GEOPHYSICAL RESEARCH LETTERS, VOL. 27, NO. 15, PAGES 2269-2272, AUGUST 1, 2000

Mesoclimatic analysis of severe weather and ENSO interactions in North Carolina

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Abstract. Connections between regional severe weather occurrences and El Niño/Southern Oscillation (ENSO) are investigated. Monthly (1950 – 1989) occurrences of tornado and wind / hail frequency are compared with sea surface temperature (SST) indices and anomalies in the tropical Pacific. Analyses indicate increase in wind/ hail events/ days, during the months of April through June of La Niña years. No direct evidence is found between tornado frequency and ENSO classes. Using seasonal composite anomalies of upper-air patterns, it is concluded that La Niña patterns leads to enhanced convection over North Carolina.

1. Introduction

El Niño-Southern Oscillation (ENSO) refers to a complex atmosphere – ocean interaction resulting in anomalies in sea surface temperatures (SST) and surface pressure distribution in the tropical Pacific, changes occurring irregularly over periods of 3 to 7 years. El Niño is the phase of the southern oscillation when a low pressure, high trade wind region is over the eastern tropical Pacific Ocean (Philander 1990). La Niña is the reverse of El Niño when sea surface temperatures in the central and eastern tropical Pacific are unusually low and trade winds are very intense resulting in above normal SST in the central to eastern basin of the Pacific. Understanding ENSO is important as it has significant implications not only on the tropical Pacific, but also global and local weather and climate patterns including socioeconomic characteristics of the region. Majority of the research concerns the large-scale implications on global climate including changes in planetary and synoptic flow patterns. Nonetheless, in recent years, there is a growing concern regarding the local scale as against global effects of synoptic scale events such as ENSO (cf. Guetter and Georgakakos, 1996, Roswintiarti et al., 1998). Accordingly, this study presents a hierarchy of statistical methods for investigating possible connections between ENSO and regional severe weather occurrence taking North Carolina as a case example.

The complexity and diverse scales of ENSO events preclude an investigation based solely on dynamical methods. We therefore present a series of grouping and statistical methods to focus on possible connections, and then investigate the dynamical explanation for the results. The underlying philosophy is that, ENSO is not directly responsible for the formation of individual thunderstorms, however, the formation of thunderstorms is directly related to synoptic flow patterns. For instance, near surface air masses could be linked to mid-tropospheric flow patterns (Schwartz and Skeeter, 1994). Additionally, for various ENSO phases, height anomalies and resulting flow patterns are already established (Ropeleweski and Halpert, 1986). Hence a regional / local scale analysis of ENSO effects on severe weather is achievable. This is the motivation for the present research involving investigation of possible relationships between severe weather and ENSO at a mesoclimatic scale.

2. Data

Severe weather data were obtained from the National Severe Storms Forecast Center (NSSFC), and the National Climatic Data Center (NCDC). For North Carolina, monthly tornado frequency from 1950 through 1989, wind and hail events for 1957 through 1988 were utilized (with exception of 1968 and 1969 due to missing values). Several studies (cf., Schaefer and Livingston, 1993) report deficiencies in this dataset (such as, geographical biases as well as an increase in reported tornadoes with time due to increasing population and awareness). However, the dataset represents the most reliable accounting of severe weather occurrence available over the United States (Bieringer et al, 1996). Therefore, these data will be used but with the knowledge that certain limitations are present.

Monthly SST indices from 1950-1989 were used in the classification and analysis of ENSO events through the Climate Prediction Center. This data set includes monthly values for all Niño regions in the tropical Pacific (Niño1+2, Niño3, Niño4, Niño3.4), and the corresponding anomalies (Philander, 1990). Individual data points exceeding the five and ninety-five percentile were considered outliers and removed from the data set by replacing them with the five and ninety-five percentile values. The data were analyzed for normality, and conversion approaches were attempted (Niyogi et al. 1997). Based on these results and that the data were only used to determine ENSO phases and linear correlation with Niño regions, the original data set (outliers removed) was retained.

