Calculation and evaluation of an air-freezing index for the 1981-2010 climate normals period in the coterminous United States

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ABSTRACT

Air-Freezing Index (AFI) is a common metric for determining the freezing severity of the winter season and estimating frost depth for mid-latitude regions, which is useful for determining the depth of shallow foundation construction. AFI values represent the seasonal magnitude and duration of below freezing air temperature. Departures of the daily mean temperature above or below 0°C (32°F) are accumulated over each August—July cold season; the seasonal AFI value is defined as the difference between the highest and lowest inflection points. Return periods are computed using generalized extreme value distribution analysis. This research replaces the methodology used by the National Oceanic and Atmospheric Association (NOAA) to calculate AFI return periods for the 1951-1980 time period, applying the new methodology to the 1981-2010 climate normals period. Seasonal AFI values and return period values were calculated for 5600 stations across the coterminous United States (CONUS), and the results were validated using United States Climate Reference Network temperature data. Return period values are typically 14-18% lower across CONUS during 1981-2010 versus a re-computation of 1951-1980 return periods with the new methodology. For the 100-year (2-year) return periods, about 59% (83%) of stations show a decrease of more than 10% in the more recent period, whereas 21% (2%) show an increase of more than 10%, indicating a net reduction in winter severity consistent with observed climate change.

1. Introduction

Recent climate studies have documented an increase in global and regional surface temperatures, with the greatest shift in warming occurring over the last three decades (Solomon et al. 2007). In the United States the increase in warming has corresponded with an increase in growing season, defined as the number of days between the last spring and first fall frost (Kunkel et al. 2004). Easterling et al. (2000) showed that the number of subfreezing days between 1910 and 1998 has decreased by four days per year in the United States, while other studies have found that the greatest decrease has occurred in the western United States (Easterling 2002; Kunkel et al. 2004). Air temperature has a well-known correlation with soil temperature and soil frost (Brown 1964); the increases seen in air temperature should be associated with a corresponding change in soil frost depth.

As long-term networks that monitor deep soil temperature are sparse and recent (Schaefer et al., 2007; Bell et al., 2013), proxy measurements of soil temperature using air temperature are necessary until adequate soil temperature data can accumulate from existing networks. Early field studies showed that the severity of air freezing has a direct correlation to soil frost depth (Brown 1964). Steurer (1989) used the 100-year return of the air-freezing index (AFI), a measure of magnitude and duration of air temperature below freezing, as a determinant of the maximum soil frost depth. Later work found that this method works best for mid-latitude regions that do not experience severe, prolonged winters (Steurer et al. 1995).

Research has shown that up to one-third of the United Stations gross domestic product (GDP) is reliant on accurate weather and climate information (Dutton 2002). Frost depth, which can be estimated with AFI, and soil temperature are important factors in construction cost and building foundations. Severity of soil frost is responsible for frost heave, a naturally occurring process that causes soils to produce an outwardly exerting force on a belowground structure (Jones et al. 1982). An accurate estimate of frost depth allows for reduced construction cost and proper preparation for future climate conditions. Trenberth et al. (2008) report that the American Home Builders Association saved the American public an estimated $300 million per year by generating new building and foundation standards that were based on the AFI research completed by Steurer and Crandell (1995).

Steurer and Crandell (1995) computed AFI and frost depth estimates that were constructed using a 30-year serially-complete dataset from 1951-1980. However, CONUS-wide average temperatures from the Climate-at-a-Glance tool (Lawrimore et al., 2007; Vose et al., 2014) show that 19 (2) of the 30 warmest years from 1895 to 2010 have occurred in the 1981-2010 (1951-1980) period. Even when statistical uncertainty is factored in (Guttorp and Kim 2013), it is clear that 1981-2010 was warmer than 1951-1980, requiring an upgraded analysis of seasonal AFI return periods.

2. Data and Methodology

NOAA's National Climatic Data Center (NCDC) is responsible for archiving U.S. and global climate records and for providing climate datasets and products. This study utilizes the same serially-complete dataset of daily maximum and minimum temperatures that were utilized to calculate NOAA's 1981-2010 frost-freeze and growing degree day normals (Arguez 2012). This serially complete dataset was produced using observations from the Global Historical Climatology Network – Daily database (Menne et al. 2012) in a manner consistent with the computation of NOAA's 1981-2010 temperature normals (Arguez et al. 2012; Arguez and Applequist 2013). A total of 5,600 stations (see Fig. 1) across the U.S. are utilized, with each daily time series covering the 1951-2010 time period. All of these stations are part of the National Weather Service's Cooperative Observer Program (COOP).

AFI values were calculated from the daily maximum and minimum temperatures for each station in the study. Departures of the daily mean temperature above or below 0°C (the index is derived using Fahrenheit air temperatures) were accumulated and can be plotted on a seasonal time curve (Steurer et al., 1995). These daily departures are commonly referred to as freezing degree days (FDDs). The cumulative seasonal FDDs totals were calculated at each station by:

Equation 1:

$$S_i = \Sigma_{i=1}^{\mathrm{N}} (T_{ave_i} - 32°\mathrm{F})$$

where, S_i is the cumulative total of degree days during the season;

T_{ave_i} is the average of the daily maximum and daily minimum temperature for a day i;

N is the number of days in a season (August 1st - July 31st).

