A Pilot Study Examining U.S. Winter Cyclone Frequency Patterns Associated with Three ENSO Parameters

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ABSTRACT

Teleconnections were used to link three El Niño–Southern Oscillation (ENSO) parameters to winter (December–February) cyclone frequencies over the United States during the 1949–96 period. Since each ENSO event is not exactly the same, small subsets of ENSO events were examined in addition to the more common composite ENSO event. Mean winter cyclone frequencies, derived by counting cyclones passing through 30, 5° latitude equal-area circles located in a grid from 70° to 120°W and 30° to 50°N were determined for classes of El Niños and La Niñas based on 1) the intensity of the equatorial Pacific sea surface temperature anomaly, 2) the intensity of the Tahiti–Darwin sea level pressure anomaly, and 3) the location of the 28°C isotherm. The average cyclone count for each class of El Niño and La Niña was compared to the average count for winters when no ENSO event occurred.

Expected differences in cyclone frequency patterns when comparing an average of all El Niño winters to all La Niña winters were found; however, large pattern differences were also determined when comparing winters with strong El Niños to moderate–weak El Niños and similarly for La Niñas. Significant differences in number of cyclones were found in 8 of 30 circles located in the Pacific Northwest, the Great Lakes, New England, and the Southeast. The differences found in the cyclone frequency patterns for El Niños and La Niñas of different intensities and locations indicated that using a composite of all El Niños or La Niñas may provide misleading information while examination of each of these parameters independently may assist in the preparation of long-range climate predictions.

1. Introduction

El Niño, La Niña, and the Southern Oscillation have gained attention through their frequent use for explaining various weather phenomena in both public and meteorological information sources over the last 20 years. These phrases refer to an oceanic–atmospheric phenomena that occurs on average every 2–4 yr and is monitored over regions of the equatorial Pacific Ocean (Bjerknes 1969; Trenberth 1976; Quinn et al. 1978; Rasmusson and Carpenter 1982; Cane 1983; Rasmusson and Wallace 1983; Ropelewski and Halpert 1990). It has been the impact of this regional phenomena on the global general circulation of the atmosphere that has drawn the attention of many atmospheric scientists (Horel and Wallace 1981; Chen 1982; Douglas et al. 1982; Nitta and Yamada 1989). Others have examined the impact of El Niño–Southern Oscillation (ENSO) on the patterns of various weather parameters such as precipitation, temperature, cloudiness, and snowfall across North America (Namias 1978; Yarnal and Diaz 1986; Angell and Korshover 1987; Trenberth et al. 1988; Kiladis and Diaz 1989; Redmond and Koch 1990).

Although many studies have identified teleconnections, defined here as linkages over great distances of seemingly disconnected weather anomalies (Glantz et al. 1991), between the occurrence of either the warm (El Niño) or cold (La Niña) events associated with ENSO and weather anomalies in various parts of the world (Ropelewski and Halpert 1986, 1987; Glantz et al. 1991; Noel 1993), the development and life cycle of each ENSO event is generally different. This was the driving force for why ENSO events were examined individually instead of always collectively. As a warm or cold event develops, the oceanic–atmospheric anomaly, characterized by its longitudinal and latitudinal patterns, influences global upper-atmospheric winter circulations and the associated surface cyclone, temperature, and precipitation patterns. A major change in El Niño evolution appears to have occurred in the mid-1970s (Phi-

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lander 1990; Glantz et al. 1991; Kerr 1992). Before 1976–77, El Niño events formed as the warm water anomalies spread westward from the coast of South America. Since 1976–77 the warm water anomalies tend to spread eastward from the western equatorial Pacific Ocean to central and eastern sections. Differences in the ENSO phenomena such as these can result in different teleconnections.

In addition to teleconnections from ENSO, other extratropical teleconnections, such as the North Atlantic oscillation (NAO) (Climate Prediction Center 1987–97), can enhance or mitigate the ENSO teleconnection during the Northern Hemisphere winter. For example, the La Niña teleconnection aided in producing a strong eastern U.S. trough in the winter of 1995/96. However, in the winter of 1996/97, the La Niña teleconnection remained but the NAO, defined here as a tendency for lower pressure to be near Iceland and higher pressure in the Azores and southwest Europe (Philander 1990), helped to shift the eastern U.S. trough westward. Therefore, changes in weather patterns cannot be solely contributed to changes in ENSO.

