Impacts of ENSO on Snowfall Frequencies in the United States

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ABSTRACT

Changes in the frequency of occurrence of snowfall during El Niño–Southern Oscillation (ENSO) events are presented for the continental United States. This study is motivated by the need to improve winter climate forecasts for government agencies (i.e., U.S. Department of Transportation and Department of Energy) and winter entertainment facilities and the need for climatological studies. Daily snowfall data from 442 stations in the U.S. Historical Climatology Network are utilized. Selected stations each have more than 20 yr with 15 or more snowfall events per year during a 97-yr (1900–97) period of study. Three categories are created for each ENSO phase, based on the magnitude of daily snowfall amounts (in millimeters)—light: (0–50.8], moderate: (50.8–152.4], and heavy: (152.4–304.8]. Differences between neutral and cold or warm ENSO winters are created to show regions with increased or decreased occurrences in each snowfall category. Statistical tests are applied at each station to provide confidence levels for the identified changes in snowfall frequency. Simple field significance tests are completed for regions that show coherent ENSO signals. Results reveal several regions with significant changes in the frequency of occurrence of snowfall between neutral and cold or warm ENSO phases. For example, the Pacific Northwest has increased (decreased) occurrences of light, moderate, and heavy snowfalls during the cold- (warm-) phase ENSO winter, with the exception of light snows during the warm phase. Other regions with significant changes include the northern and eastern Great Lakes, the Northeast Corridor, and New England. The results may allow government agencies and private companies to mitigate adverse impacts of winter storms based on predictions of upcoming ENSO phases. Winter entertainment facilities, such as ski resorts, may actually benefit from these results. Combined with other winter-precipitation studies and the ever-improving ability to forecast each ENSO phase, this analysis of snow-event frequencies should aid in preparation for winter storms.

1. Introduction

Recent studies (e.g., Smith and O'Brien 2001; Mason and Goddard 2001; Ropelewski and Halpert 1996; Sittel 1994; Yarnal and Diaz 1986) have shown the El Niño–Southern Oscillation (ENSO) to have a significant impact on winter precipitation in the continental United States. The current study relates changes in the phase of ENSO to shifts in the frequency of light, moderate, and heavy snowfall. The goal is to identify regional changes in snowfall frequencies and to compare these frequency shifts to seasonal changes in total snowfall. We anticipate that government agencies (i.e., U.S. Department of Transportation, U.S. Department of Energy), winter entertainment facilities, and avalanche forecasters may benefit from this research.

The authors were motivated by the seasonal snowfall study of Smith and O'Brien (2001, hereinafter SAO) and a continued need to improve seasonal snowfall forecasting. SAO identified seasonal changes in total snowfall associated with ENSO extreme phases for several regions in the continental United States. Total snowfall provides a partial measure for the severity of a winter, but many stakeholders require information on how rapidly the snow accumulates in order to mitigate adverse impacts. For example, the transportation industry's response to six 1-in. (25.4 mm) snowfalls will be different than its response to one 6-in. (152.4 mm) snowfall. Agencies are now trying to reduce winter road maintenance costs by considering climate variability when devising salt usage indices (Andrey et al. 2001). In addition, a better understanding of snowfall frequencies associated with ENSO combined with current knowledge of ENSO impacts on winter precipitation may further aid seasonal forecasters.

The snowfall frequency analysis takes advantage of the cooperative station data from the U.S. Historical Climatology Network (USHCN; Kaiser and Allison 1999). The USHCN data have the advantage of better

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TABLE 1. ENSO years as determined by the JMA SST index over the period of 1900–97. The listed years represent the beginning year of the ENSO phase (e.g., 1900 = Oct 1900–Sep 1901).

Warm	1902, 1904, 1905, 1911, 1913, 1918, 1925, 1929, 1930, 1940, 1951, 1957, 1963, 1965, 1969, 1972, 1976, 1982, 1986, 1987, 1991
Neutral	1900, 1901, 1907, 1912, 1914, 1915, 1917, 1919, 1920, 1921, 1923, 1926, 1927, 1928, 1931, 1932, 1933, 1934, 1935, 1936, 1937, 1939, 1941, 1943, 1945, 1946, 1947, 1948, 1950, 1952, 1953, 1958, 1959, 1960, 1961, 1962, 1966, 1968, 1974, 1977, 1978, 1979, 1980, 1981, 1983, 1984, 1985, 1989, 1990, 1992, 1993, 1994, 1995, 1996
Cold	1903, 1906, 1908, 1909, 1910, 1916, 1922, 1924, 1938, 1942, 1944, 1949, 1954, 1955, 1956, 1964, 1967, 1970, 1971, 1973, 1975, 1988

coverage over the United States and include stations at higher elevations when compared with first-order weather stations (commonly used in ENSO studies). In brief, the method categorizes daily snowfall for each winter month (November–March) as light, moderate, and heavy and counts the number of snow days in each category for each 5-month cold season (winter). Winters are classified by ENSO phase (warm, cold, or neutral), and differences between extreme (warm or cold) and neutral ENSO phases are created for each snowfall category. A z test based on a joint Poisson distribution is applied to identify individual stations with significant shifts in snowfall frequency. Regions with coherent differences are visually identified, and the field significance of the z-test results is determined for each region. Stations in the Northwest, Great Lakes, and Northeast are identified as having statistically significant changes in snowfall frequency between the neutral and extreme ENSO phases. These results are compared with several ENSO total snowfall studies.

Identification of regions with shifts in ENSO-phase snowfall frequency may be used to develop probabilistic forecasts of snowfall for upcoming winters. For example, with advance knowledge of an ENSO warm phase, one could forecast the probability of one additional 12-in. (304.8 mm) snowfall in the Northeast Corridor during the upcoming winter. Government agencies and the commercial sector may benefit by evaluating probabilities for specific snowfall magnitudes, thus, allowing them to prepare financially for winter storms.

The manuscript is organized with section 2 providing the definition of ENSO phases, a description of the data, and the station selection method. The methods used to construct the snowfall categories and statistical techniques are outlined in section 3. Results are presented in section 4, and a discussion of the results, including comparison with other snowfall studies, is in section 5. Concluding statements and potential applications are in section 6.

2. Data

a. El Niño–Southern Oscillation

ENSO is associated with changes in the sea surface temperature (SST) in the equatorial Pacific Ocean, which can be measured and used to define an ENSO index. The Japan Meteorological Agency (JMA) index is used to define the phase of ENSO (JMA 1991). There are numerous other indices from which to choose (i.e., Niño-3, Niño-4, etc.); however, the JMA index has been shown to be ''an objective procedure and . . . quite consistent with the consensus of the ENSO research community'' (Trenberth 1997). In addition, Hanley et al. (2003) compared the JMA index to the Niño indices and found the JMA index to be comparable to the Niño-3 and Niño-3.4 indices for defining ENSO warm phases. The JMA index was also found to be more sensitive to ENSO cold phases than were the Niño indices. The JMA index has been frequently used in ENSO-related studies (e.g., SAO; Smith et al. 1999; Bove 2000; Green 1996).

The JMA index is created using a 5-month running mean of the SST anomalies for the region from 4°N to 4°S and from 150° to 90°W in the equatorial Pacific Ocean. Observed SST data are used for the period from 1949 to present, and reconstructed SSTs (Meyers et al. 1999) are used for the period from 1900 to 1948. ENSO years are defined as cold (warm) when the 5-month mean of SST anomalies is less than -0.5°C (greater than 0.5°C) for 6 or more consecutive months, including October, November, and December. If the 5-month mean of the anomalies fails to exceed the warm or cold threshold for all 6 consecutive months, the year is defined as being neutral (Hanley et al. 2003).

