7.1 TORNADO OUTBREAKS ASSOCIATED WITH LAND-FALLING TROPICAL CYCLONES IN THE ATLANTIC BASIN

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1. Introduction

A tornado outbreak is considered one of the most destructive types of weather phenomenon that occurs in the United States. Since the term 'outbreak' can mean different things to different communities, characterizing exactly what constitutes a tornado outbreak can be very difficult (with the exception of very obvious cases [e.g. April 3-4, 1974]). Pautz (1969) defined a "family" outbreak as any given day consisting of 5 or more tornado occurrences within the same synoptic system. Based on his findings of the spatial distribution of tornadoes, Galway (1975) expanded Pautz's definition to include three classifications of "family" outbreaks: small (6-9 tornadoes), moderate (10-19 tornadoes), and large (≥20 tornadoes). In addition, Galway (1975) found that moderate and large outbreaks (10 or more tornadoes) were responsible for 73% of tornado deaths during 1952 to 1973 and forecasters had more skill in anticipating these types of events. From these findings, Galway (1977) concluded that previous outbreak definitions, which only accounted for the number of tornadoes, were insufficient and an intensity criterion must also be incorporated. Accordingly, we developed an approach to defining extreme tornado events based on the climatology of tornado occurrences and Fujita scale damage ratings.

From our alternative definition of an outbreak, a data set of tornado outbreaks within land-falling tropical cyclones (TCs) was developed. Land-falling TCs possess many dangerous features that affect life and property. Meteorologists are greatly challenged in forecasting the precise location and magnitude of high winds, flooding rains, and storm surge due to the unpredictable nature of a tropical cyclone's track into the mid-latitudes. Identifying tornadoes and/or tornado outbreaks within land-falling TCs present an even greater challenge to forecasters and public safety.

2. Tornado Climatology

Over the past half century, the number of tornadoes reported in the United States has increased from roughly 600 per year in the 1950s to approximately 1200 today (figure 1). The changes may not be entirely related to meteorological causes; but reporting discrepancies, increasing population and public awareness, advancements in technology, and National Weather Service vigilance all contribute to the increasing trend. Due to the inflation of reports, we must "level the playing field" to begin to compare past tornado events to the present.

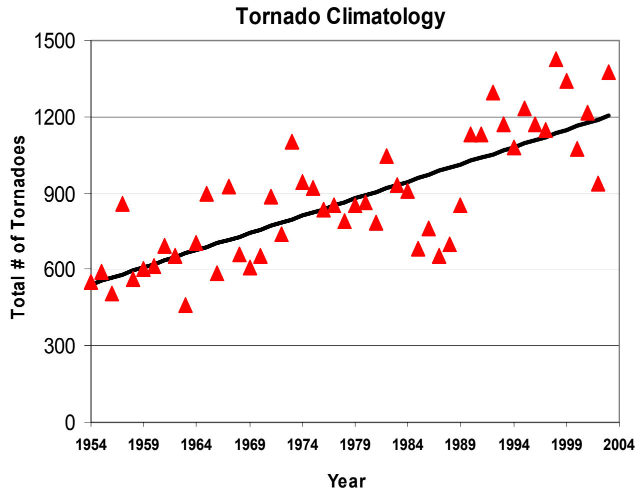

Figure 1. *Annual number of tornado reports (1954-2003) from SPC data. Black line denotes linear regression fit.*

Daily tornado reports were collected from 1954 to 2003 during one convective day (1200 to 1200 UTC twenty-four hours later), to establish the idea of a single "big tornado day". Next, a simple linear regression was performed on the annual number of tornado reports gathered from the Storm Prediction Center's Severe Plot program (see figure 1). The linear regression indicates an expected increase in the number of reported tornadoes by about 14 per year. Bruening et al. (2002) illustrated how such an approach can be utilized to adjust for the inflation and examine the progression of a tornado season through the year. (Whether a linear fit to the data is appropriate is open to debate, although the impression of a large number of tornadoes in the early 1970s and a small number in the late 1980s fits with anecdotal evidence). In consequence, the mean expected number of annual tornado reports increases from 555 in 1954 to 856 in 1977 to 1183 in 2002. Undoubtedly, the interpretation of the importance of a single "big day" changes over time. A 10-tornado day would have represented nearly 2% of the expected number of tornadoes in 1954, but less than 1% today. Using the expected values from the linear regression as a baseline, we have analyzed a number of aspects of the tornado climatology.