3. Methodology

SST indices were compiled and correlated with severe weather events. Results show that severe weather in North Carolina is most highly correlated with Niño34 (and not significantly with other Nino modes, see also Roswintiarti et al., 1998). Accordingly, El Niño is defined when the 5-month running mean of SST anomalies in the Niño34 region exceeds

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Paper number 1999GL011327.
0094-8276/00/1999GL011327$05.00

Table 1. Mean seasonal tornado occurrence by ENSO class with probabilities for equal means. 'N' is Normal, 'EN' is El Nino, 'LN' is La Nina, 'S' is season.

S	Tornado events			Pr > t Ho: $\mu_1=\mu_2$		
	N	EN	LN	N v/s LN	EN v/s LN	N v/s EN
1	0.78	0.73	1.14	0.42	0.43	0.91
2	2.02	1.04	2.40	0.63	0.15	0.23
3	0.90	0.81	0.88	0.90	0.79	0.67
4	0.20	0.41	0.63	0.08	0.39	0.37

Table 3. As Table 1 but for seasonal wind/hail days.

S	Wind/hail days			Pr > t Ho: $\mu_1=\mu_2$		
	N	EN	LN	N v/s LN	EN v/s LN	N v/s EN
1	0.59	0.52	0.29	0.28	0.45	0.77
2	2.42	1.95	3.94	0.06	0.03	0.53
3	1.75	2.04	1.90	0.84	0.87	0.68
4	0.11	0.20	0.04	0.53	0.17	0.39

0.4 K for six months or more (Trenberth, 1990). Conversely, La Niña is defined when the 5-month running mean of SST anomalies in the Niño34 region exceeds -0.4 K for six months or more. Each month from 1950-1989 was classified El Niño, Normal (non-ENSO), or La Niña based on these criteria.

Severe weather on a regional scale demonstrates large temporal variability, and so grouping is useful to remove some of the within sample / group variability. Separate analysis was performed on the wind/ hail events and the tornado events. This was done for two reasons: to prevent the wind/ hail reports from dominating tornado events, and the dynamics and seasonal peaks for each are different. In order to determine the grouping, monthly means for the entire data set were utilized. Sequential months with similar tornado and wind/ hail occurrence means were grouped together, and seasonal breaks were put where there were significant differences in monthly means. Based on these results, a seasonal grouping was considered appropriate. Analysis of monthly occurrence of severe weather was not feasible due to non-occurrence in certain months and lack of events in certain months leading to limited degrees of freedom. Yearly grouping appears to be inappropriate due to the temporal variation and peaks of severe weather occurrence. Each year was therefore separated into four seasons each with three months. January, February, and March were grouped into season 1 with sequential months following the same pattern. For ease these groupings will be called seasons even though they actually represent a simple grouping of the data to reduce some of the variability inherent in the data set. Guetter and Georgakakos (1996) utilized a similar seasonal grouping. The seasonal means for each ENSO classes (El Niño, La Niña, and Normal) were compiled for both the wind/hail and tornado data. A two-tailed t-test was then performed to determine if a significant difference exists between the seasonal means for each ENSO class.

A stepwise regression analysis was applied to determine significant relationships between SST indices and severe weather occurrence. Month, season, and year were each attempted as class variables to account for temporal variation in the data. The use of season as a class variable produced the best overall results and so further analysis utilized seasonal groupings. All available indices were then regressed on severe weather occurrence by season. Least significant variables were removed, and the process repeated until a significant fit was obtained. Significance was determined by performing a two-tailed t-test on the slope and an F test on the overall fit.

Table 2. As Table 1 but for seasonal wind/hail occurrence.