An ENSO year is defined as October of the initial year through September of the following year, using the JMA index. This ENSO-year definition is chosen to capture the mature phase of the ENSO event, which typically occurs during the boreal winter (Bove 2000). Table 1 lists the ENSO phase for the years used in this study. As an example, the ENSO warm-phase year of 1929 includes October, November, and December of 1929 and January–September of the calendar year 1930. The JMA index and years defined as cold, warm, or neutral are available online as of the time of writing, (http://www.coaps.fsu.edu/research/jma_index1.shtml).

b. USHCN data

Snowfall data from the USHCN (Kaiser and Allison 1999) are available for 1062 stations over the continental United States. Advantages of using the USHCN,

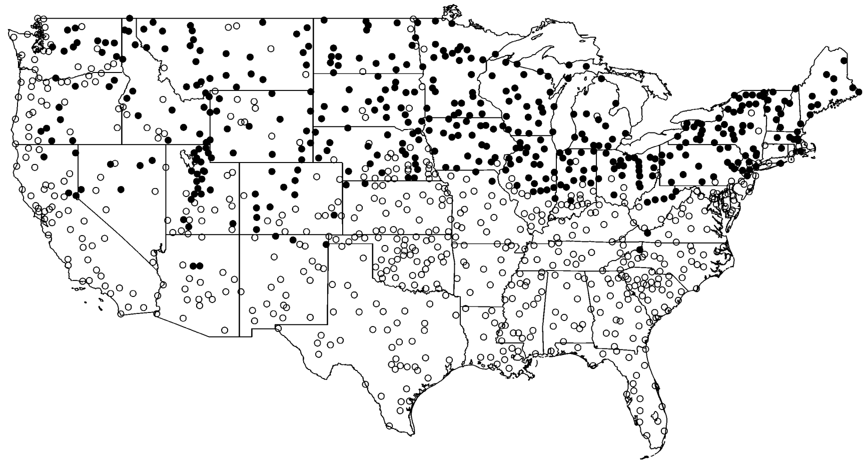

FIG. 1. Stations in the USHCN with less than 1% of their total snowfall data missing in the period 1900–97. The 442 stations that meet the minimum number of snowfall events required for this study (see text) are marked with filled circles.

as compared with first-order stations, include a higher data density and more stations in remote locations. One limitation of the USHCN is that no efforts have been made to remove the biases caused by station moves and changes in measurement practices. The authors acknowledge that the effect of such biases on the results is not known; determining the magnitude of these biases is beyond the scope of this work. The original snowfall data are provided in units of tenths of an inch. After station selection, the daily snowfall values are converted to millimeters for the snowfall frequency analysis.

The length of record varies by station in the USHCN. The longest station record begins in 1871, and the latest beginning year is 1948, with most stations having data through December of 1997 (Kaiser and Allison 1999). The data contain quality-control flags assigned by the National Climatic Data Center. Daily snowfall values flagged as ''invalid data—no edited data value available'' or ''failed aerial consistency check'' are discarded. Using a threshold of $\leq$1% of the daily data being missing or flagged suspect, the period of October 1900–September 1997 provides sufficient coverage over the United States (Fig. 1).

Snowfall is a rare event at many of the stations that pass the $\leq$1% missing daily data threshold. Each station used in this study must have at least 15 snow days during the cold season of November–March. The 15-snow-day threshold (other thresholds were tested) reduced the number of stations from 1062 to 736 while still providing reasonable coverage of the United States. An additional consideration was to include only stations with at least 20 cold seasons that exceed the 15-snow-day threshold, which further reduced the number of stations to 442 (Fig. 1). Twenty years on average will provide 5 warm, 5 cold, and 10 neutral ENSO phases. In practice, the average number of warm, cold, and neutral ENSO phases for the 442 stations was 10, 9, and 26, respectively. The combined criteria used for this study eliminated all stations in the southern states where snowfall is rare but some ENSO signals have been found (e.g., SAO; Janowiak and Bell 1998). The criteria also reduced the number of stations in mountainous regions, which limits our ability to evaluate high-elevation regions.

3. Methods

a. Data preparation

Daily snowfall totals at the selected 442 stations are categorized by their magnitude and are counted for each ENSO winter. This study is limited to the cold-season months of November–March. The authors acknowledge that snow will occur at some stations, especially at high elevations, outside of this 5-month cold season; however, snowfall at the majority of the 442 stations occurs from November through March. Light snowfalls are defined as any daily snow total that is (0–50.8] mm, moderate snowfall is defined as (50.8–152.4] mm, and heavy snowfall is defined as (152.4–304.8] mm. These ranges correspond to (0–2], (2–6], and (6–12] in., respectively.

The number of days with a total snowfall within the light, moderate, and heavy snowfall categories is counted for each 5-month winter, and each cold season is then classified as occurring during a warm, cold, or neutral ENSO phase (see section 2a). An average number of daily snowfalls per winter is then calculated by dividing the total number of snow days in each category and ENSO phase by the appropriate number of years of good data. The result is an average number of occurrences per 5-month winter for light, moderate, and heavy snowfall for the neutral, warm, and cold ENSO phases. Snowfall frequencies vary greatly across the United States within an ENSO phase. During neutral ENSO phases, the highest frequency of light snowfalls is concentrated around the Great Lakes and the eastern United States (Fig. 2a). Moderate snowfalls are concentrated along the Great Lakes and in the Mountain West (Fig. 2b), and heavy snowfalls are most likely to occur in the western United States (Fig. 2c). Extreme-minus-neutral phase differences are calculated for each snowfall category to identify changes between ENSO phases.

b. Statistical comparison

Two statistical tests are used to determine regions with significant changes in snow-day frequency for each of the snowfall categories. First, independent tests are conducted at each station to identify shifts between ENSO extreme- and neutral-phase distributions. A simple field significance test is then employed to stations in 10 regions of the country.

Snowfall may be considered as an independent or dependent variable. Daily snowfall can physically depend on a previous day's snowfall because of the spatial and temporal scale of synoptic weather systems. By contrast, days with measurable snow (snow days) are considered to be independent because ''their probability of occurrence in a given time interval depends only on the size of the interval, usually the length of time interval over which they will be counted'' (Wilks 1995). Herein, snow days are tabulated over a 5-month winter, and consecutive winters are assumed to be independent of preceding or following winters. If the analysis period is expanded to include other months (e.g., October or April), the distribution of snow days will change. Because the number of snow days per 5-month winter is a discrete random variable, the equivalence of snowfall frequency between ENSO extreme- and neutral-phase winters can be tested in terms of two Poisson populations.

A discrete random variable is distributed as a Poisson random variable with parameter μ, the mean amount of events in the population, if the probability mass function of the variable is

$$\Pr\{X = x\} = \frac{e^{-\mu}\mu^x}{x!} \qquad x = 0, 1, 2, \ldots \tag{1}$$

(Taylor 1982). Further, if $x_1, x_2, \ldots, x_n$ is a sample of size n from a Poisson distribution with parameter μ, then $\Sigma_{i=1}^{n} x_i$ has a Poisson distribution with parameter $n\mu$ (Lehmann 1986). The authors assume that the distribution of snow days for extreme-ENSO-phase winters is a Poisson random variable X with parameter μ_x, where μ_x is the expected frequency of snow days in the extreme ENSO year. In a similar way, the distribution of snow days for neutral ENSO winters is a Poisson random variable Y with parameter μ_y (the expected frequency of snow days for a neutral winter).

Under the assumption that the distributions of extreme- and neutral-phase snow days are independent Poisson distributions, a test of the equality of the Poisson distributions is applied. A null hypothesis is formulated as

$$H_0\colon \mu_x = \mu_y, \tag{2}$$

which states that the two Poisson populations represented by the two rates of snow-day occurrence, μ_x and μ_y, are statistically similar. The alternative hypothesis is defined as

$$H_A\colon \mu_x \neq \mu_y, \tag{3}$$

which states that the two rates of snow-day occurrence are not equal. Data used to test (2) include the number of snow days x that occur in n_x valid ENSO extreme years and the number of snow days y that occur in n_y valid ENSO neutral years. The total number of snow days is represented by t ($t = x + y$).

The procedure to test (2) is outlined in Lehmann (1986). The joint distribution of the independent random variables X and Y is

$$\Pr\{X = x, Y = y\} = \frac{e^{-(\mu_x+\mu_y)}}{x!y!}\mu_x^x\mu_y^y. \tag{4}$$

Given $X + Y = t$, X has a conditional binomial distribution with parameters t and $p = n_x\mu_x/(n_x\mu_x + n_y\mu_y)$; therefore,

$$\Pr\{X = x | X + Y = t\} = \binom{t}{x}\left(\frac{n_x}{n_x + n_y}\right)^x\left(\frac{n_y}{n_x + n_y}\right)^{t-x} \qquad x = 0, 1, 2, \ldots, t \tag{5}$$

under the null hypothesis.

