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A Long-Term Study of Tropical Systems Impacting Missouri

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Abstract: *This work describes an evaluation of tropical cyclones (TCs) and depressions in order to determine if the El Niño Southern Oscillation (ENSO) may related to the recent rise of TC remnants affecting Missouri or if the variability is more sensitive to a long term Pacific Decadal Cycle. Sea surface temperatures (SST), mean sea level pressure (MSLP), the Pacific Decadal Oscillation (PDO), the Atlantic Multi-decadal Oscillation (AMO), the Quasi-Biennial Oscillation (QBO), and the (ENSO) were studied to determine possible correlations with the frequency of tropical remnants affecting Missouri. The study found a significant positive correlation between the frequencies of Missouri impacts per year to the frequency of Atlantic Ocean TCs. The more active the Atlantic Ocean basin is, the more times Missouri can expect to be impacted. TC paths were classified based on their direction of travel. TC remnants interacting with frontal boundaries took a more southwest to northeast track. Whereas TC remnants that entered a more zonal weather pattern traveled along a south to north path. Results found that the positive PDO (PDO one) 1938–1946 and 1977–1998 involved a total of 10 TCs affecting Missouri, an average of 0.32 events per year. The negative PDO (PDO two) 1947–1976 and 1999–present involved a combined result of 25 TCs affecting Missouri, an average of 0.57 events per year. A similar result is found for the AMO.*

A 2005 case study shows how the rare combination of elevated SSTs in the Gulf of Mexico, anomalously low MSLP, and the negative phase QBO led to increased TC activity in the tropical Atlantic Ocean. Also, the frequency of TC affecting Missouri since 1938 was compared to the type of ENSO cycle. La Niña periods produced an average of 0.37, El Niño produced 0.31, and Neutral periods produced 0.58 TC per year. The frequency of Missouri impacts was separated by month during each respective ENSO cycle. Chi-squared tests show - with four degrees of freedom and a value of 0.99 - that the distributions of TC per month versus ENSO cycle are not significantly different. Thus, Missouri is impacted more often by TCs during August and September regardless of ENSO phase. The conclusions suggest that Missouri TC climatology is more sensitive to long term PDO cycle fluctuations, and the resulting frequency of TC in the Atlantic Ocean, than to short term ENSO variability.

Background

The potential that climate change may have on tropical cyclones (TCs), has become a topic of increasing interest recently (e.g., Pielke et al. 2005, Webster et al. 2005, Emanuel et al. 2008). The National Center for Atmospheric Research (NCAR) declares that since 1995 there has been an increasing trend in hurricane intensity. The 2005 Atlantic TC season seemed to spark debate about whether climate change was indeed the cause of the numerous devastating hurricanes in the Atlantic Ocean basin. During that year, Hurricane Katrina became the costliest storm in United States history (National Hurricane Center [NHC] 2005). A few months later, Hurricane Wilma broke the record for strongest TC ever recorded in the Atlantic with a low pressure center of 882 mb (National Climatic Data Center [NCDC] 2005, Beven et al. 2008). There were 15 hurricanes in the North Atlantic which was also a record number (Beven et al. 2008). Pielke et al. (2005) argues there has yet to be a direct connection made between climate change and hurricane activity, and that any possible future impacts will be based more on natural variability than climate changes. This position was supported later by other studies (e.g., Landsea et al. 2009, Song et al. 2010).

Nonetheless, studies have tried to relate sea surface temperature (SST) driven oscillations - including the El Niño Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) cycles - to increased TCs (e.g., Hoyos et al. 2006). This study, and similar ones, argue that an increase in SSTs provide an increased chance for the favorable conditions for TC occurrence. However, Zuki and Lupo (2008) demonstrate that increased SSTs do not necessarily mean more TCs. Hoyos et al. (2006) also tried to show that global warming is the overall reason for increases from category 4 to 5 on the Saffir-Simpson scale from 1970 to 2004. Emanuel et al. (2008) argue that TC occurrence may fall slightly, but there will be an increase in intensity. Other studies have shown a link between the interannual variability of TC activity in the Atlantic region related to changes in ENSO and PDO variability (e.g., Lupo and Johnston 2000, Lupo et al. 2008, Lupo, 2011). Research by the National Oceanic and Atmospheric Administration (NOAA) Geophysical Fluid Dynamics Laboratory has shown a decrease in the frequency of hurricanes, but a slight rise in the intensity (NOAA 2008), and this is consistent with Emanuel et al. (2008).

Other studies suggest there may be a relationship between the climate of North America, especially in precipitation, and the Atlantic Multidecadal Oscillation (AMO) (Hu and Feng, 2012; Veres and Hu, 2013 *and earlier work referenced therein*). The AMO is essentially a 70 year oscillation in the North Atlantic SSTs. Vimont and Kossin (2007) also suggest a connection between the AMO and TC frequency in the Atlantic. As some of North America's precipitation come from tropical systems and their remnants, the possibility of an AMO connection to Missouri TC occurrences should be examined. Lupo et al. (2007, 2008) suggest that this connection may not be as prominent since the ENSO and PDO are upstream of North America and, as such, would more strongly influence the jetstream. Additionally, the ENSO has been shown to correlate strongly to the Atlantic TC frequency via the jetstream (e.g. Lupo et al. 2008 *and references therein*). Additionally, this same work demonstrates a strong PDO-ENSO relationship as these are both Pacific SST phenomena and they interact.