The difference between the highest and lowest inflection points on this seasonal curve is defined as the seasonal AFI value (see Fig. 2). For example, the most extreme AFI value for the Asheville Regional Airport over the 1951-2010 period occurred during the 1976-1977 season with a AFI value of 292 FDDs. This value comes from the difference between the highest (3,034 FDDs) and lowest (2,742 FDDs) inflection point for that station's season. The August 1 to July 31 definition of the cold season, which is supported by inspecting the annual progression of T_{ave} observations for all CONUS stations, follows NCDC precedent for calculating frost-freeze normals.

Using Generalized Extreme Value (GEV) probability distribution, return periods were calculated for each station using its respective seasonal AFI values separately for 1981-2010 and 1951-1980. Return period estimates are only computed if at least 15 of the 29 seasonal AFI values are non-zero; this precludes the computation of return periods for ~10% of stations (indicated by red circles in Figure 1). The results from the GEV distribution were used to generate maximum AFI estimates for the 1.1, 1.25, 2, 2.5, 3.3, 5, 10, 20, 25, 50, and 100-year return periods. A simple χ^2 goodness of fit test was utilized to identify inferior fits of the GEV model; in these limited cases, return periods were estimated using an empirical, non-parametric approximation. The return periods were interpolated using Inverse Distance

Weighting (IDW). The depth of frost penetration was estimated for the 1981-2010 period using the 100-year return AFI values and Brown's (1964) relationship between air temperature and depth of frost penetration:

Equation 2:

$$d_{frost} = 0.0174(AFI_{100})^{0.67}$$

where, d_{frost} = the depth of frost for uncovered surface (in meters)

AFI_{100} = 100-year return AFI (°C)

Frost depth estimates were calculated for the 1981-2010 period to provide an example of how AFI can be used to estimate the depth of frost penetration.

Time series of CONUS and regional AFI over the full 1951-2010 time span were calculated via simple arithmetic averaging across the 5600 COOP stations. Regions are defined by the nine U.S. Climate Regions developed by Karl and Koss (1984). Linear regression analysis was performed on the yearly average CONUS AFI values as well as for individual climate regions.

To provide confirmation of the results and reassurance of the data used in this study, we compare our T_{ave} dataset of 5600 COOP stations with that of the United States Climate Reference Network (USCRN). USCRN stands as the premier surface observing network in the country and is specifically designed to observe climate (Diamond et al. 2013). Although USCRN stations are limited to a relatively recent period of record (the first stations were installed in 2000), Menne et al.

(2010) reported that the USCRN stations have been successful in detecting the national climate signal.

The USCRN project offers 114 high quality stations located across the CONUS. Each station is fully-equipped with three 5-minute temperature and three precipitation measurements sensors, as well as hourly solar radiation, 1.5 meter wind speed, relative humidity, ground surface temperature, and soil moisture and soil temperature sensors (if feasible). USCRN air temperature observations require triple redundancy, strong data continuity, and rigorous quality control practices. We compare the seasonal AFI values calculated from the 5,600 COOP stations used in this study with USCRN air temperature observations.

Seasonal AFI values were calculated for all 114 USCRN stations for the 2005-2010 seasons. These data were compared with corresponding AFI values from the serially-complete dataset. Comparisons between these two networks were made by matching all 114 USCRN stations with the nearest COOP station used in this study. This provided 114 paired stations to compare seasonal AFI values across the CONUS. Seasonal AFI values from 2005 to 2010 are aggregated by region to account for the short temporal overlap period of 5 cold seasons, and the coefficient of determination was calculated for these regional samples. Accounting for the effective reduction of degrees of freedom due to serial autocorrelation does not materially affect the correlation results or their interpretation.

3. Results

Seasonal AFI values across CONUS have historically ranged between 0 and 5000 FDDs. Zero values are typical for much of Florida, the Gulf Coast, and parts of Arizona, California, and coastal Oregon. The stations in these areas (denoted as red circles in Fig. 1) rarely, if ever, experience days on which the mean temperature does not reach or exceed 32°F. Thus, their cumulative FDD curves tend to increase monotonically. Not surprisingly, the highest seasonal AFI values computed for 1981-2010 are located in the northern part of CONUS stretching from the Rocky Mountains to New England. In this swath of the country, seasonal AFI values routinely exceed 1000 FDDs (Fig. 3a). The 100-year return periods (Fig. 3b) exceed 2000 FDDs in parts of the Intermountain West and the northern extents of the Great Plains, the Midwest, and New England, with the largest values (in excess of 3500 FDDs) in northern Minnesota and North Dakota. The greatest 100-year AFI return value for the 1981-2010 period was for the Hallock station in northwestern Minnesota. The 100-year return periods in the Southeastern Coastal Plain, Southern Texas, the Southwest, and along the Pacific Coast are 250 FDDs or less, highlighting how unusual it is for these areas to observe means temperatures below 32°F.