Some El Niño events produce very different weather anomalies. For example, large differences in winter 500-mb circulation, temperature, and precipitation distributions were identified when comparing two El Niño events, 1976/77 and 1982/83 (Diaz and Quayle 1978; Philander 1990; Glantz 1991). The first event featured record cold over the eastern two-thirds of North America while the second event brought record warmth and few cyclones to the northern United States and Canada. The anomalies in the equatorial Pacific were of different intensity and location for these two events, indicating a more careful examination of individual ENSO events may assist in forecasting future weather anomalies and patterns.

Despite an increased understanding of the ENSO phenomena and related teleconnections, evidence suggests that forecasted weather anomalies associated with a composite ENSO event do not always occur. For example, the National Weather Service issued a winter outlook based heavily on El Niño for the winter of 1991/92. The forecast verified well except in the southeast United States, where above average precipitation was expected but below to average amounts actually occurred. Areas in Texas received record-breaking precipitation, which was well supported by a composite El Niño. Differences in patterns like this make seasonal predictions over the United States more difficult and can further erode the public's confidence in long-range forecasts. Would examining ENSO events in two groups, one weak–moderate and the other strong, provide different and potentially useful information to long-range forecasters? For example, the composite scheme for precipitation as developed by Ropelewski and Halpert (1987) indicated no consistent pattern of winter precipitation anomalies over the West Coast including California; however, a subset of ENSO events based on SST intensity (magnitude) may yield better information for forecasting. This study's goal was to determine if ENSOs of different SST and the Southern Oscillation index (SOI; Climate Prediction Center 1987–97) intensities, and location of SST patterns produce different patterns of winter cyclone frequency across the United States. If this is the case, it will stress the need to view ENSO events not only from the traditional composite view but also from smaller subsets. Winter surface cyclones were chosen because they are associated with temperature and precipitation anomalies and this appears to be the season when ENSO events are strongly teleconnected to midlatitude locations.

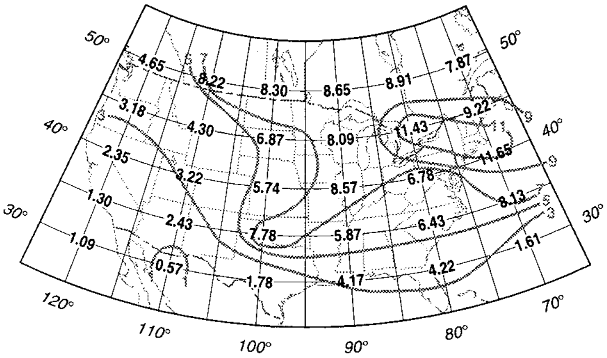

FIG. 1. Winter distribution of average cyclone frequencies for non-ENSO winters for 30 selected 5° latitude equal-area circles.

2. Data and methods

Initially, monthly cyclone counts for each of 30, 5° latitude equal-area circles (Fig. 1) were determined and then summed for each winter (December–February) during the 1949–96 period. A cyclone was counted if it tracked through any part of an equal-area circle. The use of equal-area circles as a technique for counting cyclones was chosen because it eliminated problems with area inequality and area normalization that were associated with conventional methods while providing the opportunity for direct comparison of cyclone information from one circle to another throughout the grid (Changnon et al. 1995). Winter values were then averaged for each category of ENSO event as well as the non-ENSO events. The percent difference in the mean between each category of ENSO event and non-ENSO events was determined to identify anomalies in cyclone frequency across the United States. Because cyclone count information was not available for parts of the 1979/80 and 1989/90 winters (both non-ENSO events), they were removed from the study.

A historical list of ENSO events have been derived through analysis of both oceanic and atmospheric characteristics and is shown in Table 1 (Quinn et al. 1978; Climate Prediction Center 1987–97). There were 12 El Niño winters, 10 La Niña winters, and 23 non-ENSO event winters (with 1979–80 and 1989–90 removed).

TABLE 1. Breakdown of winters into El Niño, La Niña, and non-ENSO events for period 1949–50 through 1995–1996.

