J8.4 TRENDS OF U.S. SNOWFALL AND SNOW COVER IN A WARMING WORLD, 1948-2008

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1. Introduction

The Intergovernmental Panel on Climate Change (IPCC, 2007) has described changes in temperature and cryospheric variables across the globe over the last century. Mountain glaciers, Arctic sea ice, and polar continental ice sheets are melting as global temperatures warm while satellite observations have documented the contraction of snow cover extent in North America and Eurasia. The frequency of heavy precipitation events has increased over most land areas (IPCC, 2007). Snow will continue to be significantly impacted as temperatures rise further in a greenhouse-warmed world. Additional changes in the geographical pattern of snow cover and snowfall can be expected. Snowfall is expected to decrease in some areas and increase in other areas (both in terms of amount and frequency), while snow cover is expected to continue to decrease in frequency, amount, and spatial extent, and snow season length will decrease. In recent years, the United States has experienced several major snowstorms with heavy snow, especially in the fall and winter.

This paper uses in situ observations to examine trends in snowfall and snow cover across the contiguous United States during the last half of the 20th century into the first decade of the 21st century, and to analyze the relationship between snowfall and temperature. This analysis assesses the geographic and temporal character of snowfall and snow cover changes across the U.S. in light of recent snow events.

2. Data and Methodology

Daily snowfall and snow depth data observed by the Cooperative Station Network (COOP) were analyzed because these are the only data that extend back well into the 20th century in the United States. They are widely used for snow analyses and form the basis for snow climatologies (Heim and Leffler, 1999a; NCDC, 2009a), operational snow monitoring (NCDC, 2009b), snow disaster declaration support for the Federal Emergency Management Agency (Heim and Leffler, 1999b), and calculation of operational snowfall impact scale indices (Squires and Lawrimore, 2006). Extensive quality assurance checks were applied to the daily data, including limits checks and internal consistency checks against corresponding values of precipitation and maximum and minimum temperature.

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Monthly values were computed from the daily data for the following variables:

- total snowfall (SF)
- number of days with snowfall ≥ 0.254 cm. (NDSF)
- average daily snowfall (SF / NDSF)
- number of days with snow cover (snow depth) ≥ 2.54 cm. (NDSD)
- average temperature (TAVE)
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Annual (July-June) and seasonal (winter [December-February], spring [March-May], and autumn [September-November]) values were computed from the monthly values.

Linear regression trends were computed over the period 1948-2008 for each station's SF, NDSF, SF/NDSF, and NDSD for those stations that had at least 30 years of non-missing data.

The snow-temperature analysis consisted of computing correlation coefficients between TAVE and each of the four snow variables (SF, NDSF, SF/NDSF, NDSD). Only those seasons (including annual) with snowfall or snow days > 0 were correlated against the corresponding average temperature, and each station had to have at least 30 years of non-missing data.

A further snow-temperature analysis was conducted by comparing values for warm years to values for cold years. For each season (including annual), for those years having nonzero snow data and at least 30 years of non-missing data:

1) the data were ranked in ascending order from coldest to warmest,
2) the average snow values corresponding to the five warmest years were computed (SWARM),
3) the average snow values corresponding to the five coolest years were computed (SCOLD),
4) the ratio SWARM / SCOLD was computed for each station.

The SWARM / SCOLD ratio was computed for total snowfall amount (SF) and average daily snowfall (SF/NDSF).

3. Results

3.1 Trends in Snowfall and Snow Cover for 1948-2008

Linear trends for the three seasons (autumn, winter, and spring) for the four snow variables are shown in Figures 1-4. The geographical pattern of trends for total snowfall amount in autumn reveals increasing trends in the northern Plains to central

Rockies, but generally decreasing trends from the Ohio Valley to Northeast (Figure 1, top). Winter snowfall amount decreased along the eastern seaboard and in the Far West, increased in the eastern Great Lakes, and was mixed in the central U.S. (Figure 1, middle). Decreasing trends dominated most of the country during spring (Figure 1, bottom). The annual pattern (not shown) was generally mixed, with a large area of decreasing trends in the Far West, central Plains, Ohio Valley, and east coast, with increasing trends more frequent in the northern Plains to central and southern Rockies.

The trend for number of days with snowfall ≥ 0.254 cm. is shown in Figure 2. The geographical pattern for this variable for each season is similar to that for total snowfall.