Comparing the 1981-2010 return periods with re-calculated 1951-1980 values using the same new methodology, a decrease in winter severity across much of CONUS becomes apparent. Return period values are typically 14-18% lower in the 1981-2010 period (Table 1), with a median difference (across CONUS stations for which return periods were calculated) of -66 FDDs for the 2-year return periods and -175 for the 100-year return periods. Over 58% of stations have a 100-year return period value that was at least 10% higher in the 1951-1980 period versus 1981-2010, whereas about 20% of stations show the opposite. However, care must be taken when comparing 100-year return periods from consecutive 30-year periods, as the difference is largely a function of the coldest year in each period. Differences in shorter return periods, such as the 2-year, are more in tune with observed climate change. Over 82% of stations have a 2-year return period value that decreased by more than 10% from 1951-1980 to 1981-2010, while the converse occurred for less than 2% of stations.

As stated earlier, return periods are only computed if at least 15 of the 29 seasonal AFI values are non-zero. This precluded the computation of return periods of 615 stations for 1981-2010, and 512 stations for 1951-1980. In 104 cases, we were able to compute return periods for 1951-1980 but not for 1981-2010, and the opposite was true for only one station.

A majority of the CONUS experienced a decrease in AFI across all return periods, punctuated by the changes in the 2-year return periods as depicted in Fig. 4a, which shows a decrease across the vast majority of CONUS save for small increases in northern Nevada, southwestern Oregon, and elsewhere. The most consequential decreases coincide with the areas of CONUS where winters tend to be the most severe (Fig. 3a), namely the continental regions near the Canadian border. The differences in the 100-year return periods (Fig. 4b) include increases in much of the South, Southeast, and Northwest regions, whereas the rest of the country experienced decreases, including reductions of 500 to 2500 FDDs in much of the

Great Plains and the Midwest. The Big Sandy station in north-central Montana experienced the greatest decrease in AFI (estimated frost depth, from Brown's formula) between the two periods, from 4521 FDDs (330 cm) to 2003 FDDs (191 cm), yielding a decrease in AFI (frost depth) of 2518 FDDs (139 cm). The Hill City, Idaho station experienced the greatest increase in AFI (frost depth) between the two periods, from 2299 FDDs (210 cm) to 4242 FDDs (316 cm), yielding an increase in AFI (frost depth) of 1943 FDDs (106 cm).

The 1951-2010 CONUS-averaged seasonal AFI values are shown in Fig. 5. The average value for 1981-2010 (492 FDDs) is significantly different from the 1951-2010 average (597 FDDs) at the 95% confidence level (p-value=0.00198). Linear regression analysis showed that there was a significant decreasing trend (p=0.0122, slope=-2.59 FDDs/year). An analysis of the individual climate regions found a decreasing trend in all nine climate regions (see Table 2), with trends found to be significantly different from zero at 95% confidence for the Northeast, Northern Rockies and Plains, Southwest, and Upper Midwest.

AFI values calculated for USCRN and the COOP stations match up reasonably well (see Table 3). All regions within the CONUS experienced a significant positive correlation between AFI values for COOP and USCRN stations; all coefficients of determination (r^2) exceeded 0.84 except for the Southwest region which registered ~0.65.

4. Discussion

Our results indicate that frost depth has significantly decreased across the CONUS since the 1951-1980 AFI values were reported by Steurer (1989). Similar to the previous estimates of AFI from the 1951-1980 period, the recalculated AFI values will hopefully prove beneficial in reducing U.S. construction costs (Dutton 2002) and assist in predicting possible environmental implications (Kreyling and Henry 2011). The AFI results in this study are consistent with results found in other examinations of Northern Hemisphere winter temperature trends over the past century (Easterling 2002; Kunkel et al. 2004). Other research on Northern Hemisphere climate impacts has found a reduction in mean snow cover (Dye and Tucker 2003) and a decrease in estimated frozen ground (Lemke et al. 2007). Thus, our results add to the indication that winter climate has changed over the last half-century.

Although more complex approaches can be used in determining soil frost depth with multiple meteorological measurements (DeGaetano et al. 2001), relatively good accuracy can be obtained with indices focusing on only air temperature (Gel'fan 1989; Steurer and Crandell 1995), which facilitates the computation for a larger number of stations. Early field experiments first characterized the relationship between severity of air freezing and soil freezing (Brown 1964). More in-depth studies have determined that changes in air temperature and snowfall are the two factors that are the most responsible for determining soil temperatures (Zhang et al. 2003) but recent studies have concluded that air temperature exceeds snowpack in determining soil frost depth over larger spatial areas (Zhang et al 2005). Thus, the lack of incorporating snow depth into our results will likely have some impact on the estimation of maximum penetration of frost. Using Brown's formula (Equation 2), Figure 6 displays an example of how 100-year return AFI values may be used to estimate the maximum depth of frost penetration for bare ground.

