (Δv) when the temperature aloft changes due to changes in UV radiation. We can write the equation in terms of differentials as

$$\Delta v = \frac{v}{2}\left[\frac{\Delta T_s}{T_s} - \frac{\Delta T_o}{T_o} + \frac{\Delta \delta \mathrm{CAPE}}{\delta \mathrm{CAPE}}\right], \qquad (2)$$

where we assume the ratio of the exchange to drag coefficients is unity [*Emanuel*, 1995] and that there is no change in surface temperature ($\Delta T_s = 0$).

[10] The thermal response to variations in UV near the tropical tropopause peaks at +0.24 ± 0.07 K per 0.01 Mg II units near 100 hPa [*Hood*, 2003]. Here we examine the thermal response to changes in Mg II index over our Caribbean and Gulf of Mexico region by obtaining daily temperatures (based on averaging the 6-hourly values) at lower stratospheric and upper tropospheric pressure levels (50, 100, 150, and 200 hPa) using the available 2.5° latitude spacing from the U.S. National Centers for Environmental Prediction. The thermal response is nonlinear as can be seen in Figure 2, where the response (K per 0.01 Mg II units) is plotted as a function of the Mg II quantile value. Using all but the lowest 10% of the Mg II values the mean response at 50 hPa is +0.7 ± 0.25 K per 0.01 Mg II units. However, at higher quantiles (using only the upper 20% of the Mg II values) the response is larger reaching +1.7 ± 1.2 K per 0.01 Mg II units. Similar nonlinear temperature responses to UV radiation occur at 100, 150, and 200 hPa. The uncertainty band is one standard error and is based on a sandwich estimator to account for the autocorrelation in the daily values [*Andrews*, 1991].

[11] Using the estimated near-tropopause warming responses together with the mean thermal structure of tropical cyclones [*Jordan and Jordan*, 1954] we calculate Δv from equation (2). CAPE is computed using a sea-surface temperature of 27.5°C (hurricane season mean over the region), a sea-level pressure of 1005 hPa, and a surface relative humidity of 97%. Although we assume a saturated column above the cloud layer (typical for a hurricane), at the surface saturation occurs at relative humidity slightly below 100% due to the presence of sea aerosols. The 70th percentile warming of 1.2, 1.3, 0.5, and 0.2 K at 50, 100, 150, and 200 hPa levels, respectively results in a relative warming at 100 hPa of only 1.8%, but a relative decrease in CAPE of 19.2%. These thermodynamic changes decrease the relative wind speed by 10.5%, which translates to a 4.6 m s^{-1} weakening of a 44 m s^{-1} hurricane (70th quantile tropical cyclone intensity).

[12] This theoretical estimate of a decrease in wind speed for a category two hurricane for the amount of warming in response to an increase in UV radiation associated with the 27-day solar rotational period is less than the decrease in wind speed of 6.7 ± 2.56 m s^{-1} (s.d.) estimated from the observations above, but is well within the 90% confidence limits of the statistical model. In fact, the theoretical estimates for all wind speed quantiles are within the uncertainty estimates of the model (Figure 2) and the nonlinear relationship characterized by a greater sensitivity to UV forcing at higher tropical cyclone intensities is also apparent in the theoretical results. Magnitudes of the theoretical wind

response are sensitive to surface relative humidity between 94 and 100% (greater response with higher relative humidity), but the nonlinear relationship with intensity and thus the correlation with magnitudes estimated from observations are not.

5. Other Factors

[13] Since other factors influence tropical cyclone intensity, including the El Niño-Southern Oscillation (ENSO) cycle [*Gray et al.*, 1992; *Bove et al.*, 1998; *Elsner and Jagger*, 2006] and ocean heat, we examine whether adding the Mg II index improves on a model that already contains these factors. We start with a model of daily maximum wind speeds regressed onto seasonal (August–October average) values of sea-surface temperature (SST) over the North Atlantic (from 20° to 70°N) and the Southern Oscillation Index (SOI) as an indictor of ENSO. We then create a new model by adding the daily Mg II index to the original model and compare the values of Akaike information criteria (AIC) [*Akaike*, 1974] for both models (with and without the Mg II index). The AIC is defined as