S	Wind/hail events			Pr > t Ho: $\mu_1=\mu_2$		
	N	EN	LN	N v/s LN	EN v/s LN	N v/s EN
1	1.04	1.04	1.53	0.55	0.58	0.99
2	5.58	5.36	18.8	0.003	0.009	0.96
3	3.34	3.54	2.95	0.84	0.79	0.91
4	0.11	0.20	0.04	0.53	0.17	0.39

In order to investigate the dynamical implications of anomalous Pacific SST, the NCEP / NCAR Reanalysis dataset was used (see Kalnay et al., 1996) such that ENSO events could be grouped and analyzed. Each individual ENSO event is unique, and so a case study of isolated events may yield biased results. Seasonal composite anomalies were generated for the season(s) demonstrating signals in the statistical analysis. Plots of upper-level as well as near surface flow and thermodynamic patterns were constructed and analyzed for interpretation regarding convective regimes.

4. Results

Results from the seasonal mean two-tailed t-test, shown in Table 1, indicate no significant difference (95% level) in seasonal tornado occurrence exists across ENSO classes. However, a significant difference during season two (April, May, June) between ENSO classes for the wind/hail reports exists (Table 2). That is, more wind/hail events were reported during La Niña season 2 (April, May, June) as compared with normal (non-ENSO) season 2. Indeed, such results may be biased due to the fact that the majority of the wind / hail events will be associated with regional outbreaks and occur on certain days. To test this, a revised dataset was compiled,

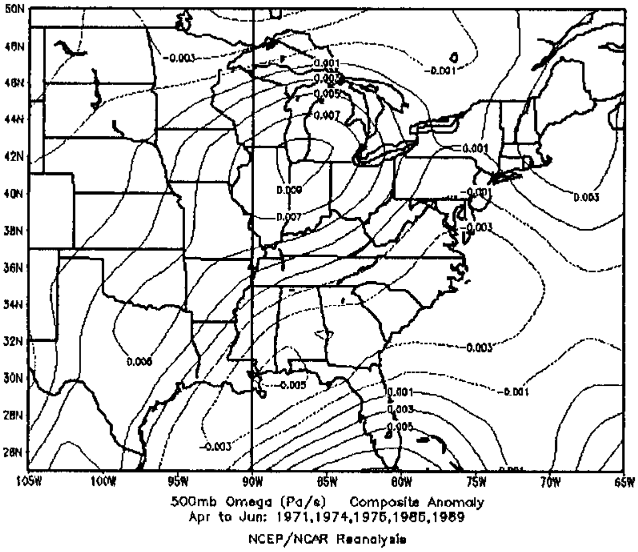

Figure 1. 500mb omega anomaly during La Niña events. A composite for 1971, 1974, 1975, 1985, and 1989 is shown. A trough parallel to the eastern coast of the U.S. is seen which can favor convective activity over southeastern US.

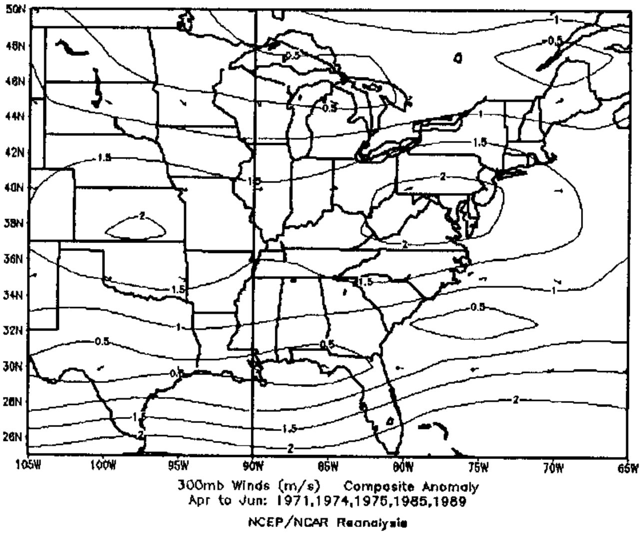

Figure 2. Composite 300 mb winds for data as in Fig. 1.

