Imhoff, K. A., and G. S. Young, 2015: ENSO influence on tropical cyclone regional landfall counts. *J. Operational Meteor.*, **3** (11), 124–132, doi: http://dx.doi.org/10.15191/nwajom.2015.0311.

Journal of Operational Meteorology
Short Contribution

ENSO Influence on Tropical Cyclone Regional Landfall Counts

KYLE A. IMHOFF and GEORGE S. YOUNG
The Pennsylvania State University, University Park, Pennsylvania

(Manuscript received 13 April 2015; review completed 5 August 2015)

ABSTRACT

A simple linear regression analysis investigates the influence of the El Niño/Southern Oscillation (ENSO) on tropical cyclone counts and regional landfall patterns in the North Atlantic basin. Tropical cyclones from the period 1871–2013 are examined using storm locations from the North Atlantic Hurricane Database. The ENSO phase is determined using several well-known indices—the extended Multivariate ENSO Index (MEI), the MEI, the Bivariate ENSO Index, and the Oceanic Niño Index (ONI). Regression statistics are computed over two time periods: a long-term historical period (1871–2005) and the more recent past (since 1950), the latter being necessary because the ONI and MEI data series do not extend prior to the mid-20th century. Landfall counts were computed over three regions of North America: (i) Canada/United States East Coast, (ii) United States Gulf Coast/Florida, and (iii) Central America/Mexico.

Results of this analysis indicate that the phase of ENSO influences interannual variability in tropical cyclone and landfall counts at a statistically significant level, no matter which index is used. However, the relationship between the phase of ENSO and tropical cyclone landfall counts differs markedly between regions. Relationships between ENSO phase and landfall counts for Central America/Mexico and Canada/United States East Coast predominantly pass the test of statistical significance for all ENSO indices used, whereas United States Gulf Coast/Florida landfall counts fail the test. The regression slope is correspondingly small for the United States Gulf Coast/Florida. Thus, during El Niño events, when tropical cyclones are less likely to form, smaller decreases in landfall probabilities exist for the United States Gulf Coast/Florida than for Canada/United States East Coast and Central America/Mexico. As a result, landfall activity over the United States Gulf Coast/Florida is less influenced by the ENSO phase than in Central America/Mexico or Canada/United States East Coast.

1. Introduction

Tropical cyclones in the Atlantic basin have a large socioeconomic impact on inhabitants along the eastern coast of North America (Pielke and Pielke 1997). Over the past few decades, people have increasingly relocated to, and have built property in, coastal regions (known as "coastal migration"), which has increased the potential impacts of these storms (Pielke and Landsea 1998). Because of the extensive losses associated with these storms, considerable research has been performed over the past few decades to develop methods by which to accurately predict these storms on a broad range of time scales (e.g., Gray et al. 1993, 1994; Lehmiller et al. 1997; Klotzbach 2014). Of interest here is the potential to predict the severity of a hurricane season—often quantified using the number of named storms—months in advance. This procedure is known as seasonal forecasting.

Seasonal forecasts of tropical cyclone activity in the Atlantic basin, as well as understanding of the environmental factors that influence these numbers, have been steadily refined over the past few decades (e.g., Gray 1984b; Gray et al. 1992; Landsea et al. 1994; Hess et al. 1995; Klotzbach and Gray 2008). The El Niño/Southern Oscillation (ENSO) has a relatively large influence on seasonal hurricane activity, with El Niño (positive ENSO phase) events typically inhibiting storm development in the Atlantic basin and La Niña (negative ENSO phase) events generally enhancing storm development (Gray 1984a; Goldenberg and Shapiro 1996; Bove et al. 1998;

Corresponding author address: Kyle A. Imhoff, 503 Walker Building, The Pennsylvania State University, University Park, PA 16802
E-mail: kai5024@psu.edu

Wilson 1999; Elsner and Jagger 2004; Yan 2006; Klotzbach 2011).

The current study is intended to expand on this prior work by examining the regional impacts of ENSO on seasonal tropical cyclone landfall counts instead of the traditional named storm counts. Specifically, the focus of the study is to quantify these impacts using regression analysis for a variety of derived ENSO indices. The goal is to determine if a relationship exists and, if so, which indices best capture it. Note that ENSO is just one of many factors that influence the interannual variability in tropical cyclone landfall counts, and this must be taken into consideration when interpreting the statistical results provided in this paper. Further, the tables herein show R^2, which is the percent variance explained by the regression—not the percent of standard deviation explained. To get that, and hence the fraction of year-to-year count fluctuation explained, one has to take the square root of R^2.