First, "big tornado days", those days that have many tornadoes in the US, can be identified as exceeding some threshold of the annual expected number, say 5% of the annual total. In addition to exceeding a minimum number of tornadoes, "big tornado days" must also include some intensity

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information. Brooks and Doswell (2001) suggest that stronger tornadoes have been reported more consistently over time, so it is natural to consider the number of significant tornadoes (F2 and greater) as an initial indication of outbreak severity. As the large increase in reports over the years suggests, application of a threshold of a fixed number of reports for any tornadoes over time is problematic. Instead, we focused on whether days exceeded a fraction of the expected value associate with the linear regression for a particular year. For instance, we can count the number of days with more than 1.5% of the linear regression value. That leads to counting days with more than 8 tornadoes in 1954, to days with at least 18 tornadoes in 2003. Identifying natural breaks in the data set would aid in the objective placement of thresholds in terms of number and intensity of tornadoes. Figure 2 illustrates the days per year that meet 'x' number of F1 or greater tornadoes. Unfortunately, there is no natural break in the data to establish a limit (F2 or greater series would yield similar results).

Since there is no natural break in the data set, one may place thresholds arbitrarily, based upon the user's need. As an initial cut, we chose 1.5% of the regression, at least 8 F1 or greater tornadoes, and at least 4 F2 or greater tornado occurrences, within a single day, to be considered an outbreak. The time series of big days for each year is generated with these thresholds (see figure 3), and it is revealed that approximately 14 days per year meet this threshold. Upon closer examination of the time series, the "any tornado" and F1 series trace each other reasonably well, as compared to the F2 series. The F2 series contains a distinct break in the early to mid-1970s and more outbreaks were identified in the first 19 years of the data set.

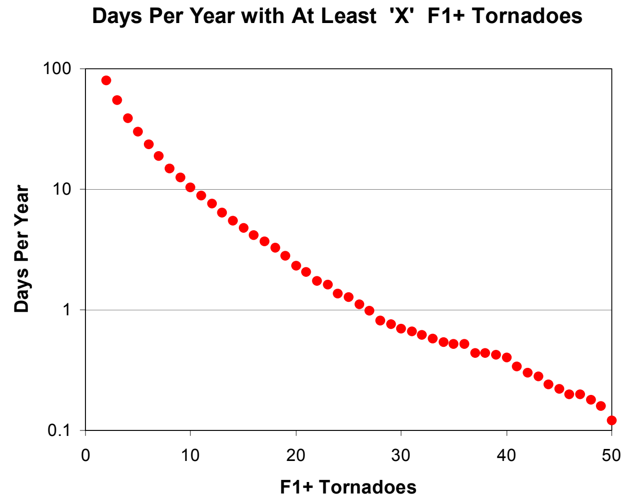


Figure 2. *Number of days per year exceeding thresholds for tornadoes of F1 or greater*

Looking at the sorted distribution of big day identifications for the early and late parts of the record helped distinguish which series is the cause of the inconsistency (figure 4). It is evident from the figure that the F2 and greater series may have some over-rating problems in the first 19 years of the data set, while the F1 and greater series is much more stationary. As a result of the over-rating problems of the F2 series, we opted for the F1 series as an intensity indicator for outbreak classification. Taking into consideration the arbitrary nature of any selected thresholds, the calculation of the number of big days per year is an interesting exercise and thresholds are user dependent.