Because the total number of snow days t is typically greater than 25, (5) can be approximated by an normal distribution with

$$\mu = t\left(\frac{n_x}{n_x + n_y}\right) \quad \text{and} \tag{6a}$$

$$\sigma = \sqrt{t\left(\frac{n_x}{n_x + n_y}\right)\left(\frac{n_y}{n_x + n_y}\right)}. \tag{6b}$$

The resulting test statistic, with a continuity correction (Bhattacharyya and Johnson 1977), is formulated as

$$Z = \left|\frac{x - 0.5 - \left(\dfrac{tn_x}{n_x + n_y}\right)}{\sqrt{t\left(\dfrac{n_x}{n_x + n_y}\right)\left(\dfrac{n_y}{n_x + n_y}\right)}}\right|. \tag{7}$$

Stations at which the null hypothesis is either rejected or accepted are identified by comparing the z statistic from (7) to the two-sided confidence level values. The hypothesis is tested at both the 90% and 95% confidence levels. Rejecting the null hypothesis provides confidence that the two tested snowfall frequencies are not equal. The sign of the z statistic, prior to applying the

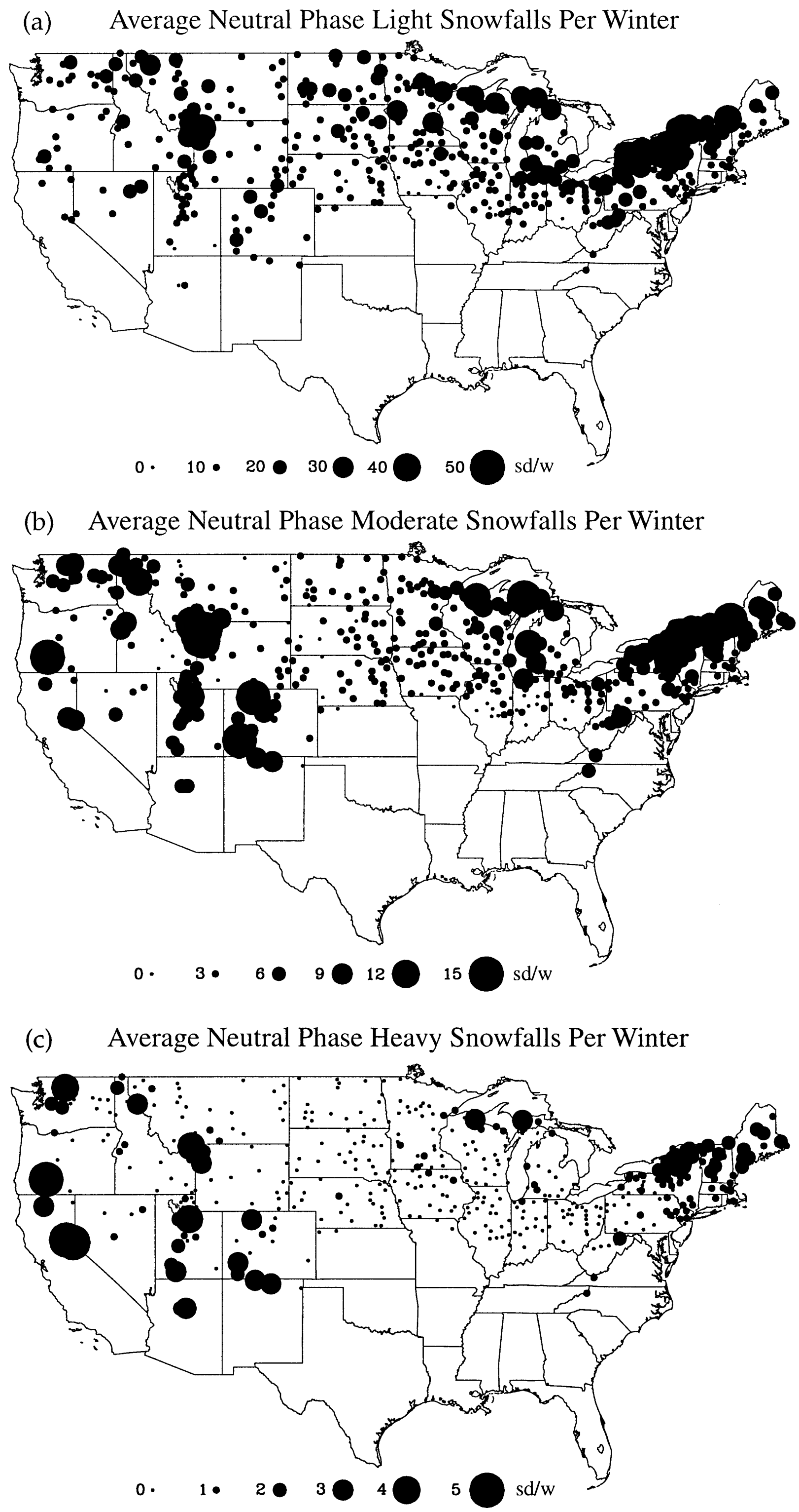

FIG. 2. Frequency (snow days per winter) of (a) light, (b) moderate, and (c) heavy snowfalls during the Nov–Mar cold season of the ENSO neutral phase. Numbers in legend correspond to minimum value for each bin.

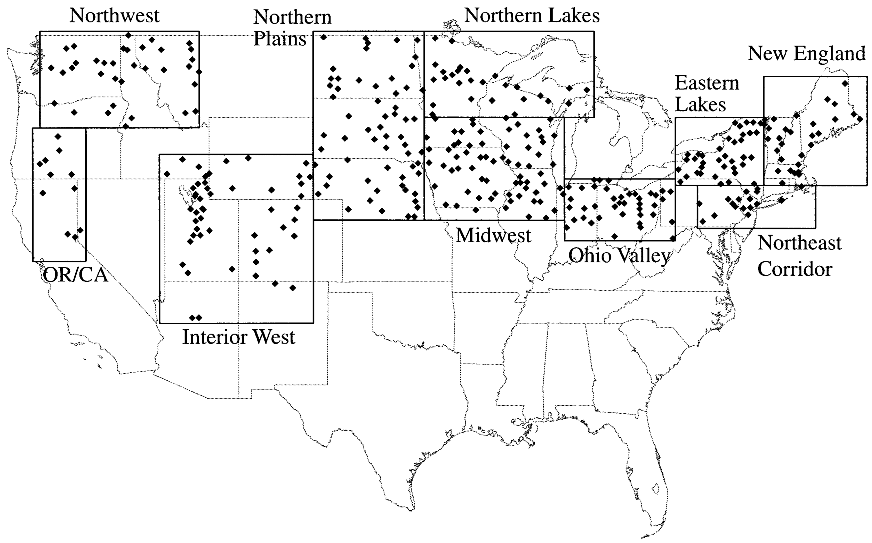

FIG. 3. Ten geographic regions used in field-significance tests and discussion of significant changes in snowfall frequency during ENSO extreme-phase winters. Diamonds mark stations used in each region.

absolute value, identifies whether the extreme-phase snowfall frequency is greater than (+) or less than (−) the neutral-phase snowfall frequency.

Determination of field significance for regional subsets of the 442 stations uses a method outlined in Wilks (1995). For a particular region, each station's z significance test is considered to be an independent trial. For N trials, the number of significant (95% level) differences d is determined and tested for field significance using a binomial distribution. Field significance occurs when $d > k$ from

$$\sum_{i=0}^{i=k} \Pr\{X = k\} > 0.95, \tag{8}$$

where k is the smallest number that makes the probability greater than 0.95. Note that the method employed treats the N trials as independent and does not consider the possible spatial correlation between stations. With this in mind, the binomial test may only provide a lower limit to the probability value for the field significance, and these results should be treated as preliminary. Wilks (1995) suggests a number of more sophisticated significance tests (e.g., Monte Carlo tests) that could be employed in the future to define further those regions with the highest probability of ENSO extreme-phase increases or decreases in light, moderate, and heavy snow days.