The purpose of this paper is to explore the relationship between the number of TC remnants affecting Missouri, their associated synoptic patterns, and the relationship to climate variability (e.g., ENSO, PDO, AMO). This study also examines the synoptic conditions may affect the TC remnant paths, and this work has no precedent in the literature thus far. TC remnants have been the cause of numerous environmental problems for Missouri. Notably, the remnants of Hurricane Ike in 2008 caused power outages, major flooding, deaths (four in Missouri), and closed roads across the state (Salter et al., 2008, Brown et al. 2010). The remnants of Hurricane Gustav interacted with a cold front passing through the Midwest to produce torrential rainfall, close to 178 mm, across areas of Mid-Missouri (NWS 2008, Brown et al. 2010). This paper will attempt to uncover a better understanding behind what guides the movement TC remnants over the Midwest. Further understanding may lead to improved disaster preparedness and emergency response.

Data and Methodology

Data

The Atlantic Best Storm Tracks from 1851–2012, which is available through the Unisys tropical system database [available online at http://weather.unisys.com], and was used in this study to determine whether TCs affected Missouri. This dataset tracks TC centers by latitude and longitude on a six hour basis (00Z, 06Z, 12Z, 18Z). In this study, tropical storms, tropical depressions, and extratropical depressions will be grouped together and called TCs from this point forward. In order to be counted, the TC must have been tracked by the National Hurricane Center. It would be difficult to count with any precision the number of systems that would have their origins in the tropics but had become extratropical. Also, data before 1944 may not be as reliable. For example, Landsea (1993) explains how the pre-1944 data was estimated for wind intensity since this period was before flight reconnaissance was performed. Nonetheless, in spite of the possibility of error, this study begins with 1938 in order to allow for a large enough sample of TC events and to be consistent with the studies of Lupo and Johnston (2000) and Lupo et al. (2008). Also, our study does not take into account intensity, only that the storms are tropical systems. Jarvinen et al. (1984) goes into further detail about possible problems associated with the Atlantic Best Storm Tracks data.

Data from the NOAA Central Library's U.S. Daily Weather Maps Project was also utilized to record synoptic conditions during periods of TC activity for this study. Since the NOAA Central Library's data are available from 1870 until 2002[1], the daily weather maps for more recent years up to the present were obtained from the Hydrometeorological Prediction Center's (HPC) archive [available online at http://www.hpc.ncep.noaa.gov/dailywxmap/index.html].

Methodology

A TC was counted as impacting Missouri if the center crossed 35° N latitude, and was between 97.5° and 87.5° W longitude. This assured that some part of the significant weather (e.g., rain bands, or winds) impacted Missouri. A few systems were very close to the defined area. More specific storm track data was used to determine if the TC center was within the designated area for this project by examining the Unisys tropical system database. Each TC was then categorized as occurring during an ENSO and PDO cycle (e.g., Mantua et al. 1997) as described below.

The categorization of ENSO years was based on the Japan Meteorology Agency (JMA) Index (e.g., Lupo et al. 2008). The periods are listed in Table 1. This index is computed using the Pacific Ocean mean SST anomalies from off the Eastern coast of Papua New Guinea to the waters off the Western bulge of South America, more specifically between 4° N and 4° S and 150°W and 90°W. El Niño (EL) occurs when the SST anomalies are at least 0.5°C or higher for six straight months. On the other hand, La Niña (LN) occurs when SST anomalies are -0.5°C or lower for six consecutive months. All other periods fall under Neutral (NEU) years. Further details about the ENSO cycle classification are described in Bove et al. (1998). For each period - EL, LN, NEU - the number of tropical systems was counted and the mean was computed.

1. Daily weather maps can be obtained from this website: http://docs.lib.noaa.gov/rescue/dwm/data_rescue_daily_weather_maps.html. A DJVU plug-in is needed to open the files. The website has a link for a free download of the required plug-in or, the DJVU viewer download page may be accessed directly at: http://www.caminova.net/en/downloads/download.aspx?id=1.

Table 1. Years separated by the El Nino and Southern Oscillation phase starting in 1938 until present.

La Niña (LN)	Neutral (NEU)	El Niño (EL)
1938	1939	1940
1942	1941	1951
1944	1943	1957
1949	1945–1948	1963
1954–1956	1950	1965
1964	1952–1953	1969
1967	1958–1962	1972
1970–1971	1966	1976
1973–1975	1968	1982
1988	1977–1981	1986–1987
1998–1999	1983–1985	1991
2007	1989–1990	1997
2010	1992–1996	2002
	2000–2001	2006
	2003–2005	2009
	2008	
	2011–2012	

PDO cycles were separated into cool and warm phases (Lupo et al. 2008). Warm (positive) PDO phases occurred during 1933–1946 and again from 1977–1998. Cool (negative) PDO phases occurred during 1947–1976 and from 1999-present. The breakdown is shown in Table 2a. The number of TC occurring in each PDO epoch was counted and their arithmetic mean was calculated. Then, negative and positive PDO epochs were combined together in order to obtain statistics for the overall periods.