El Niño	La Niña	Nonevents
1951/52	1950/51	1949/50
1953/54	1955/56	1952/53
1957/58	1956/57	1954/55
1965/66	1964/65	1958/59
1969/70	1970/71	1959/60
1972/73	1971/72	1960/61
1976/77	1973/74	1961/62
1982/83	1975/76	1962/63
1986/87	1988/89	1963/64
1991/92	1995/96	1966/67
1992/93		1967/68
1994/95		1968/69
		1974/75
		1977/78
		1978/79
		1980/81
		1981/82
		1983/84
		1984/85
		1985/86
		1987/88
		1990/91
		1993/94

To examine ENSO events of various strength, three parameters that represent known oceanic and atmospheric anomalies associated with ENSO were chosen. These three were chosen initially based on their historic weather records and use in determining ENSO events. These parameters included the greatest winter average SST anomaly in the equatorial Pacific Ocean; the intensity of winter average standardized Tahiti–Darwin sea level pressure (SLP) differences, better known as the Southern Oscillation index; and the general location of the 28.0°C SST isotherm between 5°S and 5°N as this SST is associated with triggering deep convection (Halpert and Ropelewski 1989; Climate Prediction Center 1987–96).

Those ENSO events equal to or greater than one standard deviation ($\geq 1\sigma$) from the mean for SST anomalies or SOI magnitudes were considered to be strong, while those less than one standard deviation ($<1\sigma$) were weak to moderate. Based on the strength of the winter SST anomaly, ENSO events were separated into groups (Table 2). Four El Niños and three La Niñas were considered strong using that index. Winters were then separated based on the strength of averaged winter SOI values (Table 3). Using SOI values, two El Niños and three La Niñas were found to be strong, the rest weak to moderate. Finally, winters were grouped based on the location of the 28.0°C SST isotherm between 5°S and 5°N. For El Niño events, the dividing longitude was 150°W and for La Niña events it was the date line, 180° (Table 4). The locations for the 28.0°C SST isotherm were chosen based on climatology of the strong El Niño and strong La Niña events. Generally, only during El Niño events was the 28.0°C SST isotherm east of 150°W, while only during La Niña events was the 28.0°C isotherm west of 180°. A very uniform distribution of El Niño and La Niña events was found in this grouping, with seven El Niño events east of 150°W and five west. For La Niña events, six were east of 180° while four were west.

TABLE 2. Winters separated using SST intensity for El Niño and La Niña events. El Niño events greater than one standard deviation are years with Niño 3–4 regions SST anomalies > 1.56°C. La Niña events greater than one standard deviation are years with Niño 3–4 regions SST anomalies < -1.33°C.

El Niño $\geq 1\sigma$	El Niño $< 1\sigma$	La Niña $\geq 1\sigma$	La Niña $< 1\sigma$
1957/58	1951/52	1970/71	1950/51
1972/73	1953/54	1973/74	1955/56
1982/83	1965/66	1988/89	1956/57
1991/92	1969/70		1964/65
	1976/77		1971/72
	1986/87		1975/76
	1992/93		1995/96
	1994/95		

TABLE 3. Winters separated using SOI intensity for El Niño and La Niña events. El Niño events greater than one standard deviation are winters with SOI < -2.3. La Niña events greater than one standard deviation are winter with SOI > 1.8.

El Niño $\geq 1\sigma$	El Niño $< 1\sigma$	La Niña $\geq 1\sigma$	La Niña $< 1\sigma$
1982/83	1951/52	1950/51	1955/56
1991/92	1953/54	1973/74	1956/57
	1957/58	1975/76	1964/65
	1965/66		1970/71
	1969/70		1971/72
	1972/73		1988/89
	1976/77		1995/96
	1986/87		
	1992/93		
	1994/95		

The Student's two-tailed t-test was used to determine whether significant differences in mean cyclone frequencies between ENSO events and non-ENSO events existed based on the categories of the three parameters outlined previously. Those circles that experienced significant differences at the 95% level were identified. Due to the small sample sizes, see Tables 1–4, results associated with this initial study will be limited. Addi-

TABLE 4. Winters separated using the 28.0°C SST isotherm for El Niño and La Niña events. Dividing longitude is 150°W for El Niño and 180° for La Niña.