In addition, this work could provide an ENSO-based starting point to potentially build a seasonal tropical cyclone landfall forecast system. However, this work does not delve into all the other aspects required to create such a forecast system, which lie beyond the scope of this paper. Note that ENSO index values used in the analysis are valid during the hurricane season, so a prerequisite to using this work as part of the foundation for a forecast system is the ability to accurately predict ENSO weeks to months in advance of the hurricane season. This ongoing challenge has been addressed by a number of authors (e.g., Kleeman and Moore 1997; Kirtman and Schopf 1998; Fedorov et al. 2003; Stockdale et al. 2011; Barnston et al. 2012).

2. Methods

a. Data

The tropical cyclones investigated are those that occurred in the period 1871–2013 in the North Atlantic basin. Storms that formed outside of the hurricane season (1 June–30 November) were excluded from this analysis to ensure climatological consistency. Storm landfall positions as well as classification (e.g., tropical depression, etc.) were determined using the National Hurricane Center's (NHC's) revised Atlantic hurricane database, HURDAT2 (available online at www.aoml.noaa.gov/hrd/hurdat/hurdat2.html). Landsea and Franklin (2013) discussed the details of HURDAT2 and improvements made to the revised dataset. Storms that, according to NHC, were subtropical or which never were determined to develop tropical characteristics during their life cycle were excluded from the analysis. Landfall times used for statistical analyses were determined by using either the time associated with the HURDAT2 position data point in which the storm was indicated to cross a coastline or the HURDAT2 time at which the storm was closest to the coastline, either over water or land, in cases where the storm crossed the coast between data points. Storms were required to be of at least tropical depression strength at landfall in order to be counted. Storms that were determined by the NHC to have become extratropical/subtropical prior to landfall were excluded. If a given storm made landfall multiple times over different mainland coasts, each landfall was considered separately in the final analysis, as each landfall offers the potential for additional destruction.

Tropical cyclone landfalls were separated into three regions: Canada/United States East Coast, United States Gulf Coast/Florida, and Central America/ Mexico. There are a few landfalls over the northern coast of South America that are included in the Central America/Mexico region. The separation between Canada/United States East Coast and the United States Gulf Coast/Florida occurs at the state border between Florida and Georgia. These interregional borders were selected to maximize the differences in ENSO signal and thus the potential for exploitation of the signal in future seasonal forecasting systems (Fig. 1). Landfalls over island nations were excluded because they face different challenges.

Whereas there are numerous methods to quantify the ENSO phenomena, ENSO phase values for this study are determined using a selection of derived indices in common use in the literature (e.g., Trenberth 1997; Landsea et al. 1999; Elsner and Kocher 2000; Maue 2011). Multiple indices were evaluated for two reasons. First, it is not certain a priori which index will be more strongly correlated with North Atlantic basin tropical cyclone landfall statistics. Second, while some of these indices use only data sources that have been available since the late 19th century, others require data sources that have only become reliably available since the mid-20th century. There is, thus, a potential tradeoff between quantity and quality of training data for development of a statistical relationship between ENSO and landfall counts.

Two indices were used for long-term (1871–2005) regression statistics: the Bivariate ENSO Index (BEST) and the extended Multivariate ENSO Index