$$\mathrm{AIC} = 2k - 2\ln(L), \tag{3}$$

where k is the number of parameters in the model (3 for the model without the Mg II index and 4 for the model with it), L is the maximum value of the likelihood function for the model. Given a set of data and two competing models of the data, the one with the lower AIC is chosen as the better of the two. As before, we sample the data and construct quantile regression models on each of the 10^4 samples. The method determines how well the data supports each model, taking into account the goodness-of-fit (sum-of-squares) and the number of parameters in the model. By examining the number of samples that result in a lower AIC value on the model that includes the Mg II index we determine the odds are 2:1, 4:1, and 7:1 in favor of the Mg II model as the correct one for the 60th, 70th, and 80th percentiles, respectively. We also consider the North Atlantic oscillation (NAO) and the Madden-Julian oscillation (MJO) and find they do not improve the model.

[14] Finally, while we show that the response of tropical cyclone intensity to solar UV flux is statistically significant and of the same sign and similar magnitude as predicted from the heat-engine theory, it is possible that the causality is through some other solar-related forcing. Here we provide evidence that this is not likely by again comparing quantile regression models. In each case the regression model of wind speed onto SST, SOI, and the Mg II index is compared with the regression model of wind speed onto SST, SOI plus the other forcing agent and the odds in favor of the model that includes the Mg II index is given. When the alternate forcing is total solar irradiance (total flux density without regard to wavelength) the odds in favor of the model that includes the Mg II index are 4:1, 8:1, and 7:1 at the 60th, 70th, and 80th percentiles, respectively. When the forcing is galactic cosmic rays the odds in favor of the Mg II model are 3:1, 2:1, and 3:1, respectively, and when the forcing is the 10.7 cm radio flux the odds in favor of the Mg II model all exceed 10:1. In all three cases the model that includes an index for the UV radiation flux is the model that is relatively most likely given the observations.

6. Conclusions

[15] Here we show compelling evidence that the relationship between hurricane intensity and solar activity on the daily time scale is physically linked to changes in atmospheric temperature near the top of the cyclone induced by UV radiation. This new finding sheds light on the problem of forecasting hurricane intensification. The overall greater sensitivity of the response found in the tropical cyclone wind data compared with the heat-engine theory and temperature data might result from the tropical cyclones themselves warming the temperature aloft and thus dampening the temperature-UV relationship [*Swanson*, 2008]. It is noted the theoretical results reflect a change in the maximum potential intensity of a particular tropical cyclone while the observational results reflect a change in the daily maximum wind speed over all tropical cyclones in the region. Since a tropical cyclone plays a role in moistening the stratosphere [*Romps and Kuang*, 2009] and since the dissipation of the cyclone's energy occurs through ocean mixing and atmospheric transport, a tropical cyclone can act to amplify the effect on the Earth's climate of a relatively small change in solar output. On longer time scales it is noted that a portion of the variation in tropical SST's (0.08 ± 0.2 K) lags the Schwabe cycle by 1 to 3 years, which is roughly equal to the time required for the upper 100 m layer of the ocean to reach radiative equilibrium [*White et al.*, 1997].

[16] **Acknowledgments.** The computer code for CAPE was provided by Kerry Emanuel. J.B.E. acknowledges S. Kavlakov for early discussions on this topic. The work was supported by the U.S. National Science Foundation (ATM-0738172) and by the Risk Prediction Initiative of the Bermuda Institute for Ocean Studies. Statistical analysis and modeling were performed using the software environment R (http://www.r-project.org) and the quantile regression package quantreg with special thanks to Roger Koenker.

References

Akaike, H. (1974), A new look at the statistical-model identification, *IEEE Trans. Autom. Control*, *AC-19*, 716–723.

Andrews, D. W. K. (1991), Heteroskedasticity and autocorrelation consistent covariance-matrix estimation, *Econometrica*, *59*(3), 817–858.