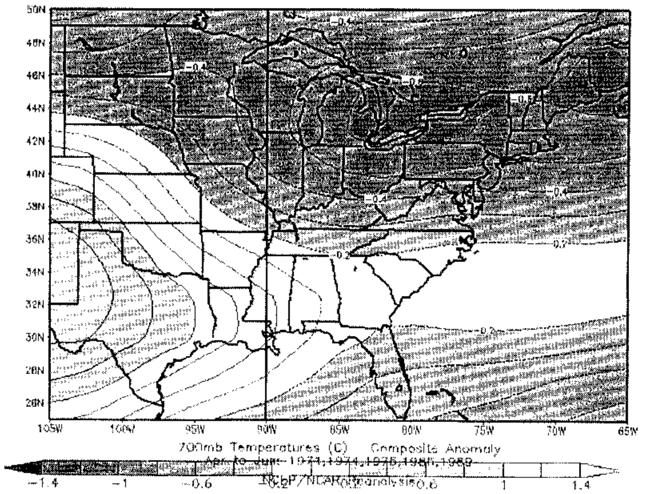

Figure 3b. Near surface (700 mb) temperature anomalies corresponding to Fig. 3a. The anomalies, which are positive in surface (Fig. 3a), are negative here. This can enhance atmospheric instability and trigger severe weather.

consisting of the number of wind/hail event days per month. Corresponding results summarized in Table 3 confirm the increase in wind/hail activity during La Niña season 2. Results from the multiple regression verify that no direct evidence exists between tornado frequency and ENSO classes in NC. The multiple regression analysis also showed that slopes obtained during season 2 for wind / hail events were significant at the 0.05 level. Based on these findings, it appears that patterns associated with La Niña season 2 have the largest impact on wind/hail activity in North Carolina.

Severe thunderstorms are favored by strong convective instabilty, abundant moisture at low levels, strong wind shear, and dynamical lifting mechanisms (Kessler, 1983). We now discuss these factors during season 2 (April, May, June) for La Niña events from 1960-1989 as compared to the corresponding normal pattern. The 500 mb height anomalies for the La Niña spring show that negative height anomalies exist from the central U.S. through the mid-Atlantic and New England region. This pattern indicates anomalous troughing over the central and eastern U.S. with the trough axis favoring central portions of the U.S thus enhancing horizontal wind divergence aloft and ascending motions in the lower troposphere (Kessler, 1983). This is consistent with Smith et al. (1997) results that showed an increase in directional shear and increased convective potential between 850 and 500 mb over the south during La Niña events. This pattern also allows increasing southward invasion of Canadian air thus increasing baroclinity, vertical shear, and surface convergence associated with cold fronts. This is clearly evident in 500 mb omega (inverse of vertical velocity) anomalies shown in Fig. 1. The gradient in the omega pattern extended from eastern NC to southern Lake Michigan (with rising motion ahead of the trough axis and sinking motion behind the trough). Figure 2 shows the composite anomaly 300 mb winds (representing the jet stream and associated upper-level dynamics). A strong positive anomaly in wind speed exists from central US to the mid-Atlantic. This anomaly increases vertical shear, which is favorable for the formation of convection. Also, this pattern is more favorable for high wind damage, as momentum is mixed downward in downdrafts ("straight-line winds") associated with strong convection. The 500 mb omega analysis (Fig.1) also indicates a strong positive anomaly centered over Lake Michigan associated with sinking motion of the migratory anticyclone behind the surface cold front. Sea level pressure anomalies associated with the La Niña spring, delineate positive anomalies over the Gulf of Mexico and western Atlantic suggesting an increasing presence of the Bermuda High (not shown). The anomalous ridging over the western Atlantic during La Niña events and associated elevated sea surface temperatures are conducive for higher dewpoint and temperature values in the lower troposphere thus increasing vertical instability. This represents flow regimes conducive to higher moisture values in the southeast including NC due to return flow around the surface based high pressure. To confirm this, mean 1000 mb and 850 mb winds were constructed for the La Niña spring. The patterns showed an increase in southwesterly wind direction and speed (not shown). The surface pressure also showed anomalous