4. Results

Changes in the number of light, moderate, and heavy daily snowfalls are identified for both ENSO extreme phases. The increases and decreases in snowfall frequency are all determined relative to the number of events during ENSO neutral-phase winters. The authors visually identify 10 geographic regions (Fig. 3) with coherent ENSO signals. The stations in these 10 regions were selected for field significance tests, and not all regions exhibit significant changes in each phase or category.

a. Light snow

The frequency of light snowfall, (0–50.8] mm, generally decreases (increases) in the central (eastern) United States during ENSO cold-phase winters (Fig. 4a). The Northwest, eastern Great Lakes, and New England regions all have increases in light snowfall at more than 40% of the stations in their respective regions (Fig. 5a). In the eastern Great Lakes and Northeast, 36% and 33%, respectively, of the stations have positive z statistics that reject (2) at the 95% confidence level. The increase in light snowfalls in these regions range from 2 up to 10 more events per 5-month cold season. In a region where light snowfalls are common (Fig. 2a) the impacts should be minimal. The only region with a significant shift to less light snowfalls during an ENSO cold phase is the interior West (Figs. 4a and 5a). Fifty-two percent of the stations in the interior West have decreases in the number of light snowfalls, with 34% having negative z statistics that reject (2) at the 95% level (Fig. 5a). In a region that averages 10–20 light snowfalls per winter, decreases ranging from 2 to 6 events could affect transportation and recreation. The decrease in light snowfalls seems to extend into the northern plains (Fig. 4a); however, the region shows almost the same percentage of stations with increased (24%) and decreased (27%) light snowfall frequencies (Fig. 5a).

ENSO warm-phase winters reveal numerous significant increases in light snowfall in the central and western United States, and decreases in light snowfall frequencies are limited to the East (Fig. 4b). Increased

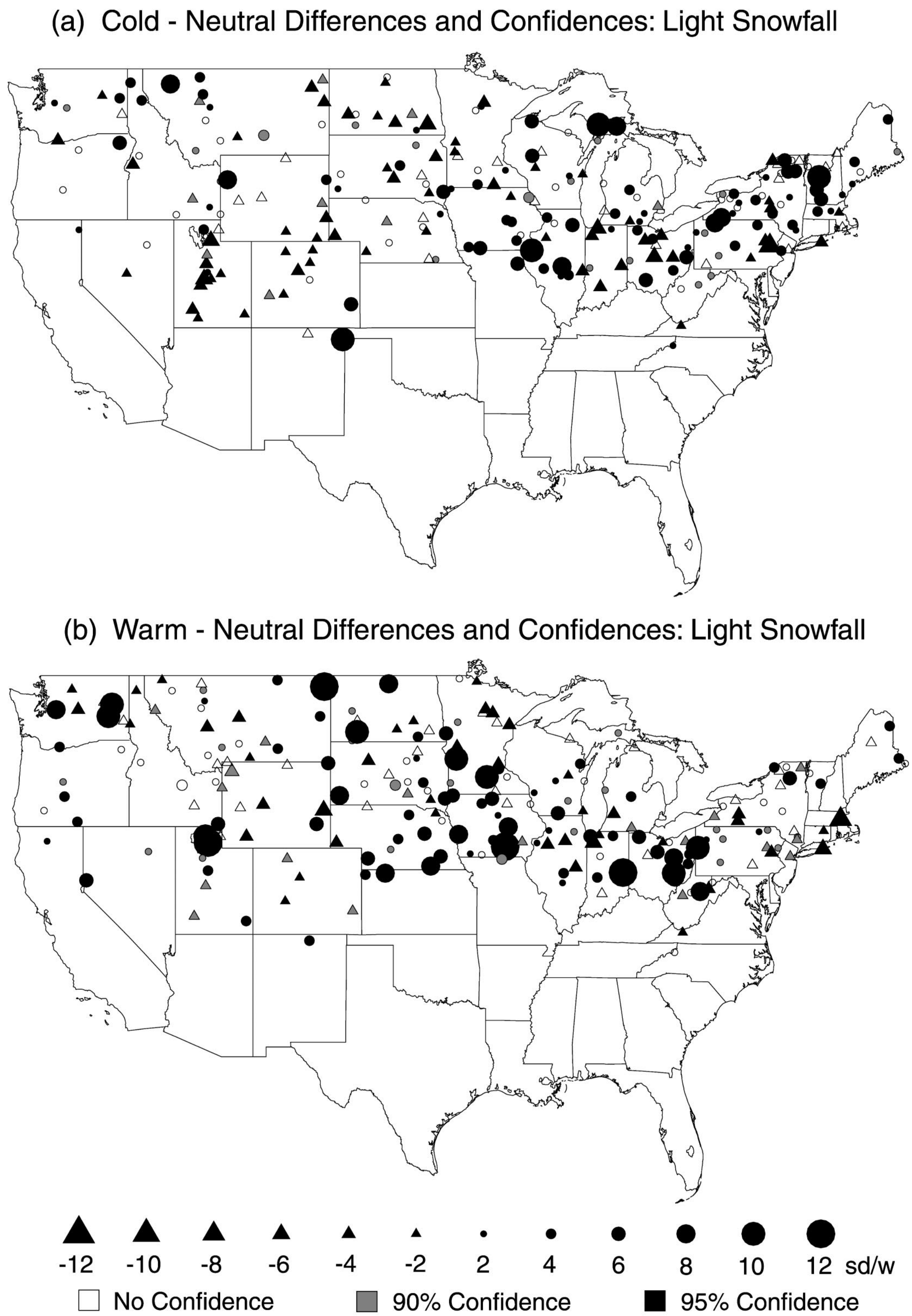

FIG. 4. Difference in the number of light snow days per winter (sd/w) for (a) cold and (b) warm ENSO phases relative to neutral-phase winters. The size of the symbol (triangles for less snowfall, circles for more) shows the magnitude of the difference between phases (sd/w). Symbols are labeled with the minimum value for each bin. Confidence levels for stations at which extreme- vs neutral-phase snowfall frequencies are rejected as being equivalent are identified by shading according to the legend.

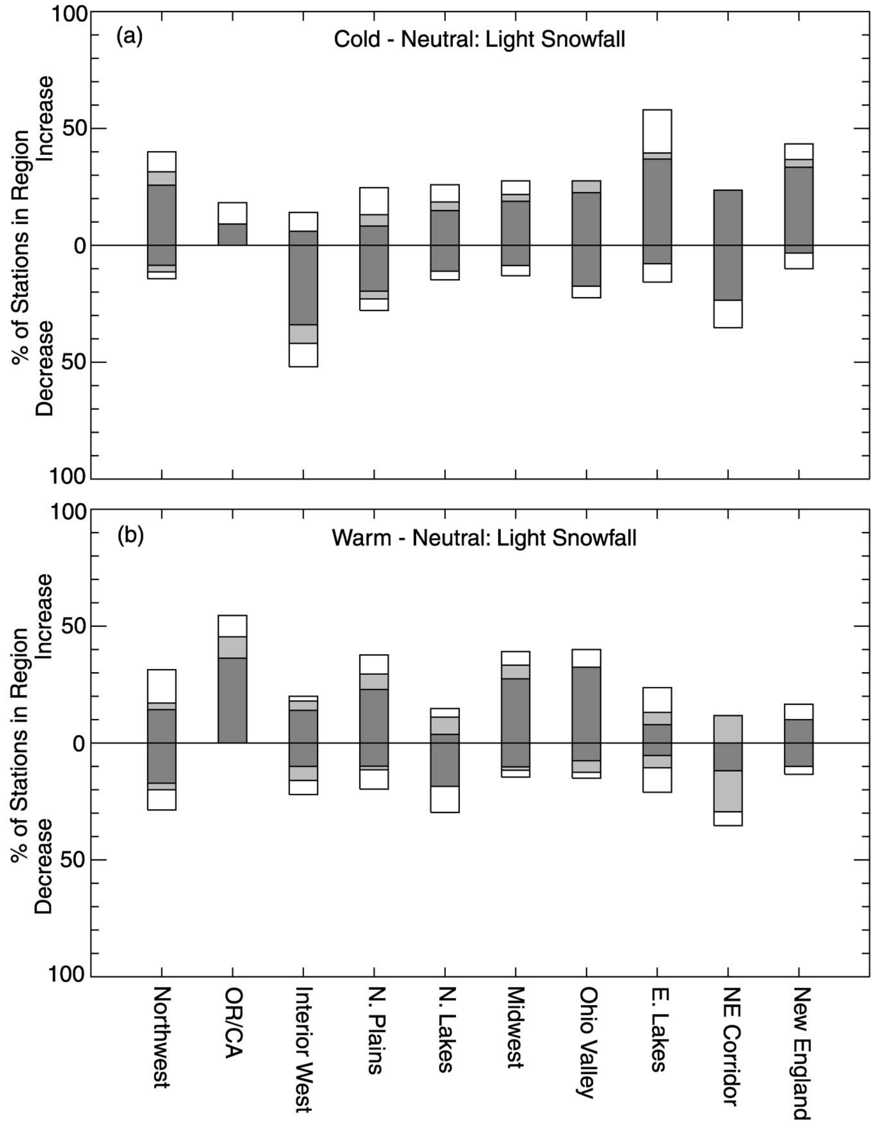

FIG. 5. Percentage of stations, within each of the 10 geographic regions, that show increases $\geq$2 sd/w or decreases ≤ -2 sd/w for light snowfall during (a) cold- and (b) warm-ENSO-phase winters relative to neutral winters. Shading denotes percentage of stations for which the equivalence of the extreme- vs neutral-phase snowfall frequencies are rejected at the 95% (dark gray) and 90% (light gray) levels.