Results from the 2-year return value comparison, between 1951-1980 and 1981-2010, show that nearly all stations in all regions experienced a decrease in seasonal AFI. These results correspond with other studies that have seen an overall decrease in the number of cold days and nights across the United States (Seneviratne et al. 2012). As AFI is a measure of winter severity, the cooling trend in annual air temperature for the Southeast could possibly be explained by more severe winters as indicated in our results, although this region generally experiences minimal frost penetration, which causes even slight changes to be highly visible. It should also be noted that decreases in frost depth far exceed increases. Some caution should be used with spatially-interpolated results. The most recognized flaw to this method is that interpolation assumes the spatial area is homogeneous across the surface when in all likelihood this in not the case. Further research should address this issue and apply methods to account for heterogeneous factors (e.g. location's topography, proximity to water, coastal effects) (Daly et al. 1997; Vose et al. 2014).

Besides the previously mentioned use of AFI for accurately determining construction costs, soil frost depth has a number of ecological implications. Plant root growth and photosynthetic response can be altered by frost depth (Noshiro and Sakai 1979; Rigby and Porporato 2008). Soil microbes also have a strong relationship with soil temperature and frost depth. For example, greater microbial activity can occur with warmer winters and result in changes in biogeochemical cycling (Clein and Schimel 1995). Soil microbes are also sensitive to freezing intensity and duration (Elliott and Henry 2009). However, there is still much research to be conducted on understanding changes in soil frost depth and severity of winter on plants and ecosystems, including the establishment and persistence of invasive species (Kreyling and Henry 2011).

5. Conclusion

Our results suggest that the AFI in the United States has changed significantly since 1951. Return period values are typically 14-18% lower across CONUS during 1981-2010 versus a re-computation of 1951-1980 return periods with the new methodology. For 2-year return periods, over 80% of stations show a decrease of more than 10% in the more recent period. These results provide a recent, accurate estimate of AFI and map products that will benefit homebuilders and the construction industry with estimating costs. -More accurate estimation of changes in air freezing and frost depth will also benefit agricultural producers and ecologists in better understanding the response of ecosystems to climate change.

The USCRN provides highly accurate air temperature measurements with triplicate configuration for better precision (Diamond et al 2012). Each station is designed to fulfill data requirements necessary for climate science. Air temperature measurements cannot be directly compared between the two networks, as aspirated fans are used at the USCRN stations. Regressions were applied to compare the AFI values calculated from the serially-completed dataset used in this study with the USCRN AFI values to determine the year-to-year variation over the five-year period. The results herein provide verification that our results are consistent with USCRN's high precision measurements in stable and open environments. Menne et al. 2010 found similar results in comparing the bias-corrected U.S. Historical Climatology Network air temperature values to USCRN air temperatures. Although the shared period between the two networks is relatively short, the use of USCRN data to validate the COOP data validates the seasonal AFI values produced in this study.

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Tables

Table 1. Aggregate differences, ratios, and percent change proportions of AFI return periods calculated using 1981-2010 data versus 1951-1980 data. Median differences are reported in degrees Fahrenheit. All other values are unitless.

Return Period	Median Difference	Median Ratio	Proportion of Stations with a decrease of 10% or more	Proportion of Stations with an increase of 10% or more
2-yr	-66	0.818	0.826	0.015
2.5-yr	-69	0.839	0.769	0.024
3.3-yr	-70	0.858	0.688	0.052
5-yr	-82	0.865	0.657	0.082
10-yr	-106	0.863	0.629	0.106
20-yr	-128	0.852	0.631	0.123
25-yr	-134	0.848	0.633	0.129
50-yr	-151	0.847	0.603	0.171
100-yr	-175	0.843	0.588	0.205

Table 2. Regressions of regional averages for AFI during the 1951-2010 period of record. Bold values indicate the p-values of slopes that are statistically different than zero at the 95% confidence level.

Climate Region	Slope	R-squared	p-value
Northeast	-3.4730	0.0826	**0.027**
Southeast	-0.2944	0.0313	0.180
Ohio Valley	-1.6860	0.0250	0.232
Upper Midwest	-6.9210	0.1084	**0.011**
South	-0.4807	0.0237	0.244
Northern Rockies and Plains	-6.3740	0.0838	**0.026**
Southwest	-2.1447	0.0828	**0.027**
West	-0.3691	0.0259	0.224
Northwest	-1.3640	0.0290	0.197
CONUS	-2.5690	0.1088	**0.011**

Table 3. Coefficients of determination between AFI values for USCRN and nearest neighbor COOP stations during the 2005-2010 seasons.

Climate Region	**R-squared**	**DF**
Northeast	0.940	42
Southeast	0.953	72
Ohio Valley	0.966	44
Upper Midwest	0.946	23
South	0.987	72
Northern Rockies and Plains	0.878	76
Southwest	0.647	58
West	0.846	32
Northwest	0.975	34
CONUS	0.933	470

Figure Captions

Figure 1. Geographic distribution of the 5,600 stations used in this study. A total of 4,984 stations (in blue) have calculated return period values for both 1981-2010 and 1951-2010. The red circles indicate stations that were “too warm” to compute return period values in either or both time periods, although the seasonal AFI values are retained.