El Niño events		La Niña events	
East of 150°W	West of 150°W	East of 180°	West of 180°
1957/58	1951/52	1950/51	1970/71
1965/66	1953/54	1955/56	1973/74
1972/73	1969/70	1956/57	1975/76
1982/83	1976/77	1964/65	1988/89
1986/87	1992/93	1971/72	
1991/92		1995/96	
1994/95			

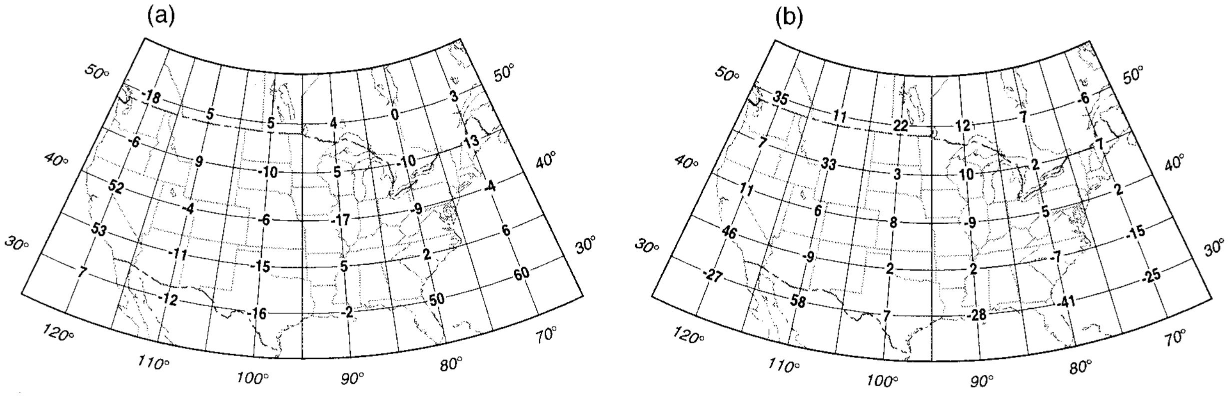

FIG. 2. Percent differences in average winter cyclone frequency from (a) 12 El Niños and (b) 10 La Niñas to 23 non-ENSO events.

tional years of data will be required to more fully determine where there are significant differences.

3. Results

a. Composite average of all ENSO events

The average number of cyclones that occur in each of the 30, 5° latitude equal-area circles during a non-ENSO event is shown in Fig. 1. The Alberta and Colorado cyclone tracks appear to join in New England where the greatest frequency of winter cyclones is generally found. Fewer cyclones occur in the West and Southwest. All future figures are based on either positive or negative percent differences from the numbers shown in Fig. 1. The percent differences in cyclone frequency between the composite average of the 12 El Niño winters and the 23 non-ENSO winters as well as the 10 La Niña winters and the 23 non-ENSO winters (Table 1) are shown in Figs. 2a and 2b. During composite El Niño winters large increases in cyclones occur over California and off the Southeast coast, while considerable decreases are found in the Southwest and in the number of Colorado cyclone tracks. Fifty percent of the circles experience increases in the number of cyclones during El Niños. During composite La Niña winters approximately 70% of all the circles experienced an increase in cyclone counts, with most circles in the west and along the northern region of the grid experiencing the largest percent increases. Fifty percent of the circles that experienced fewer cyclones during La Niñas were found in the southeast part of the grid. Only the circle located at 30°N, 80°W exhibited statistically significant differences when comparing either the composite El Niño or La Niña event to the non-ENSO event (Table 5). It should be noted that very large percent differences in the western part of the grid is partly due to the overall lower cyclone frequency counts.

TABLE 5. The 5° equal-area circles that were statistically significant at the 95% level using the Student's two-tailed t-test.

Circle	What indices were significantly different than the non-ENSO event
30°N, 70°W	El Niño with 28°C isotherm east of 150°W
45°N, 70°W	Strong El Niño based on SST
30°N, 80°W	Composite of 12 El Niño and 10 La Niña events, weak–moderate El Niño based on SST, weak–moderate La Niña based on SST, weak–moderate El Niño based on SOI, strong La Niña based on SOI, and El Niño with 28°C isotherm east of 150°W
45°N, 80°W	Weak–moderate El Niño based on SST
35°N, 100°W	Strong El Niño based on SOI
40°N, 120°W	El Niño with 28°C isotherm east of 150°W
45°N, 120°W	La Niña with 28°C isotherm east of 180°
50°N, 120°W	Weak–moderate La Niña based on SST, weak–moderate La Niña based on SOI, La Niña with 28°C isotherm east of 180°

b. SST intensity

The map of percent differences in number of cyclones for each SST category of ENSO event (Table 2) is shown in Figs. 3a–d. The pattern for strong El Niños is similar to that for the composite El Niño with large positive percent increases found over California and off the Southeast coast. The positive increases along the northern tier of circles were also greater. The decrease in cyclone frequency found in the western circles and in the Colorado track was much larger than found in the composite El Niño. The circle located at 45°N, 70°W experienced a significant increase in the number of cyclones when compared to non-ENSO events. The pattern for the weak–moderate El Niño was visibly different than that for the strong or composite El Niño. Most circles over the Rockies showed positive increases in cyclone frequency, while the circle over New England (45°N, 70°W) showed a negative decrease. Furthermore, most of the decreases were small relative to those found for the strong El Niños. Cyclones counted in circles at 30°N, 80°W and 45°N, 80°W were significantly different