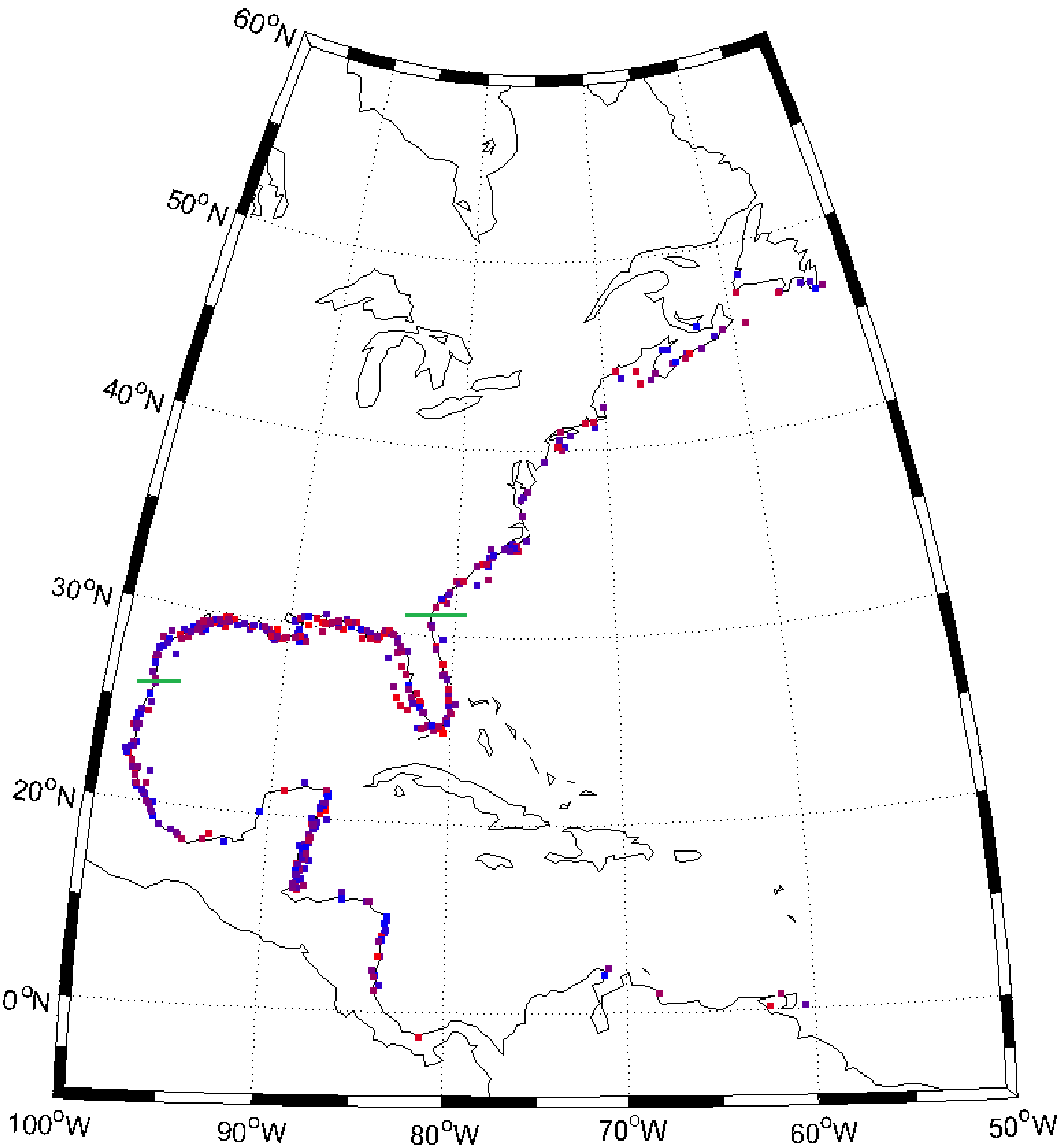

Figure 1. A map of all tropical cyclone landfalls over the Americas for the period 1950–2013. Landfall region separations are indicated by the thick green horizontal lines. Landfalls are shaded on a continuous shading scale based on the month in which the storm made landfall using values of the Oceanic Niño Index (ONI). The ENSO value for each month is that for the 3-mo running mean ONI value centered on that month. More positive values of ONI are symbolized by shades of red (to indicate landfalls during El Niño-like conditions) while more negative values of ONI are symbolized by shades of blue (to indicate landfalls during La Niña-like conditions). Shades of purple indicate ONI values closer to 0 (neutral phase of ENSO). *Click image for an external version.*

(referred to herein as the extended MEI). The BEST dataset is derived using a combination of sea surface temperature (SST) values in the Niño 3.4 region and the Southern Oscillation Index (SOI), as described in Smith and Sardeshmukh (2000). The BEST index contains data from 1870 to present and is available in 1-, 3-, and 5-mo running mean time series, with this paper utilizing the 1-mo running mean (available online at www.esrl.noaa.gov/psd/people/cathy.smith/best/enso.ts.1mn.txt). Similar to the BEST index, the extended MEI dataset incorporates a combination of sea-level pressure (SLP) and SST values in its definition. It differs from the BEST, however, in that these variables are computed over different geographical regions during different times of year to reflect the seasonal variations in where the strongest ENSO signals exist (Wolter and Timlin 2011). The extended MEI dataset contains bimonthly values from 1871 to 2005 (available online at www.esrl.noaa.gov/psd/enso/mei.ext/table.ext.html).

For the more recent past (since 1950), two different ENSO indices were selected for analysis. The first of these is the MEI. As with the extended MEI, the variables used in the MEI are evaluated over geographic regions that vary based on seasonality effects (Wolter and Timlin 1993). Six variables are used to compute the MEI: SLP, *u*- and *v*-components of the surface wind, SST, surface air temperature, and total cloud fraction. The dataset is computed bimonthly (available online at www.esrl.noaa.gov/psd/enso/mei/table.html). The second shorter-term index, and the most widely used, is the Climate Prediction Center's Oceanic Niño Index, or ONI (available online at www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml). This dataset computes SST anomalies in the Niño 3.4 region computed as a 3-mo running mean time series. In addition, the two longer-term indices were truncated to this period (since 1950) so that fair comparisons could be made with these shorter-term indices.