frequencies occur at over 35% of the stations in the Ohio valley, Midwest, and Northern Plains (Fig. 5b). Eighty-one of the 170 stations within these three regions have positive *z* statistics that reject (2) at the 95% level. Many of the increases range from 8 to 12 light snowfalls per winter. In a region that averages 10–30 light snowfall events per neutral winter (Fig. 2a), these increases could affect transportation activities. Southern Oregon and northern California (hereinafter OR–CA) had the largest percentage (54%) of stations with increases in light snowfalls (Fig. 5b). In this region, 45% of the stations have positive *z* statistics that reject (2) at the 95% level, and the number of events increased by two–eight per winter as compared with neutral ENSO phases. Only the Northeast Corridor experiences a notable decrease in light snowfalls during ENSO warm phases (Figs. 4b and 5b). Stations in the Northeast Corridor typically see 10–20 light snowfalls during neutral ENSO winters (Fig. 2a). The ENSO warm-phase reduction of two–six events would likely have a minimal impact on transportation in the region.

b. Moderate snow

Regional frequency patterns for moderate snowfall (50.8–152.4] mm, are dominated by increases during

ENSO cold phases relative to neutral phases. A signal of increased moderate snowfall frequency in the eastern Great Lakes and New England (Fig. 6a) shows a similar regional pattern to the signal found for light snowfall (Fig. 4a). Over 60% of the stations in the eastern Great Lakes and New England had increased moderate snowfall frequencies, and positive z statistics that reject (2) at the 95% level occur at 56 of the 68 stations in these two regions. Increases on the order of two events are common, with a peak increase of six or more moderate snow events in northern New Hampshire. Even in a region where 12 or more moderate snowfalls are typical during ENSO neutral winters (Fig. 2b), this increase should have a positive impact on the region's winter recreation industry. In contrast to New England and the eastern Great Lakes, a significant decrease in the number of moderate snowfalls occurs in the Northeast Corridor during an ENSO cold phase (Figs. 6a, 7a). In the Northeast Corridor, decreases of one–three moderate snow days occur where three–six events are common during neutral winters (Fig. 2b). Other regions with notable increases in moderate snow days include the Northwest, OR–CA, and the northern Great Lakes with increases at 60%, 36%, and 37% of the region's stations, respectively.

ENSO warm-phase winters reveal more significant decreases in moderate snow-day frequencies than occur during a cold phase. In contrast to the cold-phase results, the Northwest has a decrease in moderate snowfalls at 48% of the region's stations (Figs. 6b, 7b). One-quarter of the Northwest stations have negative z statistics that reject (2) at the 95% level, and on average two fewer moderate snow days occur relative to neutral winters. The Northwest typically has 9–12 moderate snowfalls per neutral winter (Fig. 2b), and so this decrease may not have a substantial impact on the region. Other regions that display a decreased frequency of moderate snow days include the northern Great Lakes and, similar to the light-snow pattern, the Northeast Corridor. In both of these regions, the decrease averages two–three events per winter (Fig. 6b). The decrease may not affect the residents of the northern Great Lakes where six or more moderate snows are typical in neutral winters. In contrast, a positive impact on Northeast Corridor transportation is expected because most stations in the Northeast Corridor average only three moderate snowfalls in neutral winters (Fig. 2b). Increases in moderate snowfalls are limited to OR–CA and the eastern Great Lakes, where 45% and 34% of these regions' stations record increases, respectively.

c. Heavy snow

Notable changes in the frequency of heavy snowfall, (152.4–304.8] mm, during ENSO cold phases are limited to the western and eastern edges of the United States (Fig. 8a). Both the Pacific Northwest and OR–CA exhibit an increased frequency of heavy snowfalls relative to neutral ENSO winters (Fig. 9a). In OR–CA, 63% of the stations have increases greater than 0.25 snow days per winter. Heavy snowfall is common in this mountainous region (Fig. 2c), but the additional heavy snow during ENSO cold phases could have a positive impact on water resource management. The most notable signal of a decrease in heavy snowfall during a cold phase occurs in the Northeast Corridor (Figs. 8a, 9a). In the Northeast Corridor, decreased heavy snowfall occurs at 82% of the stations, with 29% (47%) of the stations having negative z statistics that reject (2) at the 95% (90%) level. Decreases in heavy snow days also occur at 43% of the stations in New England, but the confidence in these decreases is not high (Fig. 9a). Frequency decreases in the Northeast Corridor average one heavy snow day per cold-phase winter (Fig. 8a). In a region that experiences on average one heavy snowfall during neutral winter (Fig. 2c), the savings to the transportation sector in the Northeast Corridor could be substantial.

During ENSO warm phases (Fig. 8b), an inverse of the cold-phase frequency differences occurs in the Northeast Corridor, New England, and the Northwest. Over 55% of the stations in the Northeast Corridor and New England experience an increased frequency of heavy snow days during ENSO warm phases. Confidences in these increases are not high, but the increases average from 0.5 to 1.25 heavy snow days per winter. In the Northeast Corridor, where heavy snowfall is not common (Fig. 2c), any increase in heavy snowfall could adversely affect the transportation industry. Decreased heavy snow days occur at 37% of the stations in the Northwest and 44% of the stations in the northern Great Lakes. Decreases are greater than 1.5 heavy snow days per winter at a few stations in both regions. Both the Northwest and northern Great Lakes typically have four–five heavy snow days in ENSO neutral winters (Fig. 2), and so the impact of the warm-phase reduction may be limited.

d. Summary

Regions described in the preceding sections that have notable increases and decreases in the frequency of light, moderate, and heavy snowfall during ENSO extreme phases are summarized in Table 2. The field significance of the change in each of these regions based on independent tests at each station shows higher confidence in the changes for light and moderate snowfall than for heavy snows. Only the Northwest increase during a warm phase and the Northeast Corridor decrease during a cold phase show field significance in the heavy snowfall category. The fact that fewer regions show field significance for heavy snowfall may be related to the smaller sample sizes for heavy snow days.

Only the Northwest during a cold phase experiences an increase in snowfall frequency in each of the three snowfall categories. The warm phase results in a shift