The trend for number of days with snow cover (snow depth) ≥ 2.54 cm. is shown in Figure 3. Snow depth has considerably more missing data than snowfall, so fewer stations have sufficient data to perform an analysis. The geographical pattern of trends for autumn (Figure 3, top) shows an increasing trend in the northern Plains and parts of the Northeast, with a decreasing trend in the Great Lakes to Ohio Valley, with the northern Plains trend as great as one to two weeks per century. Spring snow cover duration (Figure 3, bottom) has a pattern of decreasing trends at most locations, especially from the central Plains to Midwest where trends as great as one to two weeks per century were computed.

The geographical pattern for average daily snowfall (SF / NDSF) is mixed for all seasons, although coherent large regions of similar trend can be discerned (Figure 4). These include increasing trends in daily snowfall amount across parts of the Great Plains, especially in the north, and decreasing trends from parts of the central Plains into the Ohio Valley and mid-Atlantic states.

3.2 Snow-Temperature Correlations

The relationship between snow and temperature is very consistent across regions and seasons. Warmer temperatures are associated with less snowfall amount, fewer days with snowfall, and fewer days with snow cover (maps not shown). The strongest correlations occur during winter. The correlations between average daily snowfall (SF / NDSF) and temperature (Figure 5) are predominately negative in the Far West but show a mixed pattern from the Rockies eastward. Warmer temperatures in winter tend to be associated with lower snowstorm snowfall amounts (SF / NDSF) (Figure 5, middle), but some areas in the central Plains to Ohio Valley tend to have higher snowstorm snowfall amounts in the autumn (Figure 5, top) and spring (Figure 5, bottom).

3.3 Warm Years / Cold Years Ratio

The average snowfall amount for the warmest five years was compared to the average snowfall amount for the coldest five years in the record from 1948-2008. Zero snowfall values were omitted from the analysis. The results indicate that warm years generally receive less snowfall than cold years, but not for all stations, especially in autumn. During this season, there are many stations along the southern storm track east of the Rockies which have greater snowfall amounts with warmer years. But no predominant geographical pattern is obvious, as stations with ratios greater than one are mixed in with stations with ratios less than one. The greatest ratios (less than one) occur along the edge of the seasonal snow extent for all seasons.

The ratio of the average daily snowfall amount (SF / NDSF) for the warmest five years to the average daily snowfall amount (SF / NDSF) for the coldest five years was examined. There is no discernible geographical pattern in any season, with stations having higher daily snowfalls with warmer temperatures mixed in with stations having higher daily snowfalls with colder temperatures.

4. Discussion and Conclusion

Some differences in the trend, correlation, and ratio patterns may be due to data sampling issues (snowy years included in the record for some stations but missing for others) or observation time differences.

With a maximum sample size of 61 for the 1948-2008 period, and a minimum sample size of 30 required, some stations could have up to half of the years of data missing. More stringent sampling would greatly restrict the number of available stations (for example, requiring no more than four years of missing data reduces the available number of stations by a factor of ten). But even with the more restrictive sampling, mixed spatial patterns are still evident.

Observation time can significantly affect snowfall amount. Snow settles as it lies on the ground, and snow often melts as it lands or as it lies on the ground, both from warm soil below or from warm (above freezing) air, wind, or sunshine above (Doesken and Judson, 1996). Because of these properties of snow, if other factors are kept constant, snow observations late in the day may be lower than snow observations early in the day. If the observer changes observation time from morning (AM) to late afternoon (PM) or midnight (MID), or vice versa, a non-climatic trend could be introduced into the record.

Maps (not shown) of trend in total snowfall amount where the stations are grouped according to observation time category were examined. All of the maps exhibit spatial patterns showing mixed positive and negative trends, suggesting that the mixed patterns seen in the aggregate maps (e.g., Figure 1) reflect influences other than observation time.

Several general conclusions can be made from the analysis in this study:

- total snowfall amount and number of days with snowfall generally decreased during 1948-2008 in the West and Midwest, especially in the spring;
- total snowfall amount and number of days with snowfall generally increased in the northern Plains to central Rockies during the autumn, and in the Great Lakes region during winter;
- less data are available for number of days with snow cover, but this variable shows spatial patterns of trends which are consistent with those of total snowfall amount and number of days with snowfall;
- total snowfall amount and number of days with snowfall and snow cover decrease with increasing temperature during all seasons and in all regions.