The AMO is a 70 year SST oscillation in the North Atlantic was also examined here and this can be separated into two phases (e.g., Vimont and Kossin, 2007; Qu and Feng, 2012). The warm (positive) phase is associated with warm water transport into the North Atlantic and a faster thermohaline circulation, and persisted from 1938–1964 and 1995–present). The cold (negative) phase is the inverse condition and persisted from 1965–1995. These periods are shown in Table 2b and note the significant overlap between the negative AMO and the positive PDO.

Table 3. Breakdown by group of tropical storm tracks impacting Missouri.

Tropical System Track	Group	TC occurrence
SW–NE (200°–250°)	1	26
W–E (> 250°)	2	1
S–N (160°–200°)	3	4
SE–NW (< 160°)	4	4

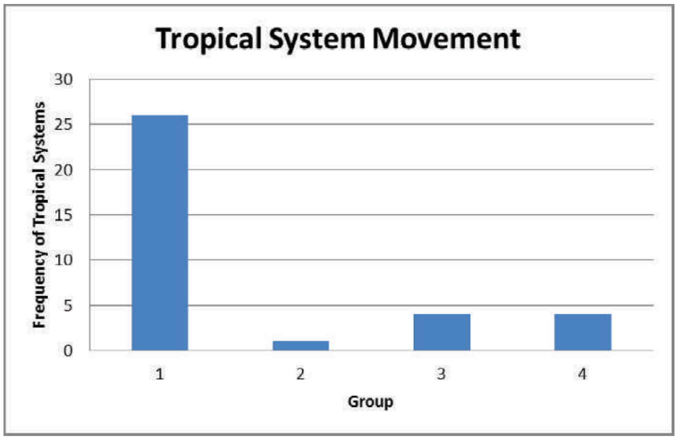
The TC found to impact Missouri were separated into additional groups. Systems were grouped by storm track, e.g. southwest to northeast (group 1), west to east (group 2), south to north (group 3), and southeast to northwest (group 4). TC tracks for this study were based on movement once the tropical systems moved over Missouri (Table 3 and Fig. 1). Synoptic conditions were inferred based on NOAA Central Library's and HPC's daily weather maps for each TC. General conditions were observed, including the position of ridges and troughs. In addition, TC events were separated by the month of occurrence (Fig. 2). This was done in order to demonstrate the annual distribution of TC impacting Missouri, and that the greatest probability for TC occurrence is greatest from August through September.

Finally, statistical significance was determined from the data means in order to determine if there were significant differences between TC occurrence during phases of ENSO, PDO, or AMO. This was done using the z-score test for the mean (e.g. Neter et al. 1988). This test was performed by comparing the number of TC systems impacting Missouri to the total frequency of Atlantic basin TCs taken from Lupo et al. (2008). The Student's t-test was also used since the samples here are relatively small, and this test works well with small samples. Also, a chi-squared test (χ^2) was used in order to test the annual distributions of TC occurrence. The means of the TC separated by month for the entire study was used as the expected frequency. Then, ENSO sub-periods were used as the observed periods for further comparison against each other, for more information on the justification for using these tests for statistical significance refer to Lupo et al. (2008).

Table 2. Phases of the a) Pacific Decadal Oscillation since 1933. (Reproduced from Lupo et al. 2008), and b) Atlantic Multidecadal Oscillation (adapted from http://www.appinsys.com/GlobalWarming/AMO.htm).

a) PDO Phase	Period of Record	b) AMO Phase	Period of Record
Phase 1 (+) warm	1933–1946	Phase 1 (+) warm	1926–1964
Phase 2 (–) cold	1947–1976	Phase 2 (–) cold	1965–1995
Phase 1 (+) warm	1977–1998	Phase 1 (+) warm	1996–present
Phase 2 (–) cold	1999–present		

Figure 1. Number of tropical systems impacting Missouri grouped by storm track direction as described in the text, 1938–2012.



Results and Analysis

Results

Counting the number of TC within the area of 97.5 and 87.5°W longitude and above 35°N latitude, there were 35 TCs. There was no discernible trend in the Missouri occurrences as the sample size was small, but there was considerable variability (Fig. 3), as there were nine and seven events in the decade of the 2000's and 1950's respectively, and as few as one during the 1990s. This corresponded to an increase in the Atlantic tropical cyclone activity since the middle to late 1990s.