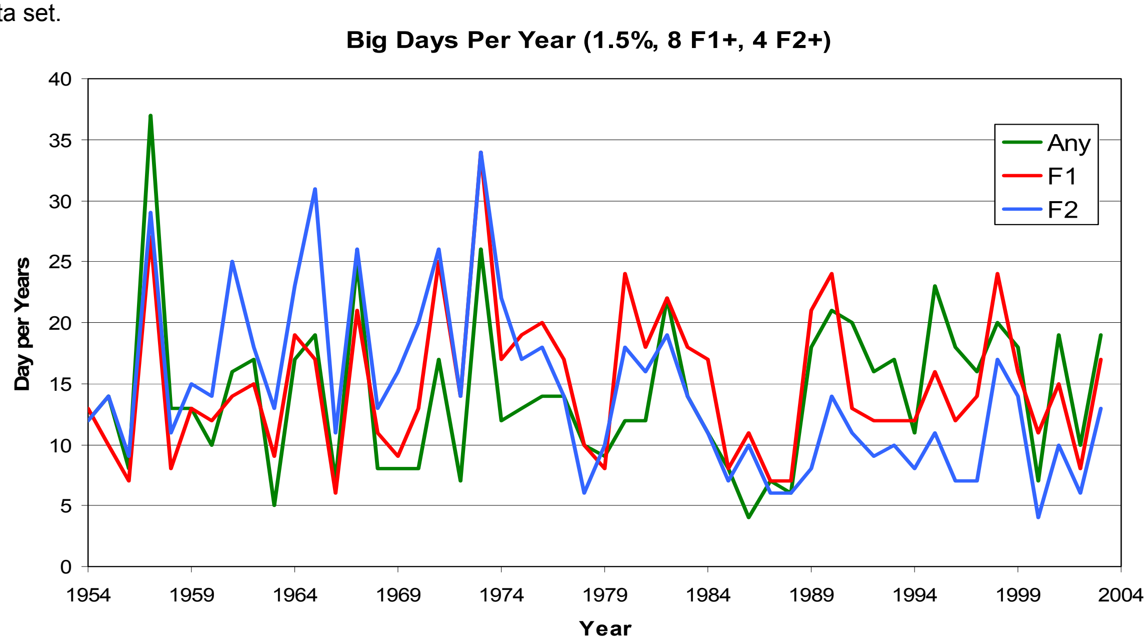
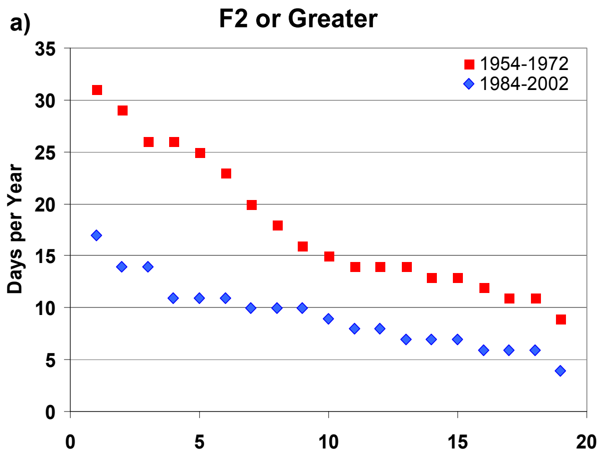


Figure 3. *Days per year exceeding "big day" thresholds for any tornado (green, 1.5% of expected value), F1 or greater (red, at least 8 tornadoes), F2 or greater (blue, at least 4 tornadoes) for 1954-2003).*