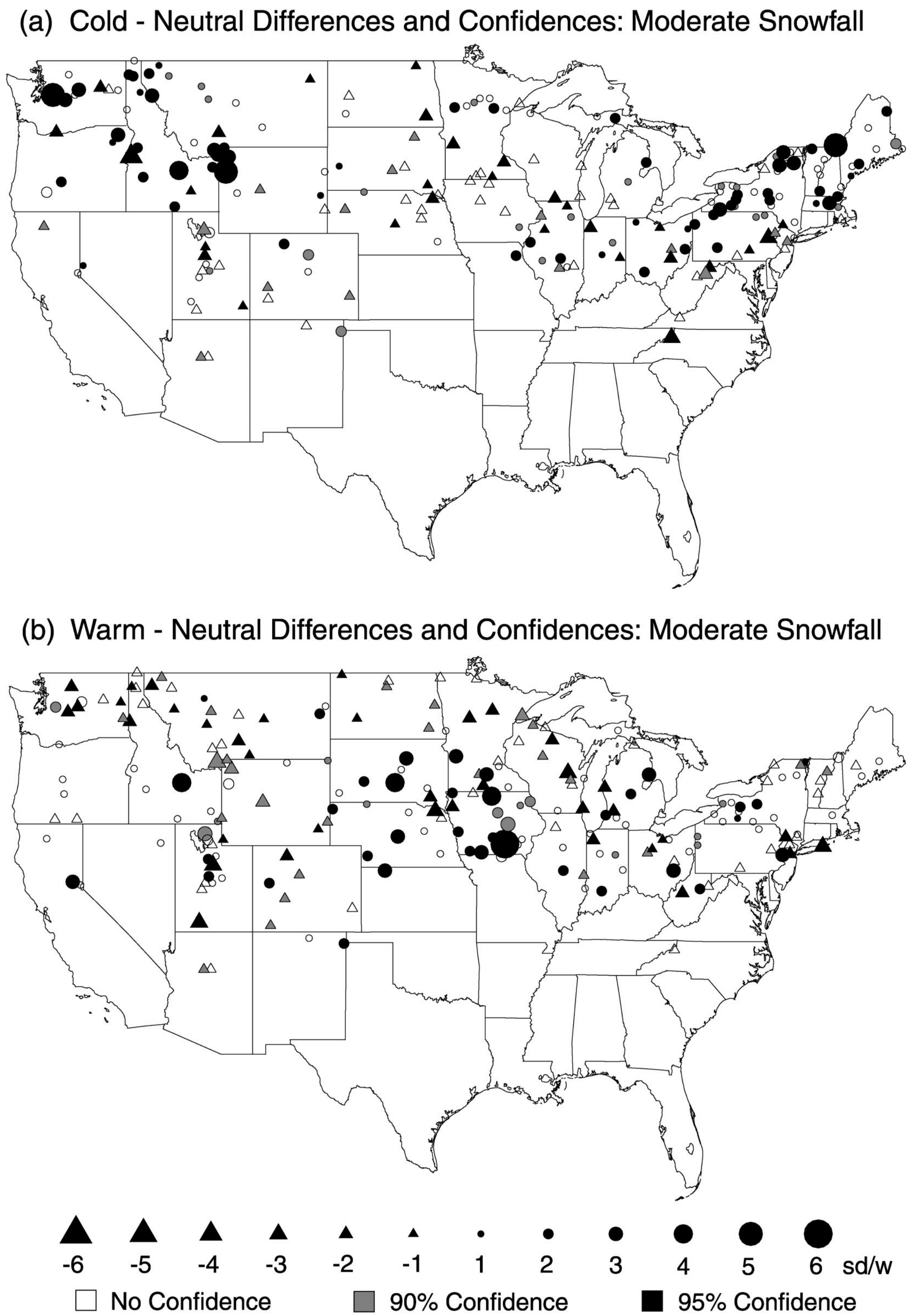

FIG. 6. Same as in Fig. 4, but for moderate snowfall.

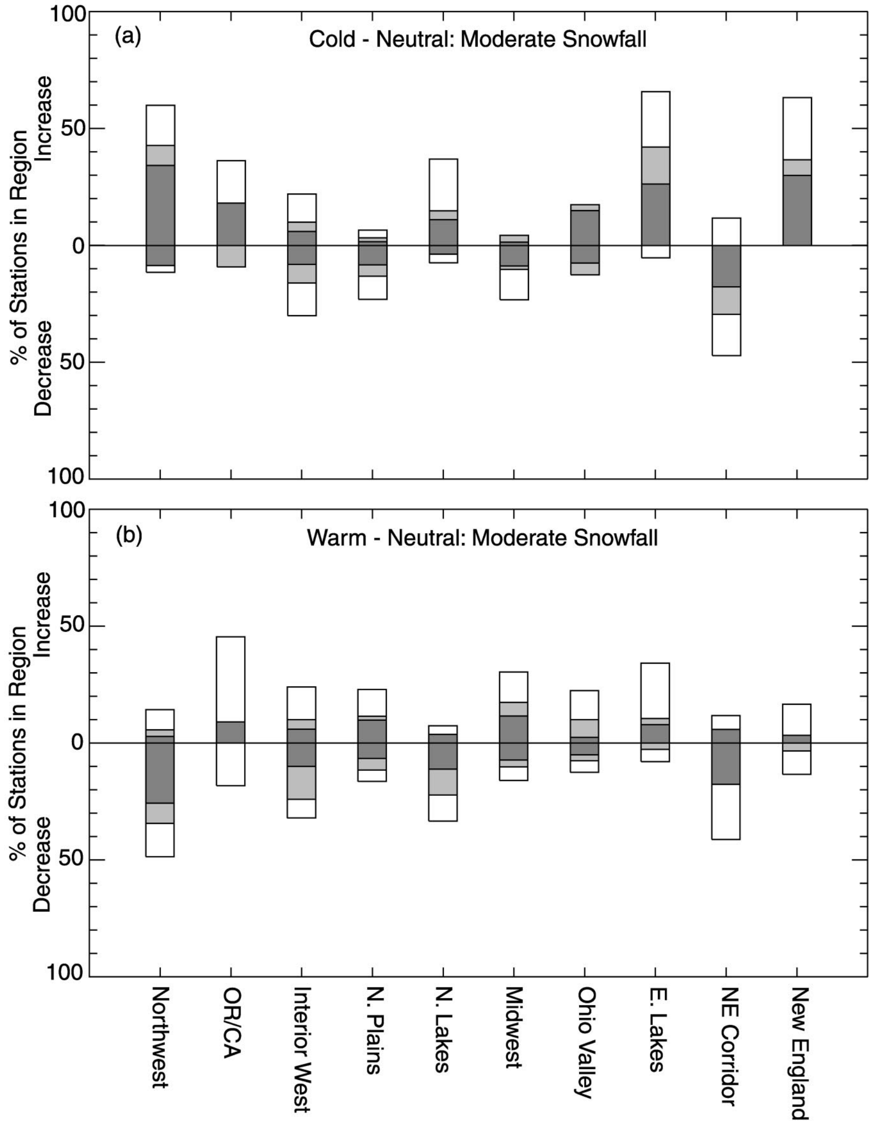

FIG. 7. Percentage of stations, within each of the 10 geographic regions, that show increases ≥1 sd/w or decreases ≤−1 sd/w for moderate snowfall during (a) cold- and (b) warm-ENSO-phase winters relative to neutral winters. Shading denotes percentage of stations for which the equivalence of the extreme- vs neutral-phase snowfall frequencies are rejected at the 95% (dark gray) and 90% (light gray) levels.

to less moderate and heavy snow days in the Northwest, but not for light snows. No regions show a decreased number of snow days in all categories during either ENSO extreme phase.

Several regions have ENSO extreme phases that are associated with increases in some snowfall categories and decreases in other categories. For example, New England experiences an increased frequency of light and moderate snowfalls but a decrease in heavy snowfalls during cold-phase winters. Only one region, the Northeast Corridor during a warm phase, has a decrease in light and moderate events followed by an increase in heavy snowfalls (Table 2).

The results of the frequency analysis (Table 2) also reveal both symmetric and asymmetric responses in regional snowfall frequencies when comparing warm versus cold ENSO phases. A symmetric response is defined as one ENSO extreme phase being associated with an increase in snow days while the opposite ENSO extreme phase is associated with a decrease in snow days. Symmetric cold- and warm-phase responses occur for heavy snow in the Northwest, Northeast Corridor, and New England and for moderate snow in the Northwest and northern Great Lakes. Asymmetric responses, in which an increase (decrease) is noted for both extreme phases, are revealed in OR–CA and the eastern Great Lakes