An examination of Missouri TC activity by their path across Missouri showed that group 1 (SW-NE) comprised of the overwhelming majority of TC with 26. The other groups totaled 9 TCs combined: one system for Group 2 (W–E), and four each for Group 3 (S–N) and Group 4 (SE–NW). This result would be expected since the main flow for the Northern Hemisphere mid-latitudes is primarily westerly. TCs should shift gradually toward the direction of the dominant mid-latitude background flow as they move toward higher latitudes from the tropics in the south. In terms of the synoptic conditions prevalent, most of the tracks occurred when high pressure was present in the eastern United States with a cold front to the northwest or a low to the north. Group 1 TC typically interacted with a cold front translating eastward across the United States. Fig. 4 shows a typical scenario when the low center track of a TC remnant was assigned to group 1. The other three categories are associated with zonal to near-zonal upper air conditions. Typical conditions for group 4 are shown in Fig. 5. High pressure dominates the U.S. with a front stretching along the Canadian border.

Figure 2. Frequency of tropical systems impacting Missouri separated by month of occurrence for the entire study period, 1938–2012.

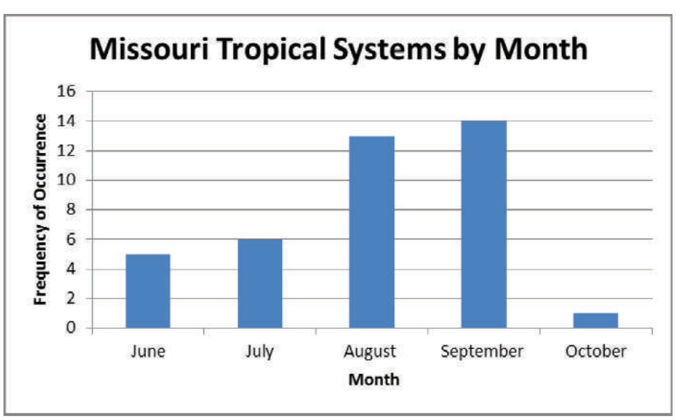


Figure 3. Graph of the total number of Atlantic tropical systems (red) and the total number impacting Missouri (blue) from 1938 (year1) to 2012 (year 75).

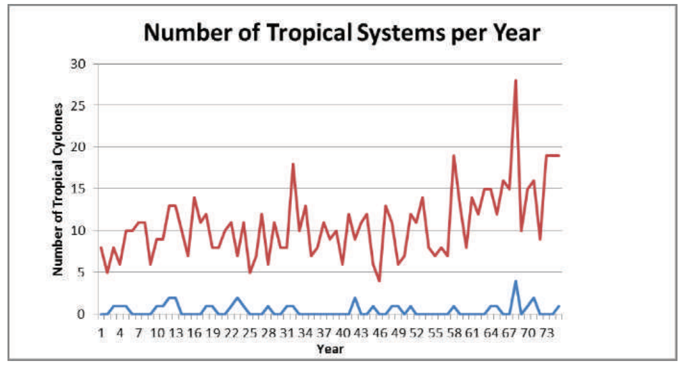


Figure 4. Surface analysis on June 25, 1968. The low over Illinois is the remnant of Tropical Storm Candy. Remnant path is denoted by arrows stretching from eastern Texas to the low center (source: NOAA Central Library U.S. Daily Weather Maps Project).

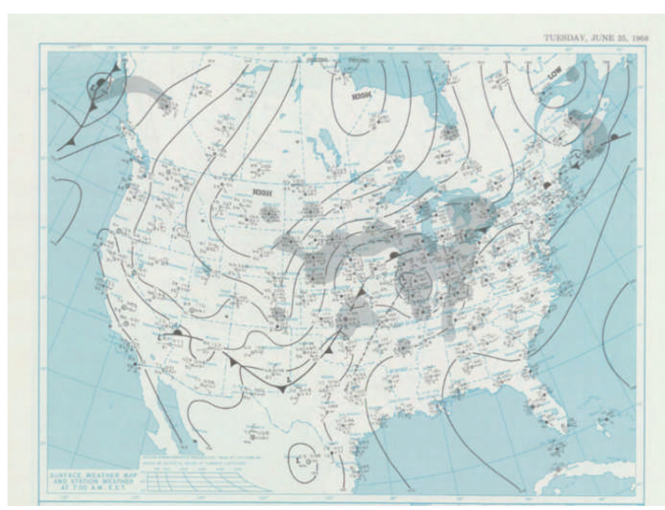


Figure 5. Surface analysis on September 1, 1950. The low over southern Illinois is the remnant of Hurricane Baker. Remnant path is denoted by arrows stretching from southern Alabama to the low pressure center (source: NOAA Central Library U.S. Daily Weather Maps Project).