Figure 2. Freezing degree days (FDDs) for the Asheville, NC Regional Airport ASOS station over the 1976-1977 cold period. COOP ID: 310300; latitude: 35.4319°N; longitude; 82.5375°W.

Figure 3. AFI (a) 2-year and (b) 100-year return periods for the 1981-2010 time period.

Figure 4. Differences in the (a) 2-year and (b) 100-year return periods calculated using 1981-2010 data versus 1951-1980 data.

Figure 5. CONUS-averaged seasonal AFI values during the 1951-2010 period. The regression line indicates a significant decreasing trend (R-squared = 0.109, p=0.01072, slope=-2.569).

Figure 6. Maximum frost depth (100-year) estimates calculated using 1981-2010 data.

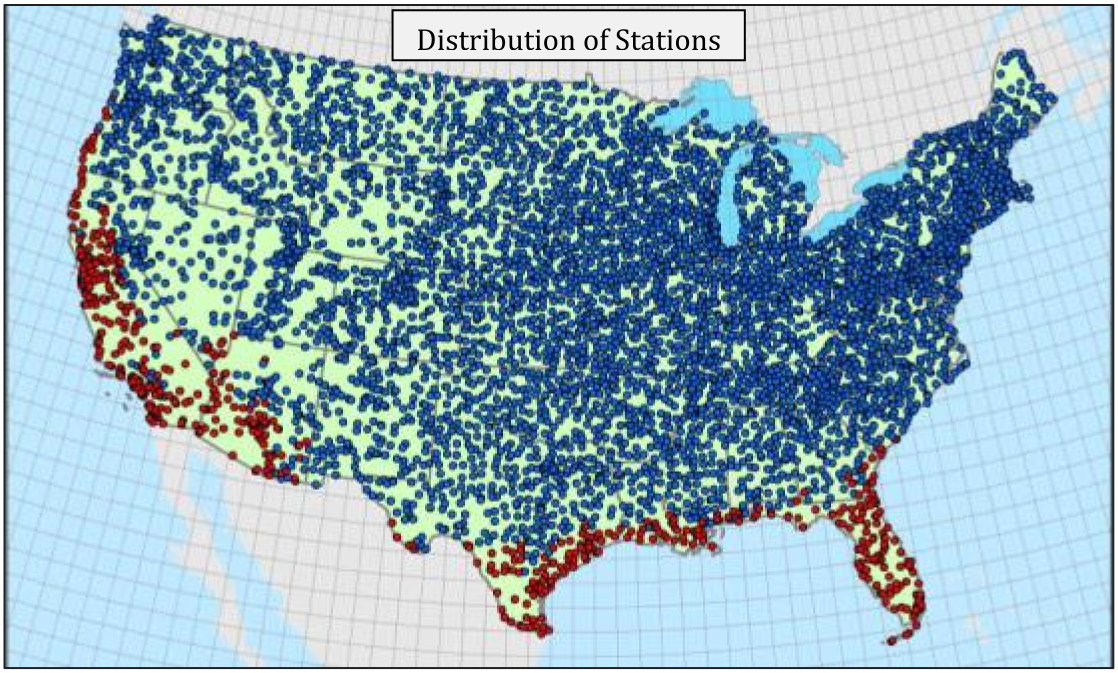

Figure 1. Geographic distribution of the 5,600 stations used in this study. A total of 4,984 stations (in blue) have calculated return period values for both 1981-2010 and 1951-2010. The red circles indicate stations that were "too warm" to compute return period values in either or both time periods, although the seasonal AFI values are retained.