b. Analysis

Linear regression analysis was used to determine the responses in seasonal landfall patterns to seasonally averaged (June–November) values of each ENSO index. For this study, the predictands are the seasonal counts of tropical cyclones and regional landfall. Thus, the predictor must be the corresponding seasonally averaged ENSO index values. Threshold values for determining El Niño and La Niña events are not required in this study given that this is a relationship, rather than categorical, analysis. The linear regressions used here take real-valued (i.e., decimal) inputs that yield a numerical, rather than categorical, output. Values computed in the analysis were the slope (m) and y-intercept (b) of the regression equation (i.e., $tc\_landfall\_count = m * ENSOind + b$), the percent variance explained (R^2) by this regression line, its F statistic, and its p value. The slope and intercept quantify the relationship between ENSO and tropical cyclone landfall counts while the other three statistics quantify the goodness of fit of this simple linear model.

3. Discussion

Linear regression analysis is used to quantify the influence of ENSO on tropical cyclone and landfall counts in the North Atlantic basin and North America. The resulting statistics are shown in Tables 1–3 for the ENSO indices listed in the previous section. Table 1 shows the linear regression statistics for the long-term historical period (1871–2005) for the extended MEI and the BEST datasets. Table 2 displays the equivalent statistics for these same ENSO indices for the more recent historical period (since 1950). It is used for comparison with Table 3 that contains the equivalent statistics from the MEI and the ONI regressions. The purpose of using multiple ENSO indices was to determine whether the influence of ENSO on the tropical cyclone and landfall counts was dependent on the index analyzed.

To quantify the similarity between ENSO indices of the pattern of variation across the set of models of the regression statistics, correlation coefficients were computed for the intercepts and slopes. These correlation coefficients reveal that the pattern of variation of intercepts and slopes are highly consistent between ENSO indices (even among the different time periods of study). Correlation coefficients were 0.99–1.00 for the regression intercepts and 0.96–1.00 for the slope values.

The regression analysis reveals statistically significant (i.e., low p value) ENSO relationships for a number of the counts over all ENSO indices analyzed. The sign of the slope values is negative across all categories and all ENSO indices analyzed, indicating that positive values of ENSO (El Niño) result in decreasing tropical cyclone counts and landfalls. Conversely, negative values of ENSO (La Niña) result in increasing tropical cyclone counts/landfalls. The first category in Tables 1–3 is the total number of tropical cyclones (determined to be of at least tropical depression strength by the NHC), which includes both landfalling and non-landfalling cyclones. The relationship between ENSO and this category is statistically significant for all ENSO indices and both time periods, with p values ranging from 0.00 to 0.03 and R^2 values ranging from 0.05 to 0.13 (Tables 1–3). These results

Table 1. Regression analysis that quantifies how closely the associations between tropical cyclone landfall patterns and seasonally averaged (June–November) ENSO values resemble linearity. “Mean” represents the average seasonal number of storms in each category/region. The “fractional sensitivity” quantifies the fraction of the average seasonal number of storms that is affected by ENSO; it is computed as the “slope” value divided by the “mean” value. The “relative sensitivity” quantifies the relative influence of ENSO on each regional landfall region as compared to the total number of landfalls; it is computed as the fractional sensitivity of each category divided by the fractional sensitivity of the total number of landfalls category. Statistics are computed using the long-term (1871–2005) historical dataset for both the extended MEI and BEI. Asterisks beside *p* values represent levels at which results pass the test of statistical significance (i.e., * = 90%, ** = 95%, and *** = 99%).

Extended Multivariate ENSO Index (1871–2005)								
Category - ENSO Index versus:	**Mean**	**Intercept**	**Slope**	**R^2**	***F* statistic**	***p* value**	**Fractional sensitivity**	**Relative sensitivity**
Total Number of Tropical Cyclones (TD or greater)	9.04	9.04	–0.92	0.05	7.39	0.01***	–0.10	N/A
Total Number of Landfalls	6.02	6.02	–1.24	0.13	20.72	0.00***	–0.21	N/A
Number of Canada/United States East Coast Landfalls	1.22	1.22	–0.37	0.08	11.86	0.00***	–0.31	1.49
Number of United States Gulf Coast/Florida Landfalls	3.04	3.04	–0.14	0.00	0.66	0.42	–0.05	0.23
Number of Central America/Mexico Landfalls	1.76	1.76	–0.72	0.12	18.30	0.00***	–0.41	1.99
Bivariate ENSO Index (1871–2005)								
Total Number of Tropical Cyclones (TD or greater)	9.04	9.05	–1.21	0.07	9.70	0.00***	–0.13	N/A
Total Number of Landfalls	6.02	6.04	–1.38	0.13	19.19	0.00***	–0.23	N/A
Number of Canada/United States East Coast Landfalls	1.22	1.23	–0.33	0.05	6.81	0.01***	–0.27	1.19
Number of United States Gulf Coast/Florida Landfalls	3.04	3.05	–0.19	0.01	0.85	0.36	–0.06	0.27
Number of Central America/Mexico Landfalls	1.76	1.77	–0.86	0.13	19.82	0.00***	–0.49	2.14

are in line with numerous previous studies that have shown influences of the phase of ENSO with interannual variability of tropical cyclone counts (e.g., Gray 1984a; Goldenberg and Shapiro 1996; Wilson 1999).