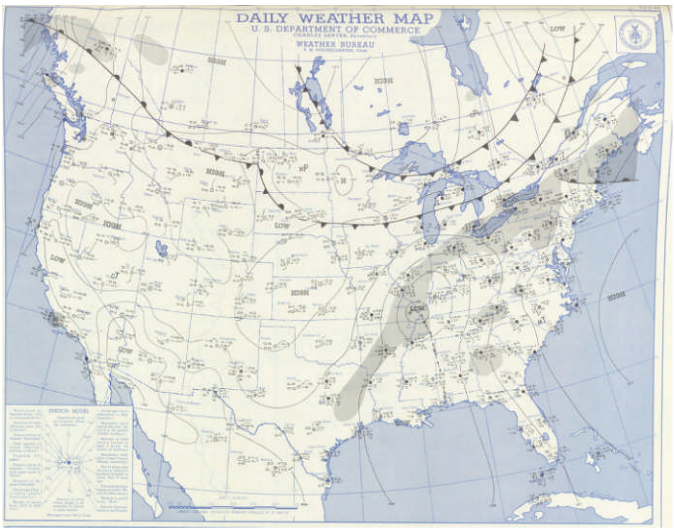
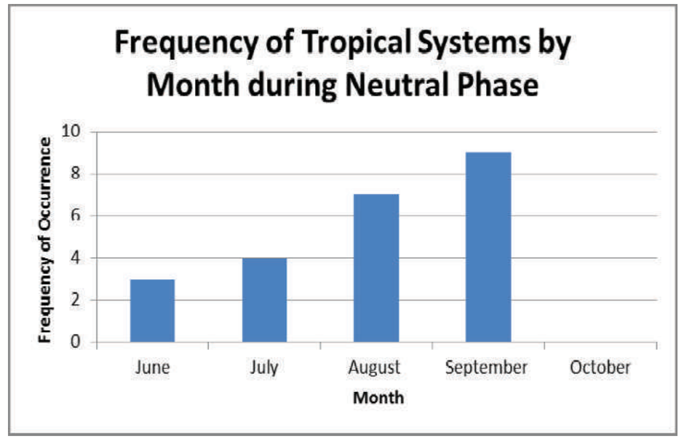


Figure 7. As in Fig. 2, except for the Neutral phases from 1938 to 2012.



In addition to separating the types of TC by month for the entire 75 year period, the types were classified by month for each ENSO phase (Figs. 6–8). These graphs demonstrate that the majority of TCs impact Missouri during August and September as expected, regardless of which ENSO phase is occurring. Even during El Niño phases which only included a total of five tropical systems for the study period, four of them occurred during August and September.

The PDO phases are separated as described in the methods section (Table 2a). The phases were separated by warm (Phase 1) and cold (Phase 2) anomalies for this study (e.g., Lupo et al. 2008). The warm (positive) PDO phase is characterized by warm waters in the eastern Pacific in general, but cold water in the western Pacific and the Gulf of Mexico (Fig. 9). The cold phase (negative) has the exact opposite configuration, with cold waters in the Eastern Pacific, but warm waters in the Gulf of Mexico. Here, we will refer to the PDO phase by the temperature anomalies found in the Pacific. The number of TCs shows more occurrences during the negative PDO phase than during the positive phase of the PDO (Table 4). When the four PDO epochs (two warm and two cold) were combined with like phases, the warm Gulf phases (negative) have about double the number of TC per year than the cold Gulf phases (positive) (Table 5). This is consistent with the findings of Lupo et al. (2008) who found more TC in the Gulf of Mexico during La Niña years (favored during negative PDO – warm gulf). The warm (cold) Gulf phases or negative (positive) PDO phases combine for 25 (10) TC occurrences or 0.57 (0.32) TC per year. The standard deviation was calculated for each phase, and during the negative (positive) PDO phase was 0.8 (0.5). The

Figure 6. As in Fig. 2, except for the La Niña phases, from 1938 to 2012.

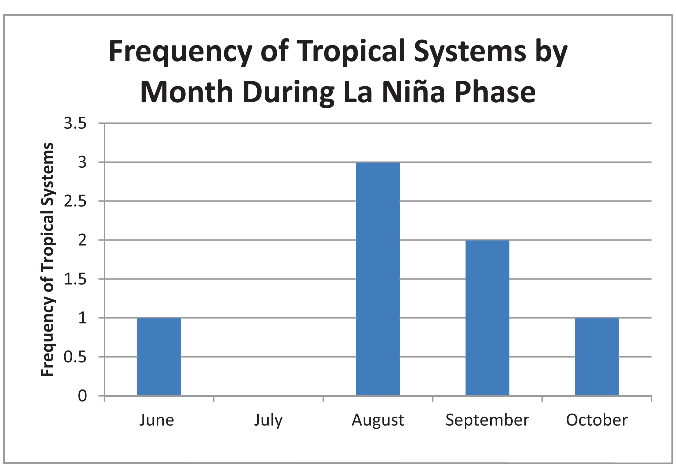


Figure 8. As in Fig. 2, except for the El Niño phases from 1938 to 2012.