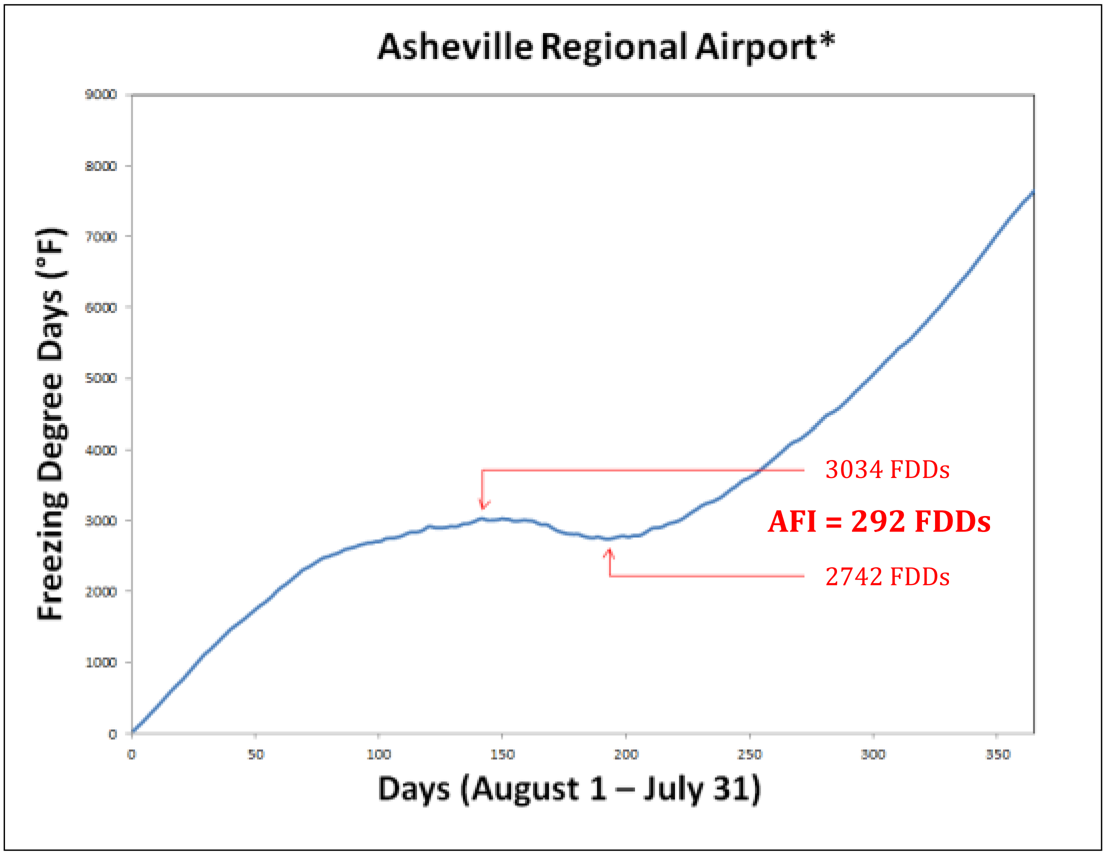

Figure 2. Freezing degree days (FDDs) for the Asheville, NC Regional Airport ASOS station over the 1976-1977 cold period. COOP ID: 310300; latitude: 35.4319°N; longitude; 82.5375°W.

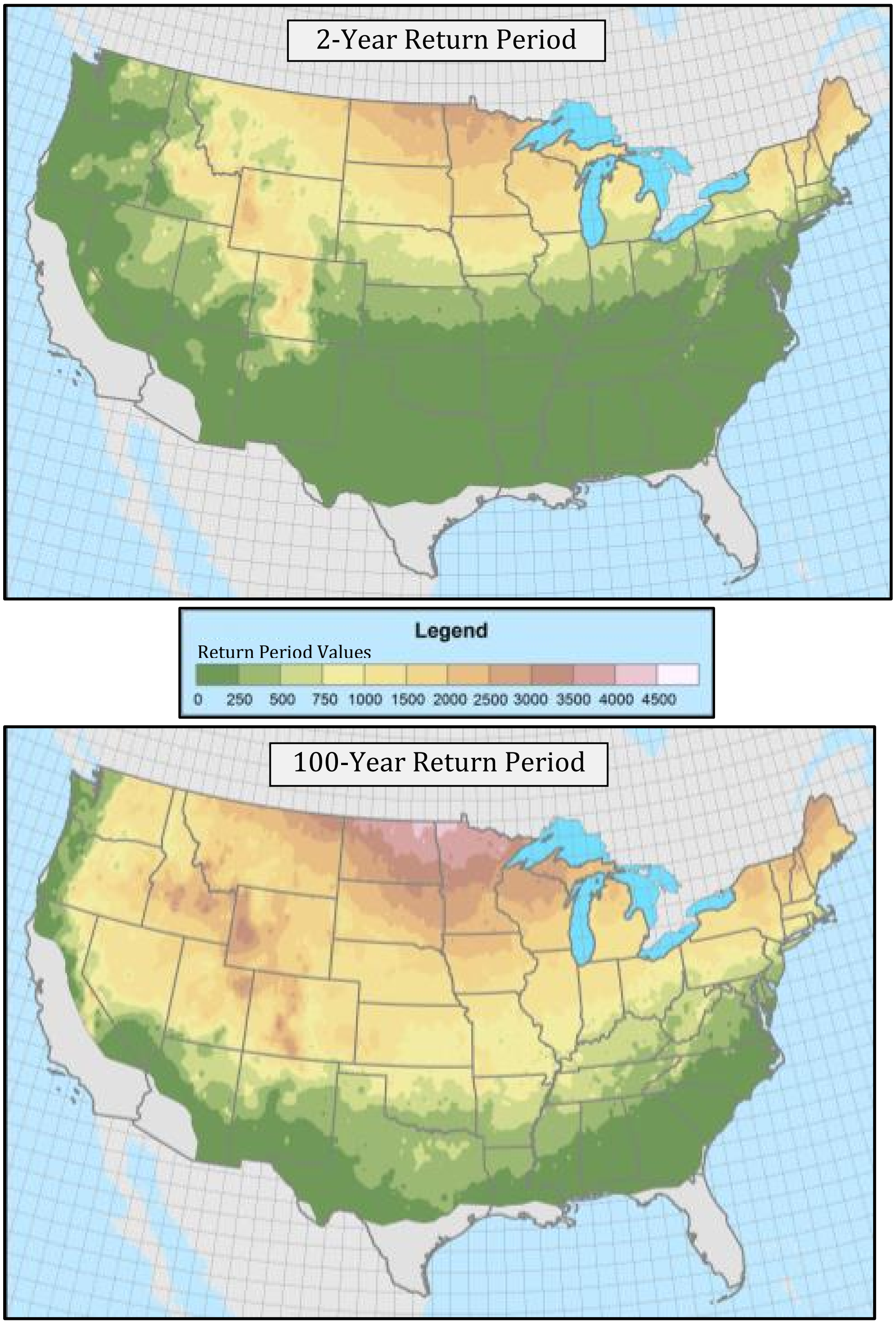

Figure 3. AFI (a) 2-year and (b) 100-year return periods for the 1981-2010 time period.