Likewise, the relationship between the total number of landfalling storms and ENSO is statistically significant across all ENSO indices analyzed (p values <0.01 for all indices). The R^2 values range from 0.13 to 0.22, which indicates that ENSO explains a higher fraction of the season-to-season variance in the number of landfalling tropical cyclones as compared to the total number of tropical cyclones.

Regression analysis of the landfall counts on a regional scale (rows 3–5 in each table) paints a more complex picture. For the Canada/United States East Coast and Central America/Mexico, the relationship between ENSO and regional landfall counts are statistically significant across all indices. P values are ≤0.01 across all ENSO indices analyzed for both landfall regions, thus passing the tests of statistical significance at the 99% level. These results indicate that during times at which ENSO values are negative (La Niña), not only are tropical cyclones more likely to form in the Atlantic basin but they are also favored to hit either Canada/United States East Coast or the coasts of

Table 2. Same as Table 1, except that statistics are computed for the period 1950–2005 for the extended MEI and for the period 1950–2013 for the BEI.

Category - ENSO Index versus:	**Mean**	**Intercept**	**Slope**	R^2	***F* statistic**	***p* value**	**Fractional sensitivity**	**Relative sensitivity**
Extended Multivariate ENSO Index (1950–2005)								
Total Number of Tropical Cyclones (TD or greater)	10.11	10.28	–1.14	0.09	5.21	0.03**	–0.11	N/A
Total Number of Landfalls	5.82	6.02	–1.30	0.18	11.59	0.00***	–0.22	N/A
Number of Canada/United States East Coast Landfalls	1.18	1.23	–0.37	0.11	6.49	0.01***	–0.31	1.40
Number of United States Gulf Coast/Florida Landfalls	2.75	2.76	–0.08	0.00	0.08	0.78	–0.03	0.13
Number of Central America/Mexico Landfalls	1.89	2.02	–0.85	0.23	15.72	0.00***	–0.45	2.02
Bivariate ENSO Index (1950–2013)								
Total Number of Tropical Cyclones (TD or greater)	10.64	10.66	–1.65	0.13	9.51	0.00***	–0.15	N/A
Total Number of Landfalls	5.98	6.01	–1.65	0.21	16.96	0.00***	–0.27	N/A
Number of Canada/United States East Coast Landfalls	1.20	1.21	–0.42	0.11	7.98	0.01***	–0.35	1.28
Number of United States Gulf Coast/Florida Landfalls	2.69	2.69	–0.04	0.00	0.02	0.90	–0.01	0.05
Number of Central America/Mexico Landfalls	2.09	2.11	–1.18	0.29	24.91	0.00***	–0.57	2.06

Central America/Mexico. One important distinction between these two landfall regions is the magnitude of the R^2 values. For the Canada/United States East Coast category, R^2 values range from 0.05 to 0.13. R^2 values are substantially higher (more than twice the magnitude) for the Central America/Mexico landfall region, ranging from 0.12 to 0.29. Thus, landfall counts over the coasts of Mexico/Central America are more sensitive to the ENSO phase.

The opposite of this sensitivity to ENSO exists for the United States Gulf Coast/Florida. *P* values are high—ranging from 0.36 to 0.98 across all ENSO indices and time periods analyzed. Slopes and R^2 values are corresponding small, indicating that ENSO has little influence on seasonal landfall counts in this region. Thus, during periods when the ENSO phase is positive (El Niño; when tropical cyclone formation is inhibited), tropical cyclones that do form have a tendency to hit the Gulf Coast of the United States in preference to other mainland coastlines.

Thus, for the two regions (Canada/United States East Coast and Central America/Mexico) with statistically significant relationships (i.e., *p* values near 0), the fraction of year-to-year count fluctuation explained by ENSO ranges from 22 to 54% and the slope ranges from –0.33 to –1.45. In contrast, for the region (United States Gulf Coast/Florida) with consistently poor *p* values (i.e., >>0), the fraction of the year-to-year fluctuation of counts explained by ENSO ranges from 0 to 11% and the slope from –0.01 to –0.19. This lack of statistical significance is an important result because it indicates the lack of ENSO's influence on storms that make landfall over the United States Gulf Coast/Florida, in contrast to the statistically significant relationship between ENSO and landfalls over the other two regions studied (Canada/United States East

Table 3. Same as Table 2, except that ENSO values are taken from the MEI and ONI for the period 1950–2013.