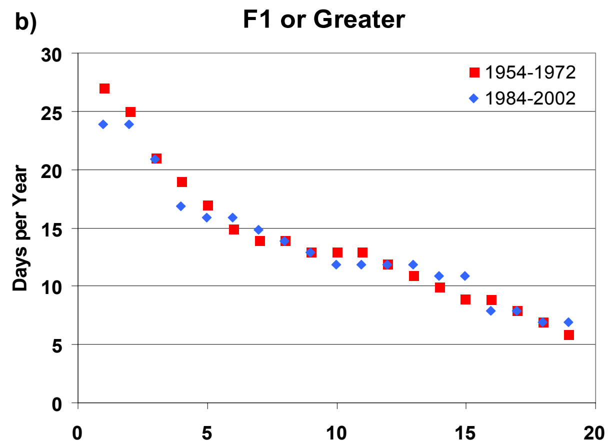


Figure 4. *Sorted distribution of number of days per year identified as big days from 1954-1972 (red) and 1984-2002 (blue). Leftmost item in each series is largest value of dataset and rightmost is the smallest. a) F2 and greater series, threshold of 4 tornadoes. b) F1 and greater series, threshold of 8 tornadoes.*

3. Land-falling Tropical Cyclones

Land-falling tropical cyclones (TCs) are a major threat to life and property. TC property losses account for 40% of all insured losses in the United States from 1984 to 1993, exceeding earthquake losses by a factor of four (Pielke and Pielke 1997). It is of great importance to correctly forecast the impact of a TC and to relay information to the public. Not only do TCs contain high winds, storm surges, heavy rain and flash flooding- add the potential for tornado outbreaks and forecasters have their hands full even more.

Based on the tornado climatology discussed previously, the definition of a tornado outbreak within a land-falling TC must be chosen arbitrarily, but with some guidance. Smith (1965) noted that non-TC related tornadoes were twice as large in path length and width over those spawned by TCs. McCaul (1987, 1991) and Spratt et al. (1997) observed shallow mesocyclones embedded within TCs with average depths of 3 to 3.5 kilometers. In addition to shallower mesocyclones in TCs, Spratt et al. (1997) concluded that traditional tornadic radar signatures such as hooks, appendages, or bounded weak echo regions were subtle, or even non-existent for TC tornadoes. It is for these reasons that less constrictive thresholds must be chosen when considering tornado outbreaks within land-falling TCs.

For this study, we chose a threshold of 1.5% of the regression value and at least 8 F1 or greater tornado occurrences to be considered an outbreak TC. Tornado reports were collected from the Storm Prediction Center's Severe Plot program and cross-checked with all U.S. land-falling TCs in the Atlantic basin from 1954 to 2003. Several days prior to and following landfall were examined to include tornado occurrences in the outer rain bands and during dissipation of the cyclone. Only those reports that were within 350 kilometers of the storm center were considered to be associated with the TC.

From this methodology, 18 land-falling TCs were identified has having a tornado outbreak within them (see table 1). Table 1 lists outbreak TCs in alphabetical order with landfall impact dates, total number of tornadoes reported, and the number of F1 or greater tornadoes. Note that 3 out of the 18, or about 17% of the outbreak TCs occurred in 1964. Hurricane Beulah had well over 100 reported tornadoes associated with her landfall (Severe Plot lists 117), while that number is disputed by other authors (Novlan and Gray, 1974, reported 141 tornadoes due to Beulah). Table 2 lists 21 non-outbreak TCs where very few or no tornadoes were reported with the tropical feature. Notice only 4 land-falling TCs had no reported tornadoes and 50% of those were in 1954. Finally, those TCs that did not meet outbreak or non-outbreak criteria were labeled “middle class” TCs. Table 3 lists these storms in alphabetical order, landfall impact dates, and Saffir-Simpson category at time of landfall. Twenty percent of these storms were intense hurricanes at landfall (category 3 or higher). It is important to note that storms that never reached hurricane strength at some point in their track (34 ms^{-1} winds) were not considered for the non-outbreak or middle class classifications. However, they were considered for outbreak classification as 2 out of the 18 outbreak TCs never achieved hurricane strength (Beryl and Candy). From this data set of land-falling TCs and the classifications of outbreak, middle class, and non-outbreak, several parameters can be compared to examine the similarities/differences between each classification.