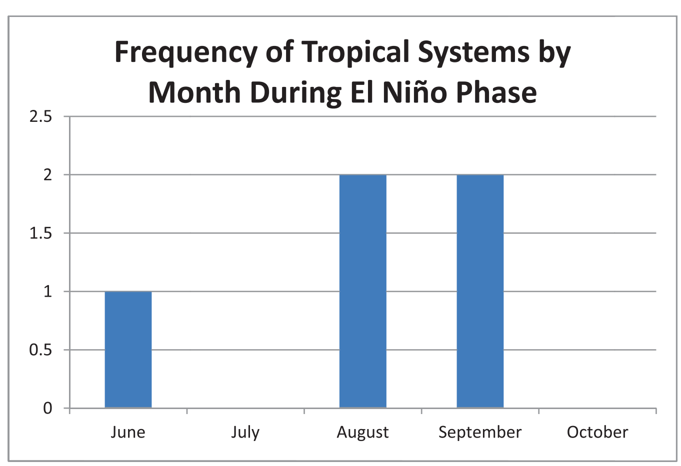
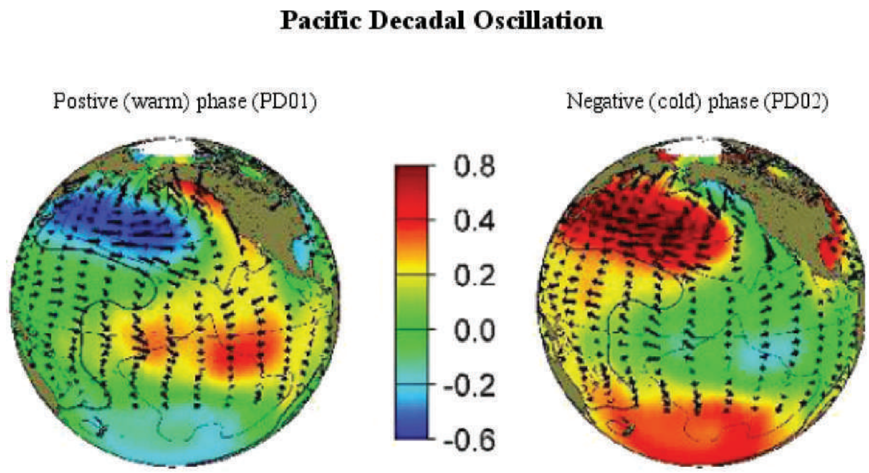


Figure 9. The phases of the PDO as described in the text. SST anomalies are shown in color in accord with the scale shown (degrees C). The arrows show anomalies in wind speed and direction. (Reproduced from Lupo et al. 2008)



mean for the entire dataset was 0.47 and the standard deviation for all phases was 0.7. Thus, while there are more TC occurrences during the warm gulf phases, the difference is not statistically significant at the 90% (p=0.10) confidence level (it was significant at p=0.15), whether the Z-score or the Student's t-test were used.

An examination of the AMO results (Table 5) demonstrate that these were similar to the PDO results in that the mean of the positive (negative) AMO TC occurrences in Missouri showed a mean of 0.58 (0.30) and the standard deviations were 0.8 (0.5). Statistical testing also showed similar results, and the differences in the means were not significant at standard levels for testing. However, for the Student's t-test, the negative AMO mean was lower and the result was significant at the 90% level (p=0.10). While the discussion in section 1 and 2b suggests that the connection should be stronger via the PDO and ENSO, there is a strong relationship between the PDO and the AMO phasing (Gray, 1998). The similarity in the statistical results may reflect this contention. Nonetheless, the PDO connection to hurricane numbers has been shown to be solid. Additionally, both the AMO and PDO results proved to be significant at the 90% (p=0.10) confidence level if tested for the entire Atlantic data set.

The TC occurrence data from each ENSO phase were tested for statistical significance as in Lupo et al. (2008) using the chi-squared test in order to determine if the annual occurrence distributions were similar. The expected frequency was established by using the total TCs per month for the entire study period (Fig. 2) and dividing by the number of years in the study to get an annual average. Then, the same was done for the tables which separated data by ENSO phase (Figs. 6–8); dividing by 19, 40, and 16 respectively. With four degrees of freedom, each ENSO phase had a chi-squared value of 0.99. This means that each ENSO phase distribution was not significantly different from the overall distribution for occurrence. Since NEU phase years have the most TC occurrences, and account for almost half of the study period, the chi-squared test for these distributions was run again. This time, the average TC per month based on NEU years were used as the expected frequency. The

Table 4. Number of tropical systems separated by PDO epoch (phase).

PDO epoch (phase)	Tropical Systems	Average/Phase
1 (1938–1946)	3	0.33
2 (1947–1976)	15	0.50
1 (1977–1988)	7	0.32
2 (1999–present)	10	0.71

Table 5. Number of tropical systems with cold and warm phases combined.

Combined PDO		
Phase 1 (+) warm: 1938–1946, 1977–1998	10 events	0.32 systems/yr
Phase 2 (–) cold: 1947–1976, 1999–present	25 events	0.57 systems/yr
Combined AMO		
Phase 1 (+) warm: 1938–1964, 1996–present	26 events	0.58 systems/yr
Phase 2 (–) cold	9 events	0.30 systems/yr

chi-squared test was applied again with similar results and the values were significant at the 99% confidence level with two degrees of freedom. These tests show that the distributions of TC are not statistically significantly different from each other, thus, they can be considered the same up to any sampling uncertainty. Both tests agree with the hypothesis that the number of TCs impacting Missouri is related to the number of events occurring in the Atlantic Ocean basin. In other words, Missouri is impacted more often during August and September regardless of ENSO phase.