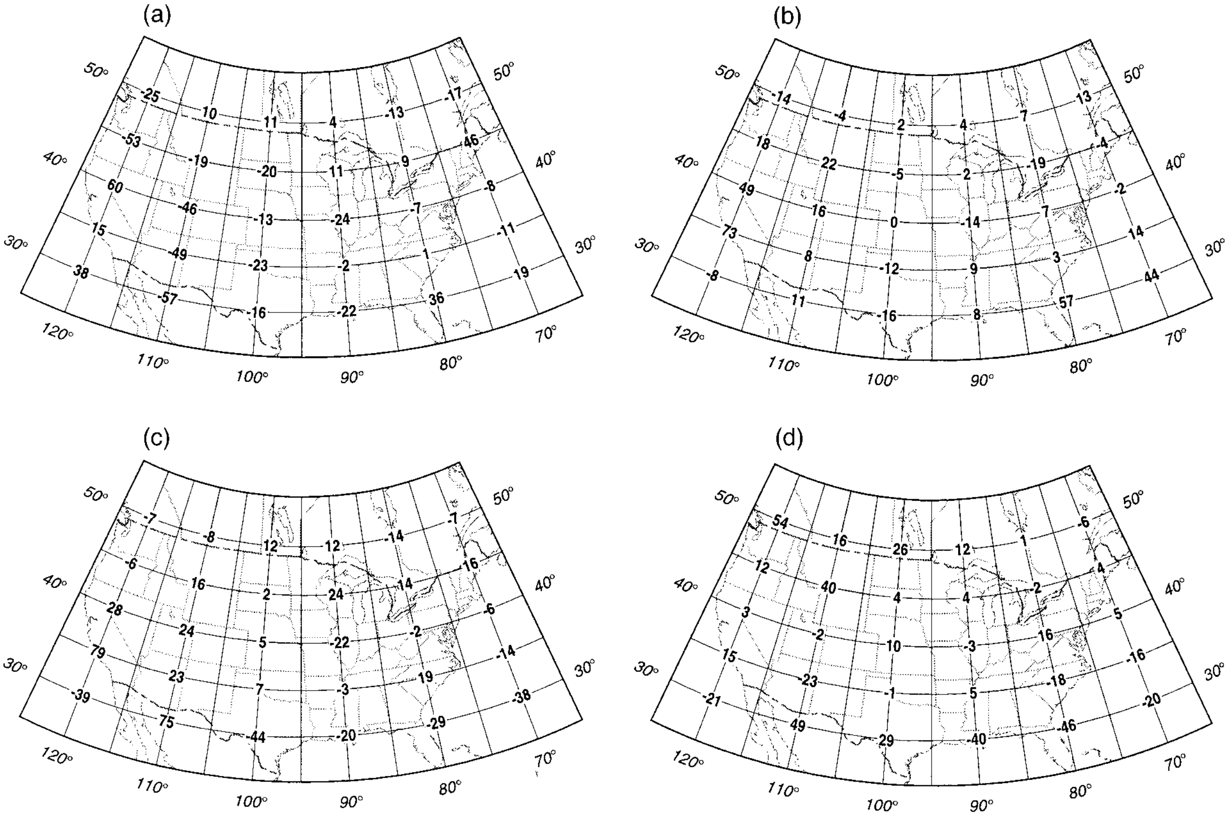

FIG. 3. Percent differences in average winter cyclone frequency from (a) 4 strong El Niños, (b) 8 weak–moderate El Niños, (c) 3 strong La Niñas, and (d) 7 weak–moderate La Niñas, to 23 non-ENSO events based on magnitude of equatorial Pacific SST anomaly.

than those for non-ENSO events based on the Student's two-tailed t-test (Table 5).