4. Tropical Cyclone Comparisons

Several parameters were examined in an effort to distinguish between each type of land-falling TC. If forecasters could improve forecasts of tornadoes in TCs, fatalities could be reduced by as much as 10% (Novlan and Gray 1974). Storm origin, landfall location,

Name	Landfall Impact	Total Tors	F1+	Name	Landfall Impact	Total Tors	F1+
Agnes	June 17-25, 1972	15	14	Cleo	August 26-Sept.1, 1964	11	9
Allen	August 8-12, 1980	25	20	Danny	August 14-19, 1985	42	29
Andrew	August 23-29, 1992	56	23	David	Sept. 2-7, 1979	34	26
Audrey	June 26-July1, 1957	22	18	Edith	Sept. 14-19, 1971	16	15
Babe	Sept. 3-9, 1977	16	14	Georges	Sept. 24-Oct. 1, 1998	49	21
Beryl	August 14-19, 1994	35	27	Gilbert	Sept. 15-20, 1988	41	13
Beulah	Sept. 18-22, 1967	117	21	Hilda	Oct. 2-6, 1964	12	10
Carla	Sept. 10-14, 1961	18	17	Isbell	Oct. 14-16, 1964	9	8
Candy	June 23-27, 1968	32	19	Opal	Oct. 4-6, 1995	35	8

Table 1. *Outbreak Tropical Cyclones listed in alphabetical order, dates of landfall impact, total number of reported tornadoes, number of reported F1 or greater tornadoes. Total=18*

Table 2. *Same as Table 1 but for Non-Outbreak Tropical Cyclones. Total=21*

Name	Landfall Impact	Total Tors	F1+	Name	Landfall Impact	Total Tors	F1+
Alice	June 24-27, 1954	0	0	Fern	Sept. 8-11, 1971	3	2
Alma	June 7-12, 1966	4	2	Florence	Sept. 8-12, 1988	4	0
Bob	July 21-27, 1985	5	1	Fran	Sept. 5-8, 1996	2	1
Bonnie	June 25-28, 1986	5	5	Gladys	Oct. 16-20, 1968	2	2
Bret	Aug. 21-24, 1999	5	0	Gloria	Sept. 26-28, 1985	2	1
Camille	Aug. 16-20, 1969	3	1	Gordon	Nov. 15-22, 1994	6	3
Chantal	July 31-Aug. 3, 1989	6	1	Hazel	Oct. 14-16, 1954	0	0
Cindy	Sept. 16-20, 1963	0	0	Hugo	Sept. 21-23, 1989	2	2
Debra	July 22-27, 1959	1	0	Irene	Oct. 15-18, 1999	5	4
Dennis	Aug. 29-Sept. 7, 1999	2	1	Kate	Nov. 20-23, 1985	0	0
Dora	Sept. 9-14, 1964	3	2				

Name	Landfall Impact	Category
Alicia	Aug. 17-21, 1983	3
Bertha	July 11-13, 1996	2
Betsy	Sept. 7-12, 1965	3
Bob	Aug. 17-19, 1991	2
Bob	July 10-13, 1979	1
Bonnie	June 24-27, 1986	1
Carmen	Sept. 7-9, 1974	3
Celia	Aug. 3-5, 1970	1
Cindy	June 8-11, 1959	1
Connie	Aug. 11-14, 1955	1
Danny	July 20-26, 1997	1
Diana	Sept. 8-14, 1984	1
Diane	Aug. 16-20, 1955	1
Elena	Aug. 30-Sept. 4, 1985	3
Eloise	Sept. 22-24, 1975	3
Erin	Aug. 1-5, 1995	1
Ethel	Sept. 16-17, 1960	1
Flossy	Sept. 23-27, 1956	1
Floyd	Sept. 15-19, 1999	2
Frederic	Sept. 12-14, 1979	2
Gracie	Sept. 29-Oct. 2, 1959	3
Ione	Sept. 19-20, 1955	1
Isabel	Sept. 18-19, 2003	2
Juan	Oct. 27-Nov. 1, 1985	1
Lili	Oct. 2-4, 2002	1