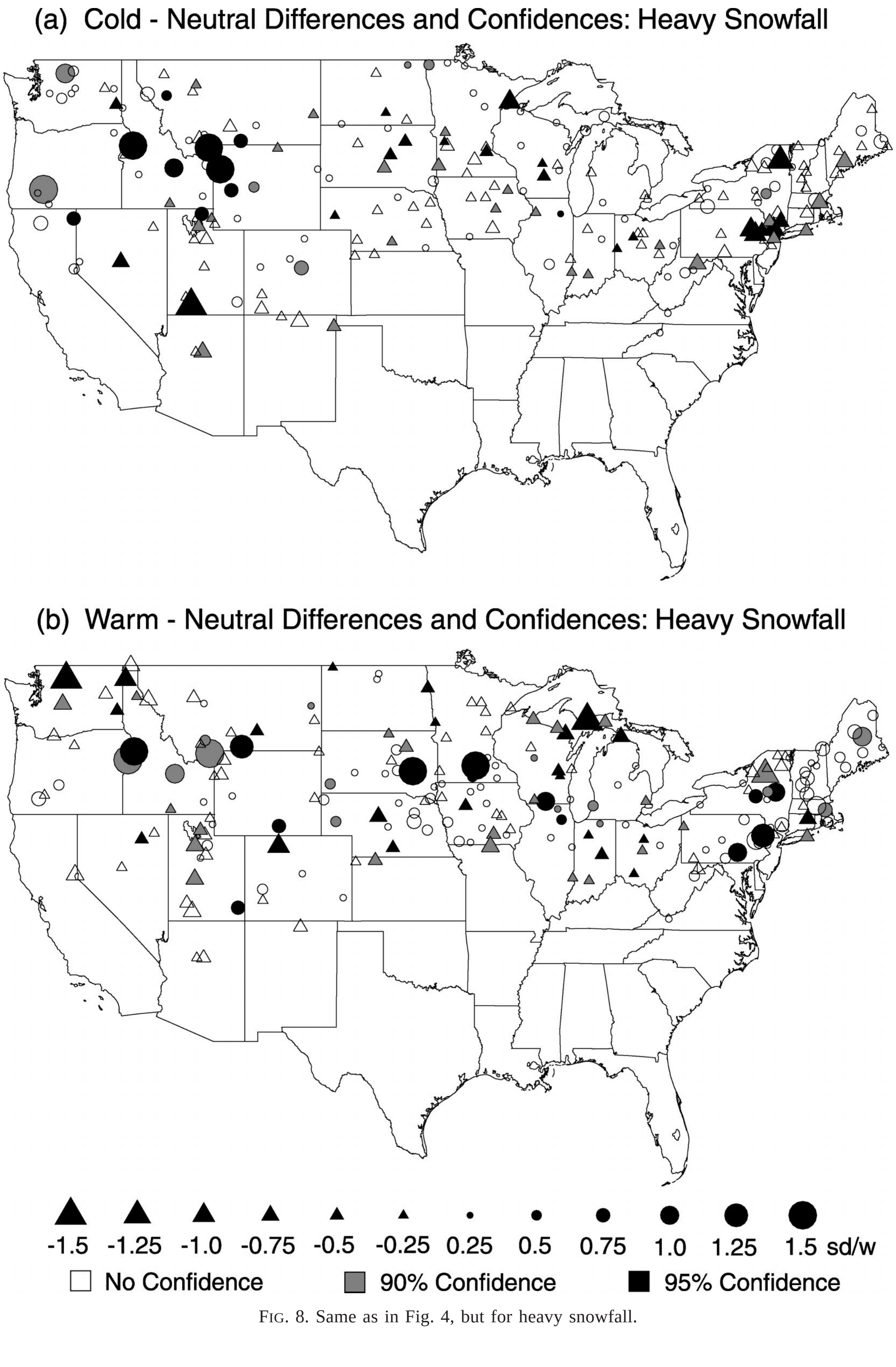

FIG. 8. Same as in Fig. 4, but for heavy snowfall.

TABLE 2. Summary of regions with ENSO extreme-phase increases (I) or decreases (D) relative to neutral winters. Marked regions have 33% or more of the stations within the region with increases ≥2 (1, 0.25) or decreases ≤−2 (−1, −0.25) in snow days per winter for light (moderate, heavy) snowfalls. Increases and decreases marked in boldface signify field significance of independent tests (Wilks 1995).

	Light snow		Moderate snow		Heavy snow	
Region	Cold	Warm	Cold	Warm	Cold	Warm
Northwest	**I**		**I**	**D**	I	**D**
OR–CA		**I**	**I**	I	I	
Interior West	**D**					
Northern Plains		**I**				
Northern Great Lakes			**I**	**D**		D
Midwest		**I**				
Ohio valley		**I**				
Eastern Great Lakes	**I**		**I**	**I**		
Northeast Corridor		D	**D**	**D**	**D**	I
New England	**I**		**I**		D	I

(Northeast Corridor) for moderate snowfalls. Similar asymmetric ENSO associations have been identified by SAO and Hoerling et al. (1997).

It is clear that significant changes in the frequency of snowfall events occur during ENSO extreme phases over the continental United States. The pattern of the significant changes varies by ENSO phase and snowfall category (Table 2). In the following section, these shifts in snowfall frequency are compared with past research on total snowfall accumulations during ENSO years.

5. Discussion

Numerous studies (e.g., Mason and Goddard 2001; Ropelewski and Halpert 1996; Yarnal and Diaz 1986) have defined relationships between ENSO phase and total winter precipitation, but only recently has the focus turned specifically to snowfall. Janowiak and Bell (1998) and Kunkel and Angel (1999) both evaluated ENSO associations with total wintertime snowfall. SAO more recently evaluated shifts in the total seasonal snowfall quartiles during ENSO extreme phases at first-order weather stations. In contrast, Clark et al. (2001) focused on ENSO impacts on snowfall in the montane western United States using snow water equivalent (SWE) measurements. These studies all documented changes in measures of total snow accumulation. Because some stakeholders need additional information on the frequency of snowfall events, the current snowfall frequency results now are compared with these past works on total snowfall.

A one-to-one comparison of the snowfall frequency results with the past snow total analyses is difficult because of the different time periods evaluated. Herein, snowfall frequencies are evaluated for a 5-month cold season, November–March. This time period is most similar to the winter totals studied by Janowiak and Bell (1998). SAO evaluated total snowfall over 3-month seasons, early, middle, and late winter. The lack of seasonal differentiation in the current study makes comparison with SAO difficult. The authors acknowledge that using snow-day totals over the whole winter may smooth out some seasonal variations caused by ENSO. The SWE study of Clark et al. (2001) was limited to the latter cold-season months of January–May. Comparisons are made primarily to Janowiak and Bell (1998), SAO's midwinter (December–February), and the January–March results from Clark et al. (2001).

SAO noted an increase (decrease) in total snowfall in the Pacific Northwest and northern Rockies during ENSO cold (warm) phases. Clark et al. (2001) found a similar relationship in SWE in the Columbia River basin, but they noted that the warm-phase decrease in SWE was less robust than the cold-phase increase. Janowiak and Bell (1998) also noted a cold-phase increase in the Northwest's total snow and found no decrease during the ENSO warm phase. With the exception of light-snow frequency in a warm phase, the authors found a corresponding frequency increase (decrease) in all snowfall categories during ENSO cold (warm) phases (Table 2). This result implies that a direct relationship exists between an increase (decrease) in the number of snowfall events in ENSO cold (warm) phases and the total amount of snowfall received in the Northwest. The change in snow-event frequency and total snowfall may be related to changes in winter jet-stream patterns (Smith et al. 1998) and the number and strength of storms that affect the Northwest.

Another region where several past studies agree with the current frequency findings is over the northern Great Lakes. Janowiak and Bell (1998) noted decreases in total snowfall over the Great Lakes during ENSO warm phases and increased total snowfall over Minnesota during the cold-phase winters. SAO found a similar decrease (increase) over the northern Great Lakes during the late winter of ENSO warm (cold) phases. The current frequency analysis only identifies field-significant decreases (increases) in the moderate snowfall category during ENSO warm (cold) phases; however, general decreases (increases) in light and heavy snow are shown in Figs. 5 and 9, respectively.

One region of disagreement between the past snow total studies and the current frequency analysis occurs in the interior West. The only significant decrease in