Bove, M., J. Elsner, C. Landsea, X. Niu, and J. O'Brien (1998), Effect of El Niño on US landfalling hurricanes, revisited, *Bull. Am. Meteorol. Soc.*, *79*(11), 2477–2482.

Elsner, J. B., and T. H. Jagger (2006), Prediction models for annual US hurricane counts, *J. Clim.*, *19*(12), 2935–2952.

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., J. Kossin, and T. Jagger (2008), The increasing intensity of the strongest tropical cyclones, *Nature*, *455*, 92–95.

Emanuel, K. (1991), The theory of hurricanes, *Annu. Rev. Fluid Mech.*, *23*, 179–196.

Emanuel, K. (1994), *Atmospheric Convection*, 580 pp., Oxford Univ. Press, New York.

Emanuel, K. (1995), Sensitivity of tropical cyclones to surface exchange coefficients and a revised steady-state model incorporating eye dynamics, *J. Atmos. Sci.*, *52*(22), 3969–3976.

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

Gray, W., C. Landsea, P. Mielke, and K. Berry (1992), Predicting Atlantic seasonal hurricane activity 6–11 months in advance, *Weather Forecast.*, *7*(3), 440–455.

Heath, D. F., and B. M. Schlesinger (1986), The Mg 280-nm doublet as a monitor of changes in solar ultraviolet irradiance, *J. Geophys. Res.*, *91*, 8672–8682.

Holland, G. (1997), The maximum potential intensity of tropical cyclones, *J. Atmos. Sci.*, *54*(21), 2519–2541.

Hood, L. L. (2003), Thermal response of the tropical tropopause region to solar ultraviolet variations, *Geophys. Res. Lett.*, *30*(23), 2215, doi:10.1029/2003GL018364.

Jagger, T. H., and J. B. Elsner (2006), Climatology models for extreme hurricane winds near the United States, *J. Clim.*, *19*(13), 3220–3236.

Jordan, C., and E. Jordan (1954), On the mean thermal structure of tropical cyclones, *J. Meteorol.*, *11*(6), 440–448.

Koenker, R., and G. Bassett (1978), Regression quantiles, *Econometrica*, *46*(1), 33–50.

Lean, J. L., G. J. Rottman, H. L. Kyle, T. N. Woods, J. R. Hickey, and L. C. Puga (1997), Detection and parameterization of variations in solar mid- and near-ultraviolet radiation (200–400 nm), *J. Geophys. Res.*, *102*, 29,939–29,956.

Romps, D. M., and Z. Kuang (2009), Overshooting convection in tropical cyclones, *Geophys. Res. Lett.*, *36*, L09804, doi:10.1029/2009GL037396.

Swanson, K. L. (2008), False causality between Atlantic hurricane activity fluctuations and seasonal lower atmospheric wind anomalies, *Geophys. Res. Lett.*, *35*, L18807, doi:10.1029/2008GL034469.

Trenberth, K. (2005), Uncertainty in hurricanes and global warming, *Science*, *308*(5729), 1753–1754, doi:10.1126/Science.1112551.

Viereck, R. A., and L. C. Puga (1999), The NOAA Mg II core-to-wing solar index: Construction of a 20-year time series of chromospheric variability from multiple satellites, *J. Geophys. Res.*, *104*, 9995–10,005.

Viereck, R., L. Puga, D. McMullin, D. Judge, M. Weber, and W. K. Tobiska (2001), The Mg II index: A proxy for solar EUV, *Geophys. Res. Lett.*, *28*, 1343–1346.

Webster, P., G. Holland, J. Curry, and H. Chang (2005), Changes in tropical cyclone number, duration, and intensity in a warming environment, *Science*, *309*(5742), 1844–1846, doi:10.1126/Science.1116448.

White, W. B., J. Lean, D. R. Cayan, and M. D. Dettinger (1997), Response of global upper ocean temperature to changing solar irradiance, *J. Geophys. Res.*, *102*, 3255–3266.

J. B. Elsner, R. E. Hodges, and T. H. Jagger, Department of Geography, Florida State University, 113 Collegiate Loop, Tallahassee, FL 32306, USA. (jelsner@fsu.edu)