Table 3. *"Middle Class" Tropical Cyclones. Listed in alphabetical order, dates of landfall impact, and Saffir-Simpson category at time of landfall. Total=25*

Saffir-Simpson categories at landfall and time of tornado, Julian date, and ENSO phase were a few of the parameters examined.

Figure 5 illustrates the Julian date of landfall for both outbreak and non-outbreak TCs. Unfortunately, the figure reveals that there is no separation between the 2 types of events by time of year alone except possibly the occurrence of an outbreak TC does not extend as late into the hurricane season. Since there is no distinction in the time of year an outbreak TC can hit, we broke down the data set into origins and landfall locations to identify trends. There are three possible origin locations of TCs: Atlantic ocean, Caribbean Sea, and the Gulf of Mexico. Similarly, we broke down the landfall location into three categories: Texas/Louisiana coast, Mississippi/Alabama/West Coast of Florida, and the East Coast of Florida northward to New England. Figure 6 shows the origin of outbreak, non-outbreak, and middle class TCs with respect to the three origins listed above. Clearly, outbreak and middle class TCs

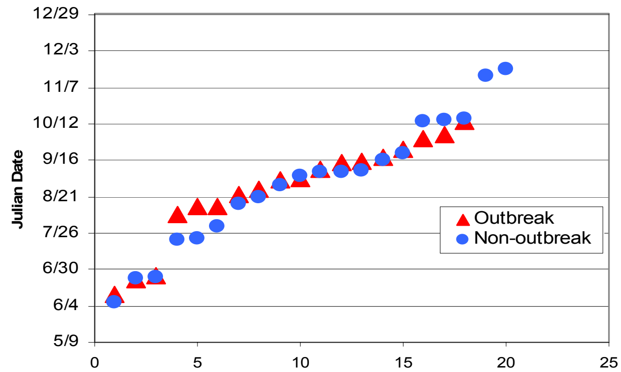


Figure 5. *Julian date of outbreak (in red) and non-outbreak (in blue) tropical cyclones. Data is sorted from the earliest date on the left to the latest date on the right.*

tended to originate in the Atlantic while non-outbreaks favored the Gulf of Mexico. McCaul (1991) stated that it is well known that most TCs that make landfall along the Gulf Coast generate at least a few tornadoes. Figure 7 illustrates that Gulf Coast landfalls were favored by outbreak TCs. Middle class TCs had more variation

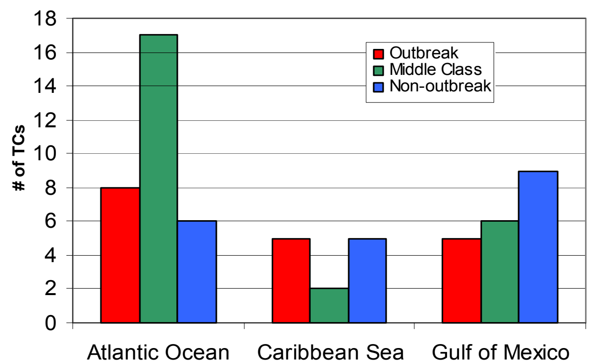


Figure 6. *Origins of Tropical Cyclones from the Atlantic Ocean, Caribbean Sea, and Gulf of Mexico. Outbreak (in red), Middle Class (in green), and Non-outbreak (in blue).*