Multivariate ENSO Index (1950–2013)								
Category - ENSO Index versus:	**Mean**	**Intercept**	**Slope**	R^2	***F* statistic**	***p* value**	**Fractional sensitivity**	**Relative sensitivity**
Total Number of Tropical Cyclones (TD or greater)	10.64	10.70	–1.46	0.11	7.52	0.01***	–0.14	N/A
Total Number of Landfalls	5.98	6.05	–1.64	0.22	17.60	0.00***	–0.27	N/A
Number of Canada/United States East Coast Landfalls	1.20	1.22	–0.44	0.13	8.92	0.00***	–0.37	1.33
Number of United States Gulf Coast/Florida Landfalls	2.69	2.69	–0.05	0.00	0.04	0.85	–0.02	0.07
Number of Central America/Mexico Landfalls	2.09	2.14	–1.15	0.28	23.99	0.00***	–0.55	2.00
Oceanic Niño Index (1950–2013)								
Total Number of Tropical Cyclones (TD or greater)	10.64	10.70	–1.93	0.12	8.73	0.00***	–0.18	N/A
Total Number of Landfalls	5.98	6.05	–1.99	0.21	16.69	0.00***	–0.33	N/A
Number of Canada/United States East Coast Landfalls	1.20	1.22	–0.52	0.12	8.27	0.01***	–0.44	1.31
Number of United States Gulf Coast/Florida Landfalls	2.69	2.69	–0.01	0.00	0.00	0.98	0.00	0.01
Number of Central America/Mexico Landfalls	2.09	2.14	–1.45	0.29	25.56	0.00***	–0.69	2.09

Coast and Central America/Mexico). Thus, for combinations of landfall region and ENSO index where the *p* value indicates statistical significance, roughly 25–50% of the year-to-year fluctuation in landfall counts is explained by ENSO, while in the region where the *p* value indicates no statistical significance at most 10% of the year-to-year fluctuation in landfall count might be ENSO-related. Another way of quantifying the influence of ENSO on the landfall regions analyzed is through two derived statistical variables: the "fractional sensitivity" and "relative sensitivity" that are also shown in Tables 1–3. The fractional sensitivity is the slope of each landfall region's regression divided by the seasonal mean number of landfalls in that region. This can be thought of as the fractional change in landfalls resulting from an increase or decrease of each ENSO index value by 1 unit. As expected, the largest fractional sensitivities occur for the Mexico/Central America categories (i.e., as much as a 69% change in landfall count using the ONI index) while the lowest fractional sensitivities occur for the United States Gulf Coast/Florida category (i.e., as low as 0.00 for the ONI index).

The "relative sensitivity" statistic is the ratio of the fractional sensitivity of each landfall region to the fractional sensitivity of total landfalls. So, a relative sensitivity >1 indicates a landfall region that has a higher sensitivity to the phase of ENSO as compared to the total landfall count across all regions. Values are >1 for both the Canada/United States East and Central America/Mexico categories across all ENSO indices and all time periods analyzed. Relative sensitivities are >2 for the Central America/Mexico category for most of the ENSO indices in the recent past (since 1950), which indicates that the influence of ENSO on the region's landfall counts is more than twice that of the influence for total landfalls. Conversely, values are <<1 for the United States Gulf Coast/Florida category across all ENSO indices and time periods analyzed. In fact, for the recent past, the relative sensitivity is near zero for the United States Gulf Coast/Florida region across all ENSO indices.

The ONI index yields the highest *p* value for the United States Gulf Coast/Florida landfall region and very low *p* values (near 0) for the remainder of the regions. The other statistics show corresponding patterns. Thus, this index provides the clearest depiction of the effects of ENSO on landfall distributions across the Americas (Fig. 1). Tropical cyclone landfalls occurring in the period 1950–2013 are shaded by ENSO phase, on a continuous scale, using ONI values where highly positive ONI (El Niño) months are shaded red and highly negative ONI (La Niña) months are shaded in blue, with the various shades of purple representing values closer to 0 (neutral). Consistent with the statistics, the United States Gulf Coast of the United States (and the east coast of Florida) is dominated by landfalls occurring during El Niño months (red dots) whereas the coastlines of Central America, Canada, and the United States East Coast north of the Florida/Georgia border primarily get struck by tropical cyclones during La Niña months (blue dots).