The cross-correlation test was performed between the frequency of Atlantic Ocean tropical systems considered the independent variable here and the frequency of Missouri impacts, which was considered the dependent variable. Nearly every local maximum in Atlantic Ocean TC activity results in an increase in frequency for Missouri TCs (Fig. 3). Nonetheless, a few years failed to conform to this relationship. The correlation between the two variables was 0.36, which was the highest value obtained with no time delay. This value indicates a positive correlation, and this was significant at the 95% confidence level). Thus, this indicates that the chance of Missouri experiencing a tropical cyclone is related to the overall number of Atlantic storms in a season.

Case Study - 2005 Hurricane Season

Of the 28 named TCs during the 2005 hurricane season, four impacted Missouri (see Unisys website): the remnants of Hurricanes Arlene, Dennis, Katrina, and Rita. The ENSO phase was determined to be Neutral for 2005 (Table 1). The TC remnants impacted Missouri during June, July, August, and September. Hurricanes Dennis, Katrina, and Rita were classified as Group 1 (SW-NE) for this study. Hurricane Arlene was classified as a Group 3 (S-N) track since the track of the low pressure center was mainly south to north. Low pressure center paths, as defined and produced by Unisys, are not shown here, but strongly resemble Figs. 4 and 5 for each respective hurricane. Each hurricane except Arlene interacted with cold fronts.

Hurricanes Dennis, Katrina, and Rita each encountered fairly similar synoptic conditions. Each TC was impacted and absorbed by a cold front moving across the United States (not shown). The conditions were similar to those shown in Fig. 3, in that a cold front passed through during the same time frame as the TCs. Not all interacted with cold fronts immediately upon landfall, but each TC interacted with a cold front at some point. While not the focus of this study, TC interactions with frontal boundaries may produce elevated rainfall amounts for the state (e.g., Moon et al. 2009).

The difference in synoptic conditions during the course of Hurricane Arlene is in the movement of low pressure systems (Figs. 10 and 11). In Fig. 10, an occluded low was situated over northern Wisconsin, and another area of low pressure exists in southeast Colorado. High pressure was sandwiched between the lows. During the next 24 hours, the occluded low over Wisconsin dissipated and the low in southeast Colorado shifted northeast into northern Kansas and became occluded (Fig. 11). Thus, remnants of Hurricane Arlene did not interact directly with a cold front, nor was it absorbed as the other systems were, and resided in a high pressure region after making landfall. This may explain why the TC traveled in a south to north fashion.

A few different atmospheric and oceanic anomalies are the reason for the high frequency of TC impacting Missouri during 2005. Zuki and Lupo (2008) demonstrate that SSTs alone are not enough to produce high numbers of TC occurrences. One such anomaly is the quasi-biennial oscillation (QBO). Various papers (e.g., Gray 1984; Landsea et al. 1998; Lupo et al. 2008) have shown increased development and activity in the Atlantic basin associated with negative (easterly phase) QBO anomalies, which last about 12–15 months each (e.g., Landsea et al.

Figure 10. The 0600 UTC surface analysis for June 12, 2005. Hurricane Arlene remnants are positioned in south central Tennessee. Note the position of the surface fronts (source: HPC Daily Weather Map Archive).

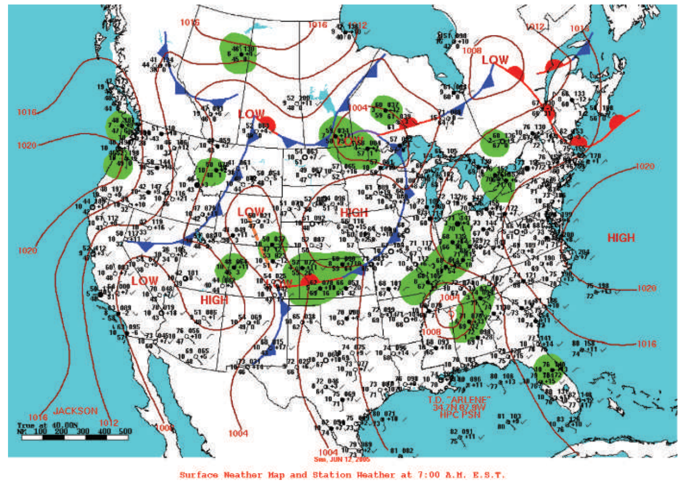
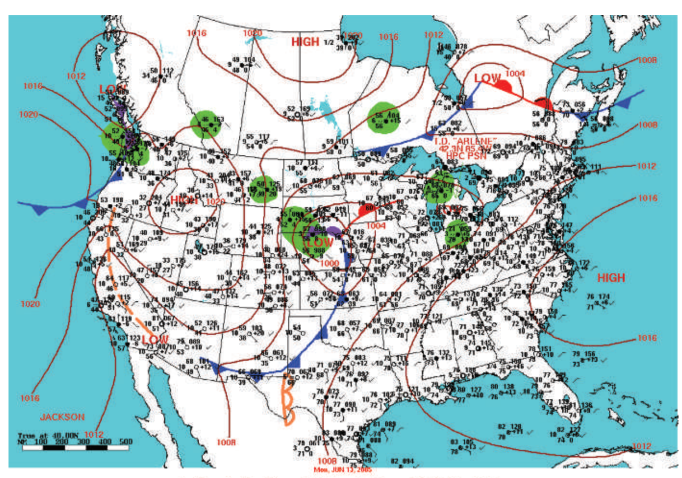


Figure 11. As in Fig. 14, except for 0600 UTC June 13, 2005. Remnants are located over the Great Lakes.