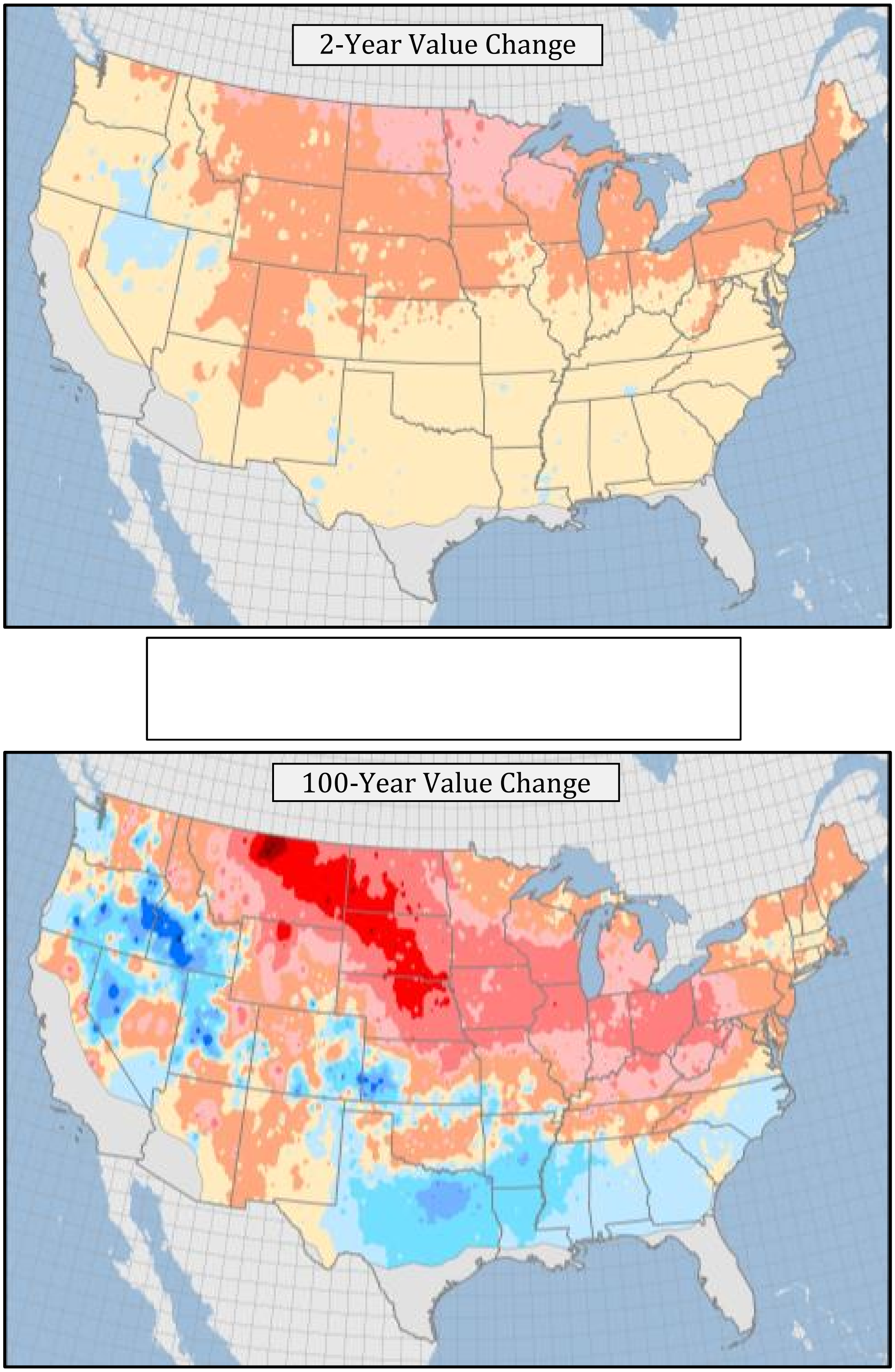

Figure 4. Differences in the (a) 2-year and (b) 100-year return periods calculated using 1981-2010 data versus 1951-1980 data.