For La Niña events the patterns for each category were much more similar to the composite La Niña than those for El Niño. The pattern for the strong La Niñas differed in the Pacific Northwest, where negative decreases were found. There were no major pattern differences between winters with weak–moderate La Niñas and the composite. However, the mean number of cyclones determined for two circles, 30°N, 80°W and 50°N, 120°W, were significantly different (fewer, greater respectively) than the mean determined for non-ENSO events (Table 5).

c. SOI intensity

The patterns for the four SOI categories of ENSO events (Table 3) are shown in Figs. 4a–d. The strong El Niño pattern exhibits large differences from that of the composite El Niño. All circles on 100° and 110°W experience negative decreases, some of them very large. One circle, 35°N, 100°W, exhibited a significant decrease in cyclones (Table 5). Both source areas of Alberta and Colorado track lows experienced large negative decreases. Further, only one circle in the Southeast experienced a large positive increase in cyclones. Large positive increases in cyclones occur over the Great Lakes and New England. Overall, during strong El Niños more than 70% of all circles experience fewer cyclones than during non-ENSO winters. The pattern for weak–moderate El Niños is generally similar to that for the El Niño composite. A greater number of western circles experience a greater number of cyclones during these El Niños than during the composite El Niño. One circle, 30°N, 80°W, experienced a statistically significant increase in cyclones when compared to the mean for non-ENSO events.

The pattern for strong La Niñas was similar to the La Niña composite except for a few exceptions. First, the two circles, one located over northern California and the other over Oregon, experienced decreases in cyclones; the circles along 40°N (except at 120°W) experienced a greater number of cyclones (i.e., more Colorado cyclone tracks). The changes in Colorado cyclones is likely related to changes in the jet stream and teleconnection patterns. The circle 30°N, 80°W experienced a significant decrease in number of cyclones (Table 5). For weak–moderate La Niñas the number of cyclones along the lee of the Rockies is smaller. The circle located at 50°N, 120°W exhibited a significant increase in cyclones. However, most of the rest of the