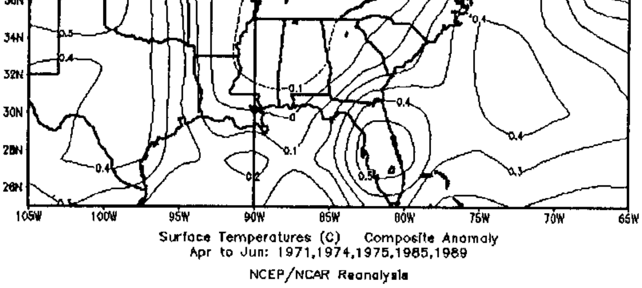

Figure 3a. Surface temperature anomalies for data as in Fig. 1. The trough is still visible in the composite fields.

troughing over the mid-Atlantic coast possibly a pre-frontal trough serving as an additional forcing mechanism. Additionally, instability in the form of temperature lapse rate was investigated by plotting surface and near surface temperature anomalies. Figure 3a and figure 3b show surface and 700 mb temperature anomalies respectively. A positive anomaly at the surface and a negative anomaly at 700 mb is obtained which increases instability. Also, a strong gradient was obtained over NC in the surface temperature composite anomaly indicating increased horizontal baroclinity due to the earlier mentioned cold front. In summary, synoptic patterns and resulting dynamic and thermodynamic factors associated with La Niña springs appear to significantly enhance/increase severe wind and hail events over NC.

5. Conclusions

Typically, the effects of ENSO on global and synoptic scales have been studied. However, there is an increasing significance and growing interest to resolve the impacts of ENSO on a regional scale. This paper demonstrates an integrated statistical - dynamical approach to assessing the importance of ENSO on severe weather taking North Carolina as an example. Analysis provides a definitive evidence of scale interactions and an increase in wind / hail events during the months of April - June of La Niña years. No direct evidence is found for a relationship between tornado occurrence and ENSO. The synoptic flow patterns and regional thermodynamics are more favorable to the formation of convection over NC. Troughing is more likely over the central portions of the U.S. Vertical wind shear, divergence aloft, and angular momentum are more favorable for the formation of convection as a result. This pattern also results in stronger fronts that penetrate further south. Results also indicate anomalous surface ridging over the Gulf of Mexico and western Atlantic resulting in southwesterly flow over the southeastern U.S. This pattern would increase the potential for warm moist flow off the Gulf of Mexico supplying the southeastern U.S. with the necessary thermodynamical properties for storm formation. The interaction of this warm moist flow with the cold, dry air from the north, mentioned above represents near optimal conditions for severe storm formation. The approach presented here can be effectively applied to other geographical regions for understanding different locally significant events and their modulation via ENSO, thus providing a greater understanding of local scale implications of climate change for policy makers and interpreting global modeling studies.

Acknowledgements. The authors wish to thank Prof. David A. Dickey from the Department of Statistics, NC State for his input into this project. Thanks are also due to Dr. Ellen J. Cooter, NOAA / EPA, Mr. Kermit Keeter, NOAA /NWS, Raleigh, and Dr. Orbita Roswintiarti, NC State, for their review, and detailed comments. Images were plotted using the NOAA-CIRES Climate Diagnostics Center web page (http://www.cdc.noaa.gov). The State Climate Office of North Carolina is supported by College of Physical and Mathematical Sciences, Department of Marine, Earth, and Atmospheric Sciences, and College of Agriculture and Life Sciences.

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(Received December 22, 1999: accepted March 03, 2000.)