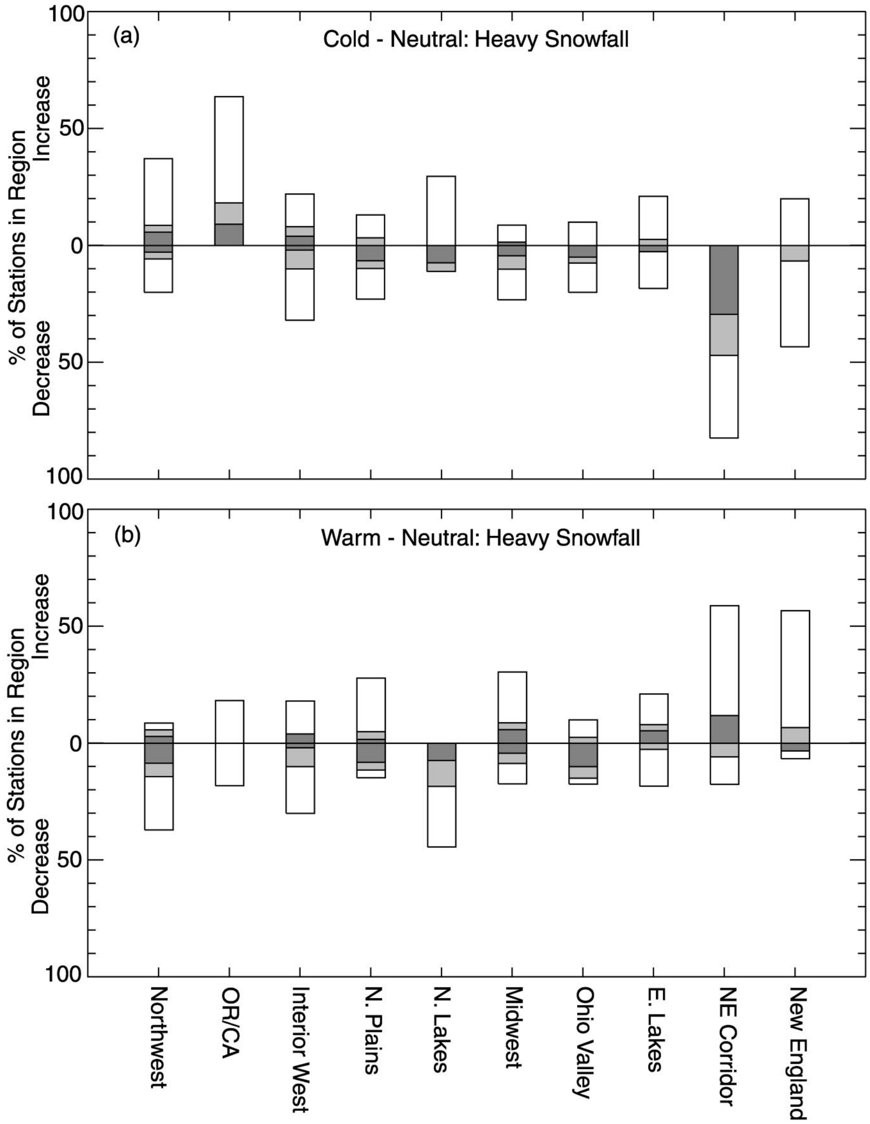

FIG. 9. Percentage of stations, within each of the 10 geographic regions, that show increases ≥0.25 sd/w or decreases ≤−0.25 sd/w for heavy snowfall during (a) cold- and (b) warm-ENSO-phase winters relative to neutral winters. Shading denotes percentage of stations for which the equivalence of the extreme- vs neutral-phase snowfall frequencies are rejected at the 95% (dark gray) and 90% (light gray) levels.

snowfall frequency occurs for light snowfall during ENSO cold phases (Fig. 5a; Table 2). No significant snowfall frequency signal was found in the interior West during a warm phase. SAO showed no shift in snow totals during their midwinter, but they did note an increase in early winter total snowfall in the Great Basin during both ENSO extreme phases. Janowiak and Bell showed an increase in snow total near the Four Corners area during ENSO warm phases. Clark et al. (2001) find decreased (increased) SWE during the cold (warm) phase in the southern Colorado River basin; however, these results were not consistent throughout the interior West. The disagreement among the results from several authors shows the complexity of studying snowfall in the mountainous terrain of the West. Several factors, including the number, elevation, and exposure (west slope vs east slope) of stations chosen for any ENSO analysis will affect the results in this region. In addition, ENSO variations may occur on shorter timescales in the interior West, and these signals may be averaged out when looking at a 5-month winter.

For the northeastern United States, the relationship between total snowfall and snowfall frequency becomes more complicated. During the cold ENSO phase, an increase (decrease) in light and moderate (heavy) snowfall frequency is found in New England. Increased light and moderate snow frequencies are also noted in the eastern Great Lakes (Table 2). In the Northeast Corridor, the frequency analysis reveals a significant decrease in moderate and heavy snowfalls. In summary, the cold phase in the Northeast is associated with increased (decreased) snowfall frequency inland (near the coast). SAO found an increase in total snowfall during cold-phase winters in a region stretching from New Hampshire to Virginia, with the majority of SAO's stations being located inland from the coast. During the warm phase, SAO found a decrease in total snow in the same region. Field-significant decreases in snowfall frequencies are not found inland during a warm phase. On the contrary, increased moderate snows are found in the eastern Great Lakes (Table 2). Janowiak and Bell found no notable signals in wintertime total snowfall in the Northeast.

The variation in snowfall frequencies associated with ENSO from the coast to inland areas may be related to the complex nature of winter precipitation in the Northeast. Winter precipitation in this region is strongly influenced by coastal cyclones. Subtle changes in the intensity and track of these coastal storms can greatly change the amount and type of winter precipitation over the Northeast. Hirsch et al. (2001) studied the occurrence of East Coast winter storms (ECWS) and found "on average, El Niño winters (December–February) were associated with over 44% more East Coast storms than ENSO neutral winters." In theory, when ECWS track close to the coast, warmer conditions and less snowfall (e.g., light and moderate categories for the Northeast Corridor) will occur near the coast and an increased snowfall will occur inland (e.g., moderate snow in the eastern Great Lakes). If the ECWS track farther offshore, the increase may occur nearer to the coast (e.g., Northeast Corridor heavy snow). Hirsch et al. (2001) also found that cold-phase ECWS track from west to east and farther north than occurs during ENSO warm phases. The cold phase is also associated with a prominent polar jet over the eastern United States (Smith et al. 1998). In theory, cold air north of the polar jet and a west-to-east cyclone track may result in more frequent light and moderate snow on the north side of the cyclones (in the eastern Great Lakes and New England). Less moderate and heavy snow may occur in the Northeast Corridor during the cold phase because the region would be in the warmer inflow region of the more northerly storm track. The reduction in heavy snows in New England during a cold phase may be the result of the cyclones being drier, faster-moving (e. g., Alberta clipper type) systems.

It is clear that no single atmospheric factor regulates the frequency of light, moderate, and heavy snows. These hypotheses only consider some synoptic–dynamic factors and do not consider the role of the Great Lakes, topographic features, or variations in surface and upper-level thermal structure. Future work will be needed to investigate the relationship among the ENSO extreme-phase frequency differences, total snowfall patterns, and atmospheric dynamics.

6. Conclusions

Changes in ENSO extreme-phase frequency of light, moderate, and heavy snowfall are identified for the continental United States. Significant differences between neutral- and extreme-phase ENSO winters are tabulated for 10 regions of the continental United States. Simple field-significance tests identify regions with increased or decreased snow days in each snowfall category.

Principal results are summarized in Table 2. As an example, increased (decreased) snowfall frequencies are identified in the Northwest during the cold (warm) ENSO phase. The results in the Pacific Northwest are expected in light of past snowfall studies (SAO; Clark et al. 2001; Janowiak and Bell 1998). Increased light and moderate snowfall frequencies are also noted in the OR–CA region during a warm phase, which contrasts with the larger-scale pattern in the Pacific Northwest. Other regions with significant snowfall frequency changes associated with ENSO include the northern and eastern Great Lakes, the Northeast Corridor, and New England.

Apparent relationships among total snowfall, snowfall frequency, and ENSO have been identified through our research and past studies (e.g., SAO; Clark et al. 2001; Janowiak and Bell 1998), although regional differences occur in the results. It is important to note that all of these studies focus only on ENSO, one major interannual influence on climate. Other climate oscillations that operate on interannual to decadal timescales (e.g., Pacific decadal oscillation, North Atlantic Oscillation, and Arctic Oscillation) have been shown to influence wintertime precipitation (Bove 2000) and circulation (Hurrell 1996; Gershunov and Barnett 1998) patterns. The role of these interdecadal climate oscillations in seasonal snowfall and snow-event frequency needs additional study.

Understanding the potential shifts in snowfall frequency during ENSO extreme phases may allow government and private agencies to mitigate adverse impacts of winter storms. Winter entertainment facilities may actually benefit from these results. For example, ski resorts in New England and the northern Great Lakes may expect good ski conditions during ENSO cold phases, with more natural snow and lower costs for artificial snowmaking. For the transportation sector, knowing that an increased number of heavy snowfalls are expected in lieu of light snowfalls during the ENSO warm phase in the Northeast Corridor may change budgeting priorities for warm-phase winters. Combined with the findings of other winter precipitation studies, the ever-improving ability to forecast the phase of ENSO and the current snow-frequency study should lead to improved seasonal snowfall forecasts.

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