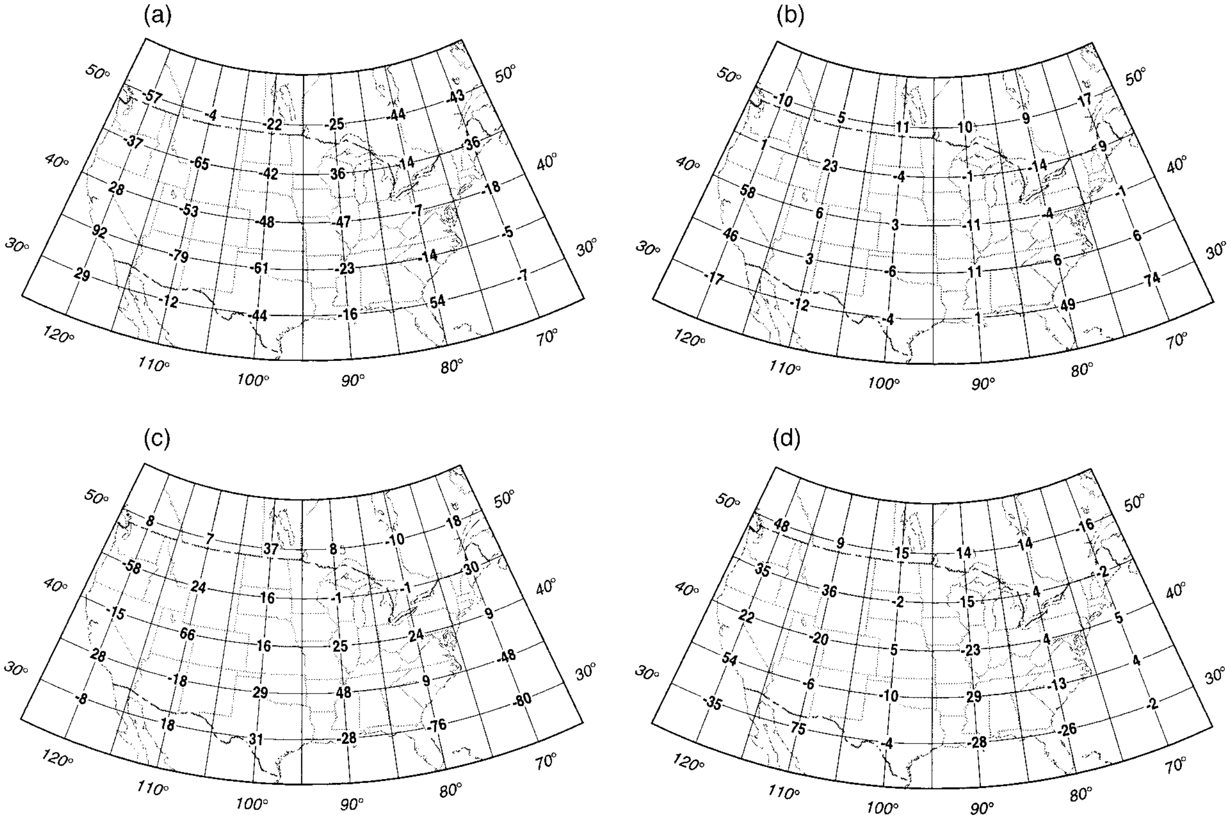

FIG. 4. Percent differences in average winter cyclone frequency from (a) 2 strong El Niños, (b) 10 weak–moderate El Niños, (c) 3 strong La Niñas, and (d) 7 weak–moderate La Niñas, to 23 non-ENSO events based on magnitude of SOI anomaly.

circles experience a similar type of change in cyclone frequency as that in the La Niña composite.

d. Location of the 28.0°C SST isotherm

In this part of the study, the location of the 28.0°C SST isotherm was used to separate ENSO events into subgroups (Table 4). Figures 5a–d show the El Niño and La Niña patterns when the 28.0°C was east–west of 150°W for El Niño events and east–west of 180° for La Niña events. El Niño events east of 150°W were similar to the composite El Niño, but the overall magnitude was enhanced. There were larger negative decreases of cyclones from the Rockies through the central United States to the mid-Atlantic states. Significant positive increases were noted over the southeast part of the United States (30°N, 70°W and 30°N, 80°W) and especially California (40°N, 120°W). For El Niño events with the 28.0°C SST isotherm west of 150°W, cyclone frequency decreased in the southeast United States, while it increased 15%–30% from the Great Lakes through the upper Midwest into the northern plains and northern Rockies. This is indicative of the northern jet stream and Alberta Clipper track displaced farther south during these types of El Niños. In western Texas, cyclone frequency decreased even more. Finally, in California there was much more variability, with increases and deceases of 30%–70% seen. Overall, 43% of the circles changed signs from the composite El Niño.

For the La Niña events east of 180°, the pattern was very similar to the composite La Niña over the eastern half of the United States. The largest differences were over the Pacific Northwest where increases of nearly 120% were found. Two circles (45°N, 120°W and 50°N and 120°W) experienced significant increases in cyclones when compared to non-ENSO events (Table 5). Increases of a smaller magnitude, 10%–30%, spread across the northern Rockies into the upper plains. There was a decrease in cyclones across California of 10%–50%. For La Niña events west of 180°, there were three distinct differences from the composite La Niña. The first was about a 25% decrease off the southeast U.S. coastline from the composite La Niña. The second was about a 35% decrease in Texas. Finally, there was a 30%–50% decrease in the Pacific Northwest. The Pacific Northwest appears to be highly variable during La Niña events.

4. Conclusions and future research

Three parameters of ENSO were examined to discern how differences in their magnitude could influence win-