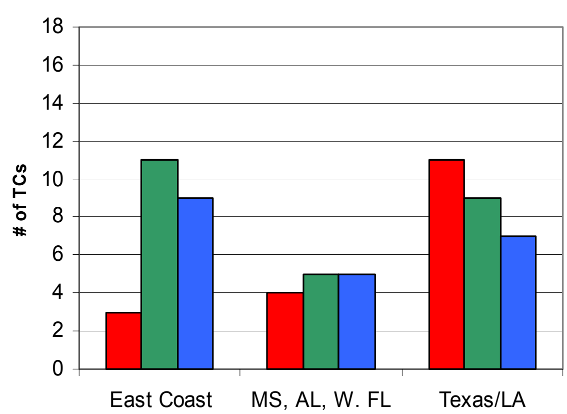


Figure 7. *Same as Figure 6 but Landfall Locations.*

with 11 East Coast landfalls and 9 Texas/Louisiana landfalls.

Lastly, the role of El Niño-Southern Oscillation (ENSO) was investigated to determine if outbreak TCs preferred a certain phase. Only storms of Atlantic origin were examined because the Gulf of Mexico and Caribbean Sea are closed systems of warmer water and would not be affected as much by ENSO phase. To determine what phase of ENSO each land-falling TC was in, we utilized the Southern Oscillation Index (SOI). The SOI is the standardized anomaly of mean sea level pressure difference between Darwin, and Tahiti (http://www.bom.gov.au/climate/glossary/soi.shtml). Negative values between -5 and -35 are consistent with El Niño conditions and positive values between +5 and +35 are considered La Niña. Anywhere between ±5 is regarded neutral, or having no preferred ENSO phase.

Bove et al. (1998), Pielke and Landsea (1999), and Gray (1984) all determined that Atlantic TC activity was suppressed both during and following El Niño years. By the same token, Pielke and Landsea (1999) showed that La Niña years promoted a higher incidence of damaging storms and more damage *per* storm. From this data, one would deduce that outbreak TCs would most likely occur during La Niña conditions, yet that is almost exactly the opposite. Figure 8 revealed that outbreak TCs originating in the Atlantic Ocean showed either no preference for ENSO conditions (i.e. neutral) or subsequent El Niño years. The calculations for the figure were the average of the previous May through February SOI (year prior to the event) and plot that value for each classification of TC. It should be noted that this is a small sample of only 50 years of land-falling tropical cyclones (1954-2003) and one must still keep in mind the implications of the arbitrary nature of the outbreak definition, and the reporting problems of tornadoes both associated and not associated with land-falling tropical cyclones.

In addition, more work has yet to be done in terms of examining the location of tornado reports with respect to storm center and time of day. Tornadoes within land-falling tropical cyclones are generally a difficult feature to forecast and warn for. In any event, the dangers of land-falling tropical cyclones must be relayed to the public to ensure timely and safe preparations and evacuations.

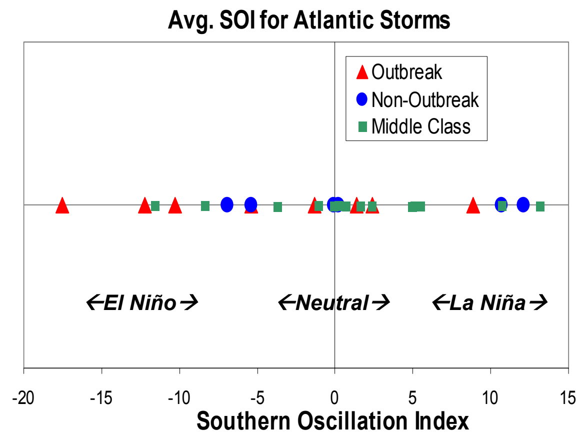


Figure 8. *Average Southern Oscillation Index for all Atlantic Ocean storm originations. Avg. SOI was computed from May to February the year prior to event. Outbreaks (in red), Non-outbreaks (in blue), and Middle Class (in green).*

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