This paper does not delve into the potential reasons for favored United States Gulf Coast/Florida landfalls during El Niño events, but a possibility could be that the phase of ENSO influences the synoptic patterns that affect the steering patterns of the tropical cyclones. Another possibility is that ENSO may impact favored regions for storms to form and thus their proximity to coastlines on which they can make landfall. Prior work by Colbert and Soden (2012) has examined some of these influences on tropical cyclone tracks for storms originating in the main development region.

4. Conclusions

This study investigates the influence of ENSO on seasonal Atlantic basin tropical cyclone landfall count variability within three specified regions of North America: Canada/United States East Coast, United States Gulf Coast/Florida, and Central America/Mexico. The study investigated all storms of at least tropical depression strength that formed within the temporal bounds of the hurricane season (1 June–30 November) for the period 1871–2013. Through the use of linear regression analysis, seasonal tropical cyclone counts as well as tropical cyclone landfall counts were determined to be negatively correlated with the sign of ENSO (specified by seasonally averaged ENSO values) for multiple ENSO indices and time periods, complimenting many previous studies on total basin counts. In contrast, landfall counts over the United States Gulf Coast and Florida were shown to lack correlation with—and thus be rather insensitive to—the ENSO phase.

This study was limited to a statistical analysis of ENSO's influence on tropical cyclones and their landfalls. Additional work is needed to determine the physical mechanisms that explain the impacts of ENSO described in this paper. Likewise, investigation of the influence of other teleconnection patterns (e.g., Quasi-biennial Oscillation, North Atlantic Oscillation, Atlantic Meridional Mode, etc.) on tropical cyclone landfall patterns potentially could provide additional understanding of the interannual variability in regional-scale tropical cyclone landfall counts. A logical next step in this investigation is the creation of a regionalized seasonal tropical cyclone landfall count prediction model, analogous to those in use for basin-wide named storm counts.

These findings illustrate the potential value of a more regional perspective in seasonal tropical cyclone forecasts and, thus, the communication of the potential consequences of these impacts at a regional level. A better understanding of these regional effects can assist in better informing the public, determining appropriate annual preparation activities, and potentially limiting socioeconomic losses.

Acknowledgments. The authors are thankful for the valuable insights provided by Dr. Steven Feldstein, Paul Knight, and Dr. Steven Greybush. Dr. Jenni Evans provided beneficial guidance early on regarding tropical cyclone tracks and landfall patterns. Guidance from the anonymous reviewers was crucial to the ultimate evolution of this research. The authors also are very grateful to the following organizations for providing data that made this investigation possible: the NOAA Earth System Research Laboratory, the NOAA Climate Prediction Center, and the NOAA Hurricane Research Division.

REFERENCES

Barnston, A. G., M. K. Tippett, M. L. L'Heureux, S. Li, and D. G. DeWitt, 2012: Skill of real-time seasonal ENSO model predictions during 2002–11: Is our capability increasing? *Bull. Amer. Meteor. Soc.*, **93**, 631–651, CrossRef.

Bove, M. C., J. B. Elsner, C. W. Landsea, X. Niu, and J. J. O'Brien, 1998: Effect of El Niño on U.S. landfalling hurricanes, revisited. *Bull. Amer. Meteor. Soc.*, **79,** 2477–2482, CrossRef.

Colbert, A. J., and B. J. Soden, 2012: Climatological variations in North Atlantic tropical cyclone tracks. *J. Climate*, **25**, 657–673, CrossRef.

Elsner, J. B., and B. Kocher, 2000: Global tropical cyclone activity: A link to the North Atlantic Oscillation. *Geophys. Res. Lett.*, **27,** 129–132, CrossRef.

____, and T. H. Jagger, 2004: A hierarchical Bayesian approach to seasonal hurricane modeling. *J. Climate*, **17,** 2813–2827, CrossRef.

Fedorov, A.V., S. L. Harper, S. G. Philander, B. Winter, and A. Wittenberg, 2003: How predictable is El Niño? *Bull. Amer. Meteor. Soc.*, **84**, 911–919, CrossRef.

Goldenberg, S. B., and L. J. Shapiro, 1996: Physical mechanisms for the association of El Niño and West African rainfall with Atlantic major hurricane activity. *J. Climate*, **9,** 1169–1187, CrossRef.

Gray, W. M., 1984a: Atlantic seasonal hurricane frequency. Part I: El Niño and 30 mb Quasi-Biennial Oscillation influences. *Mon. Wea. Rev.*, **112,** 1649–1668, CrossRef.

____, 1984b: Atlantic seasonal hurricane frequency. Part II: Forecasting its variability. *Mon. Wea. Rev.*, **112,** 1669–1683, CrossRef.