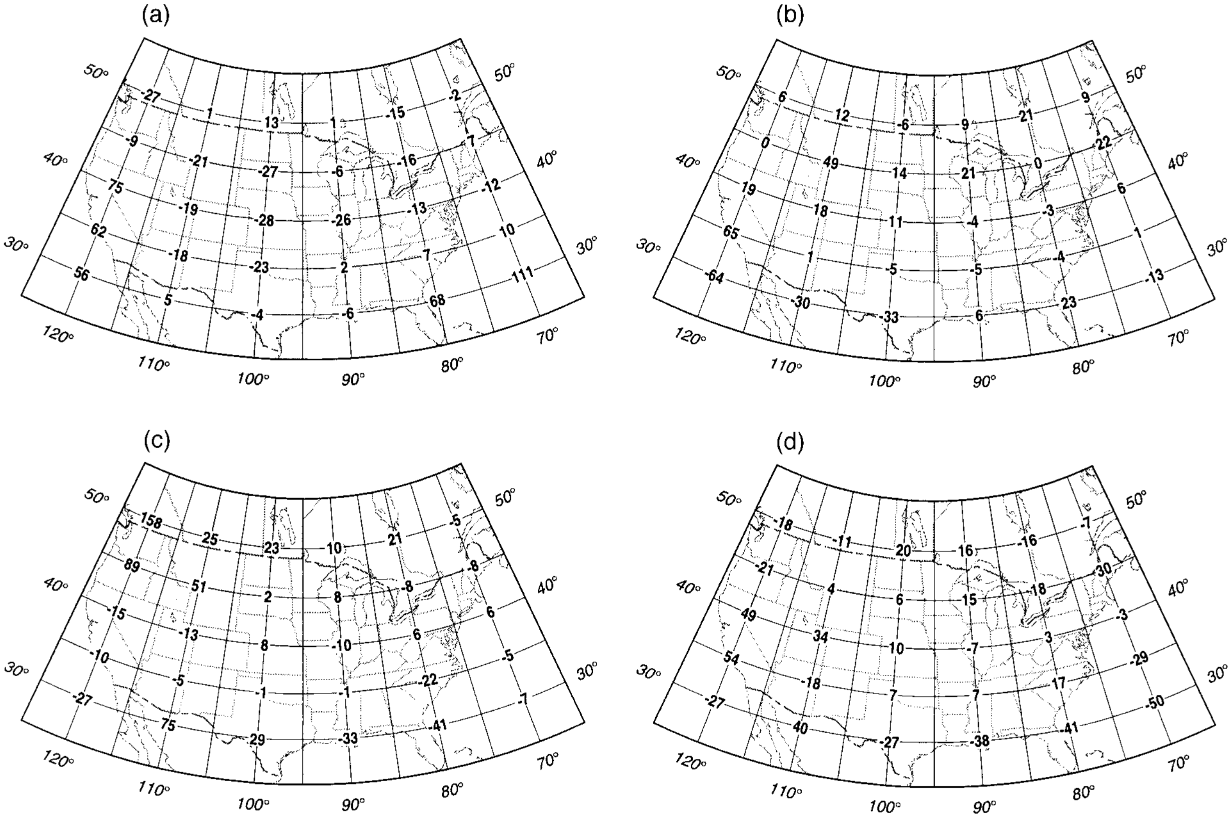

FIG. 5. Percent differences in average winter cyclone frequency from (a) seven El Niños where 28.0°C SST isotherm east of 150°W, (b) five El Niños where 28.0°C SST isotherm west of 150°W, (c) six La Niñas where 28.0°C SST isotherm east of 180°, and (d) four La Niñas where 28.0°C SST isotherm west of 180°.

ter cyclone frequencies across the United States. Both oceanic (SST) and atmospheric (SLP) characteristics of ENSO were evaluated. El Niños and La Niñas were separated by 1) intensity of SST and SOI into two groups—strong ($\geq 1\sigma$) and weak–moderate ($< 1\sigma$)—and 2) location of 28.0°C SST isotherm. The percent difference in number of cyclones passing through each of 30, 5° latitude equal-area circles between each category of ENSO event and non-ENSO events was determined. Those circles with significant differences based on the Student's two-tailed t-test were identified.

For each index major differences in either the magnitude of cyclones or the type of anomaly (either positive or negative) or both were identified when comparing nonevents to El Niño and La Niña winter cyclone frequency patterns. This was apparent over the West Coast where a large range of differences occurred between the composite ENSO and the categorized ENSO events. These results indicated that each El Niño and La Niña should be viewed not only using a composite ENSO scheme but also independently, considering the magnitude SST and SOI anomalies, the location of the 28.0°C SST isotherm, and possibly others such as low-level easterly winds and the NAO, before determining the pattern of winter cyclones across the United States.

Based on a comparison of all ENSO indices with non-ENSO events, 8 of 30 equal-area circles experienced significant differences in the mean number of cyclones. These were located along the West Coast, Texas, the eastern Great Lakes, New England, and the Southeast. Because of the small sample sizes associated with each ENSO index, a much longer period of observations would help determine whether other circles experienced significant differences. However, the results presented here warrant additional research in the way we view ENSO. The data indicates the danger of too much averaging when attempting to make long-range outlooks. For this approach to work, significant gains from GCMs will be necessary. The data shows not all indices indicate the same anomalies, raising the question of just how useful a composite ENSO parameter would be and what are the best indices to examine.

Finally, this work has potential application to the long-range climate forecasting of winter precipitation and temperature anomalies. Further study could examine precipitation and temperature anomaly patterns associated with each category of ENSO event.

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