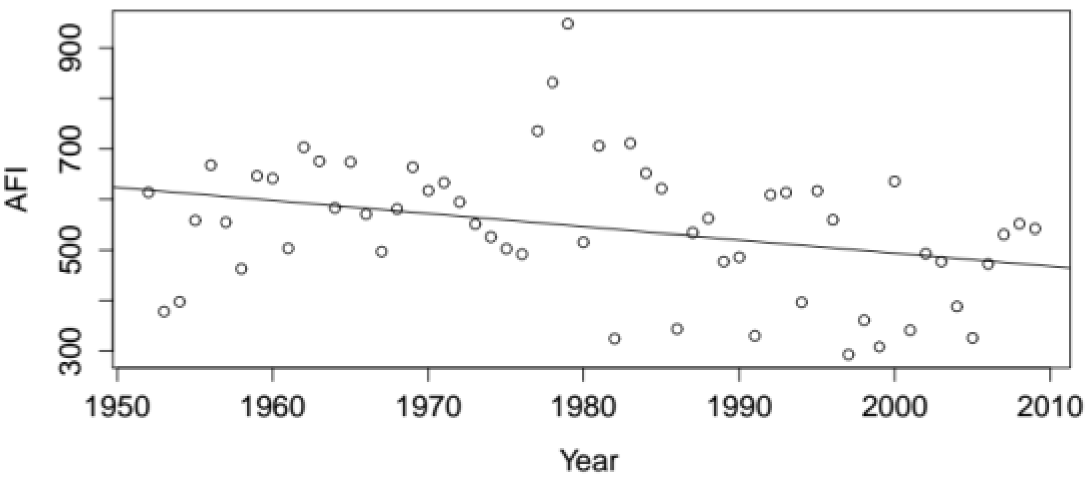

Figure 5. CONUS-averaged seasonal AFI values during the 1951-2010 period. The regression line indicates a significant decreasing trend (R-squared = 0.109, p=0.01072, slope=-2.569).

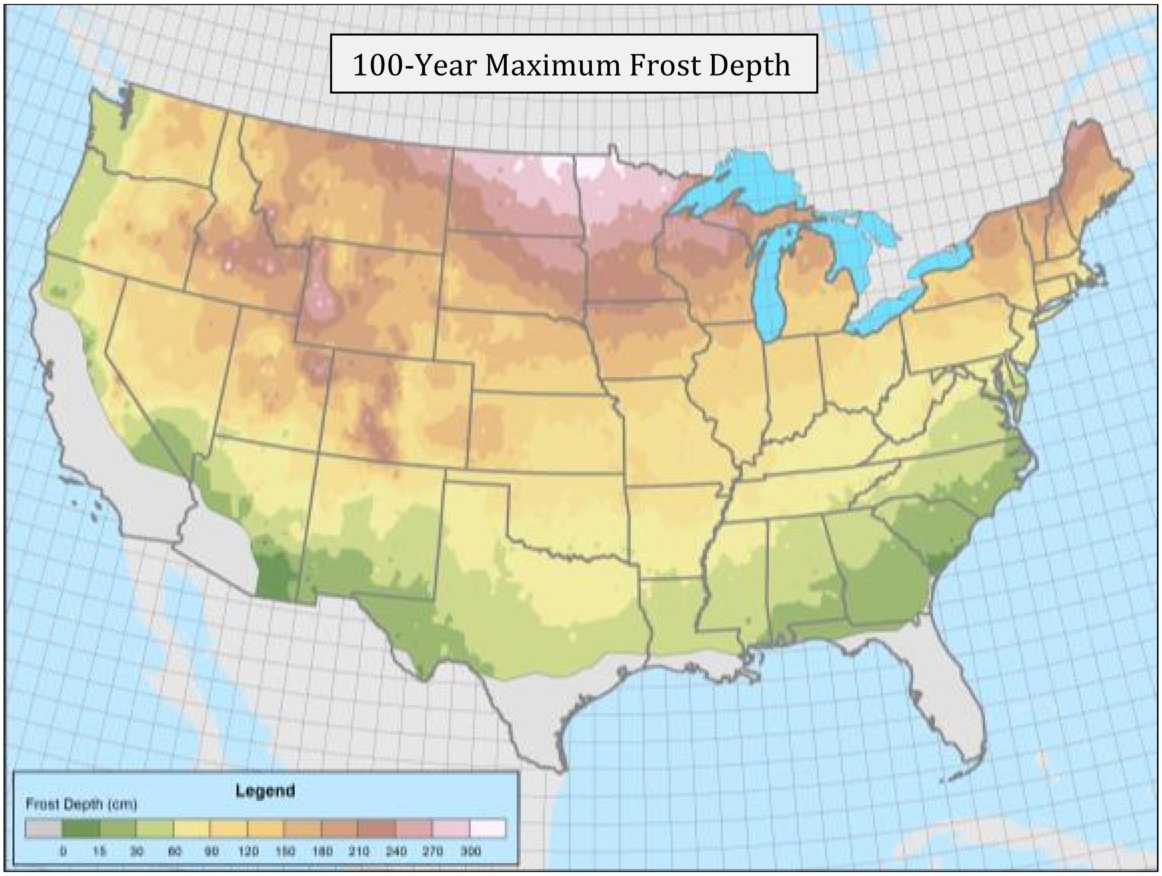

Figure 6. Maximum frost depth (100-year) estimates calculated using 1981-2010 data.