____, C. W. Landsea, P. W. Mielke Jr., and K. J. Berry, 1992: Predicting Atlantic seasonal hurricane activity 6–11 months in advance. *Wea. Forecasting*, **7,** 440–455, CrossRef.

____, ____, ____, and ____, 1993: Predicting Atlantic basin seasonal tropical cyclone activity by 1 August. *Wea. Forecasting*, **8,** 73–86, CrossRef.

____, ____, ____, and ____, 1994: Predicting Atlantic basin seasonal tropical cyclone activity by 1 June. *Wea. Forecasting*, **9,** 103–115, CrossRef.

Hess, J. C., J. B. Elsner, and N. E. LaSeur, 1995: Improving seasonal hurricane predictions for the Atlantic basin. *Wea. Forecasting*, **10,** 425–432, CrossRef.

Kirtman, B. P., and P. S. Schopf, 1998: Decadal variability in ENSO predictability and prediction. *J. Climate*, **11,** 2804–2822, CrossRef.

Kleeman, R., and A. M. Moore, 1997: A theory for the limitation of ENSO predictability due to stochastic atmospheric transients. *J. Atmos. Sci.*, **54**, 753–767, CrossRef.

Klotzbach, P. J., 2011: El Niño–Southern Oscillation's impact on Atlantic basin hurricanes and U.S. landfalls. *J. Climate*, **24,** 1252–1263, CrossRef.

____, 2014: Prediction of seasonal Atlantic basin accumulated cyclone energy from 1 July. *Wea. Forecasting*, **29,** 115–121, CrossRef.

____, and W. M. Gray, 2008: Multidecadal variability in North Atlantic tropical cyclone activity. *J. Climate*, **21,** 3929–3935, CrossRef.

Landsea, C. W., and J. L. Franklin, 2013: Atlantic hurricane database uncertainty and presentation of a new database format. *Mon. Wea. Rev.*, **141,** 3576–3592, CrossRef.

____, W. M. Gray, P. W. Mielke Jr., and K. J. Berry, 1994: Seasonal forecasting of Atlantic hurricane activity. *Weather*, **49,** 273–284, CrossRef.

____, R. A. Pielke Jr., A. M. Mestas-Nuñez, and J. A. Knaff, 1999: Atlantic basin hurricanes: Indices of climatic changes. *Climatic Change*, **42,** 89–129, CrossRef.

Lehmiller, G. S., T. B. Kimberlain, and J. B. Elsner, 1997: Seasonal prediction models for North Atlantic basin hurricane location. *Mon. Wea. Rev.*, **125,** 1780–1791, CrossRef.

Maue, R. N., 2011: Recent historically low global tropical cyclone activity. *Geophys. Res. Lett.*, **38,** L14803, CrossRef.

Pielke, R. A., Jr., and R. A. Pielke Sr., 1997*: Hurricanes: Their Nature and Impacts on Society*. John Wiley and Sons, 279 pp.

____, and C. W. Landsea, 1998: Normalized hurricane damages in the United States: 1925–1995. *Wea. Forecasting*, **13,** 621–631, CrossRef.

Smith, C. A., and P. Sardeshmukh, 2000: The effect of ENSO on the intraseasonal variance of surface temperature in winter. *Int. J. Climatol.*, **20,** 1543–1557, CrossRef.

Stockdale, T. N., and Coauthors, 2011: ECMWF seasonal forecast system 3 and its prediction of sea surface temperature. *Climate Dyn*., **37**, 455–471, CrossRef.

Trenberth, K. E., 1997: The definition of El Niño. *Bull. Amer. Meteor. Soc.*, **78,** 2771–2777, CrossRef.

Wilson, R. M., 1999: Statistical aspects of major (intense) hurricanes in the Atlantic basin during the past 49 hurricane seasons (1950–1998): Implications for the current season. *Geophys. Res. Lett.*, **26,** 2957–2960, CrossRef.

Wolter, K., and M. S. Timlin, 1993: Monitoring ENSO in COADS with a seasonally adjusted principal component index. Proc., *17th Climate Diagnostics Workshop*, Norman, OK, NOAA/NMC/CAC, 52–57. [Available online at www.esrl.noaa.gov/psd/enso/mei.ext/WT1.pdf.]

____, and ____, 2011: El Niño/Southern Oscillation behaviour since 1871 as diagnosed in an extended multivariate ENSO index (MEI.ext). *Int. J. Climatol.*, **31,** 1074–1087, CrossRef.

Yan, T., 2006: Interannual variability of climatology and tropical cyclone tracks in North Atlantic and Western North Pacific. Ph.D. dissertation, North Carolina State University, 240 pp.