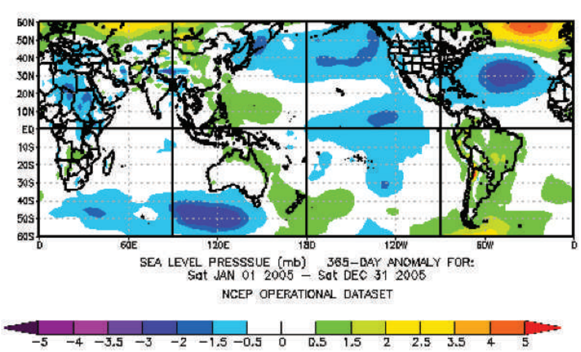
1998). This is because less wind shear exists to hinder developing tropical systems.

Warmer than average Gulf SSTs also helped strengthen Atlantic TCs. Since TCs gain energy as they move across warm water and warm water eddies (Bosart et al. 2000), this increases the TC strength. TCs with increased strength likely have a better chance of holding together and reaching Missouri as a tropical entity. The combination of decreased upper-level wind shear and warmer Gulf waters resulted in prime conditions for areas of disturbances in the tropical Atlantic Ocean region to form into TCs (Knaff 1997; Landsea et al. 1998; Bosart et al. 2000; Shay et al. 2000).

One more reason for the high frequency of TCs in 2005 can be attributed to below normal sea surface pressure (SSP) anomalies. Landsea et al. (1998) found that lower than normal SSPs resulted in a higher occurrence of tropical disturbances in the Atlantic. Fig. 12 shows that SSP anomalies across the tropical Atlantic Ocean basin were 2 mb below normal for the year. SSP was also slightly below normal in the Gulf of Mexico. These corresponded to higher SST in those regions. Also, Knaff (1997) found that in the tropical Atlantic, anomalously low pressure coincides with more mid-level moisture, warmer mid-level temperature, and weak 200–850 mb vertical wind shear.

Lastly, during the year 2005, there were more TC occurrences in the Atlantic Ocean basin than during any other year (see Unisys archive). A graph comparing the total number of TCs for the Atlantic every year to the number of TCs impacting Missouri suggests a correlation between the two (Fig. 3). Along with evidence found in this case study, the large increase in tropical system frequency also led to a record number of TC for Missouri. This relationship is one more piece of evidence supporting the hypothesis that Missouri is impacted more frequently with increased numbers of Atlantic TCs.

Figure 12. Sea Level (Surface) Pressure (mb) anomalies during the year 2005 (source: Earth System Research Laboratory Atmospheric Variables Plotting Page: http://www.esrl.noaa.gov/psd/data/reanalysis/reanalysis.shtml).



Conclusions

This study was performed based on the results of Lupo et al. 2008 which was an update of Lupo and Johnston 2000. Both of these papers discovered a relationship between the PDO and TC variability in the Atlantic and Pacific Oceans. From the data obtained during this study, it appears that the number of TC impacting Missouri is more sensitive to fluctuations in the PDO than in the ENSO cycle. The TC frequencies were also connected to variations in the AMO. However, because of this study's constraint on how TC were counted as impacting Missouri, the TC frequencies for the study are likely to be lower than actual observations. The latitude and longitude constraints for this study were implemented to simplify reproduction of the work. Thus, some of the TC tracks which fell less than a degree outside the boundaries specified may have impacted Missouri, but were not counted. These TCs may have impacted Missouri's weather in some fashion (i.e. increased precipitation or wind). More work could be done to determine exactly which TCs impacted Missouri. Comparing local weather reports and newspaper headlines to the timing of storm tracks will provide a more accurate database of these TC occurrences.

It is hypothesized that during years when Atlantic basin TC activity is above normal, Missouri should see an increase in TC remnant activity as well. The data showing maxima in occurrences during August and September may help emergency management services prepare for possible natural disasters. Also, these result demonstrated that TC occurrences were much higher during the negative PDO period, which was found to be statistically significant. During these months, emergency managers may want to keep a closer eye on activity in the Gulf of Mexico. Also of note is that while this study used a relatively long time period, a relatively small sample was gained from the observations. A much larger sample of TC observations would be needed to determine if the results are more than a coincidence. A larger sample could also be broken down into ENSO variability within each PDO (or AMO) phase. However, this work was produced as the foundation for further investigation in the future.

Finally, further research is needed to determine if TC remnant interaction with cold fronts enhances the dangers associated with them, although the work of Moon et al. (2009) implies that this is the case. Recognized patterns from this study suggest that the paths of TCs are influenced by frontal weather associated with mid-latitude wave cyclones.

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