The SF / NDSF variable was used as an indicator of what happens when it does snow. The analysis suggests that:

- there is a mixed pattern of trends in the average daily snowfall amount, but generally decreasing trends in the West and Midwest;
- there is some indication of increasing trends in the Plains, especially in the favored lee cyclogenesis regions;
- there is a mixed pattern of correlations between temperature and average daily snowfall amount, indicating that average daily snowfall may be heavier with warmer temperatures (up to the point where temperatures are too warm for snow to form) in some locations and seasons.

5. References

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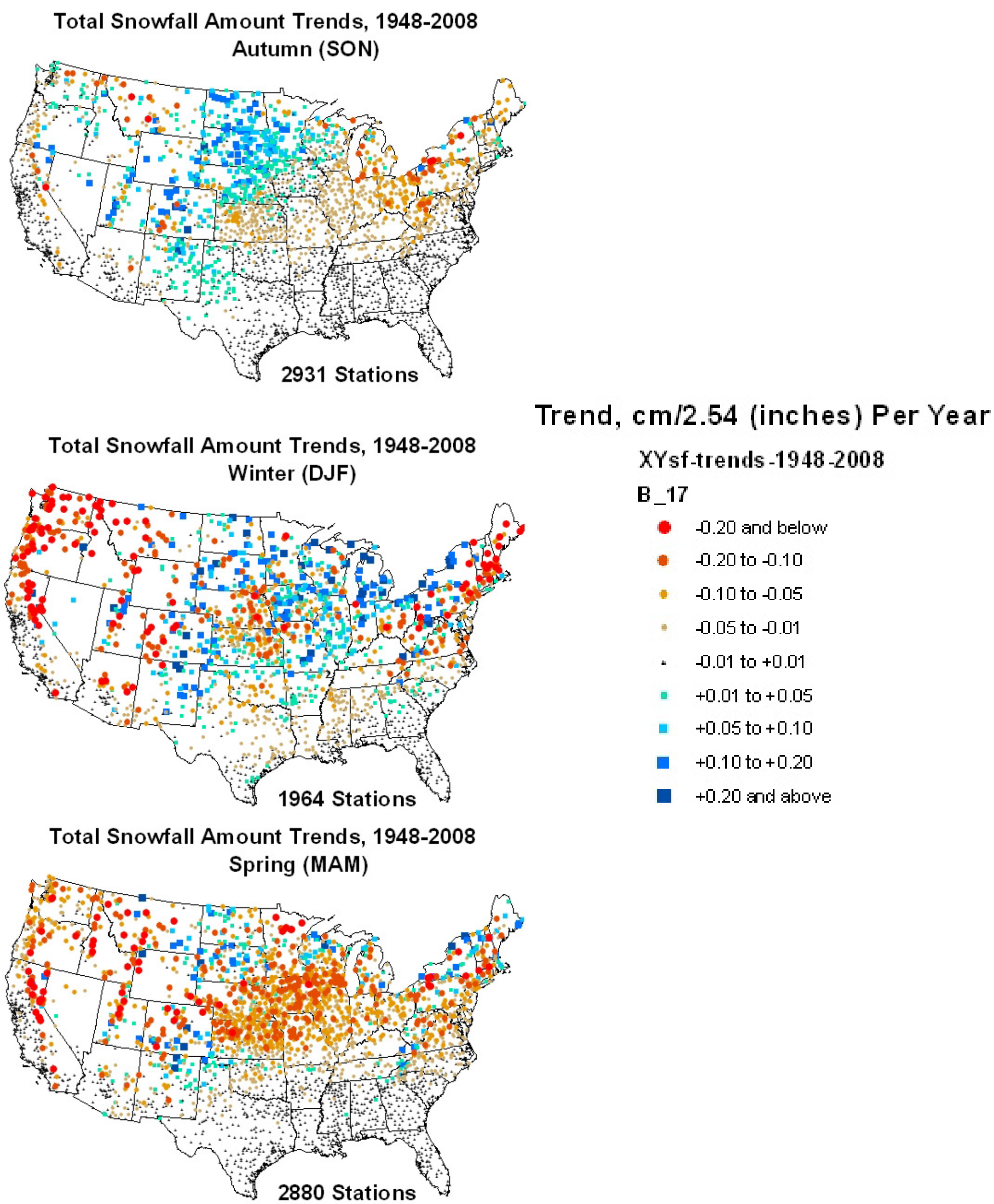

Figure 1. Linear regression trends for total snowfall amount for autumn, winter, and spring for the period 1948-2008. The number of stations with sufficient non-missing data to compute a trend is indicated for each season.

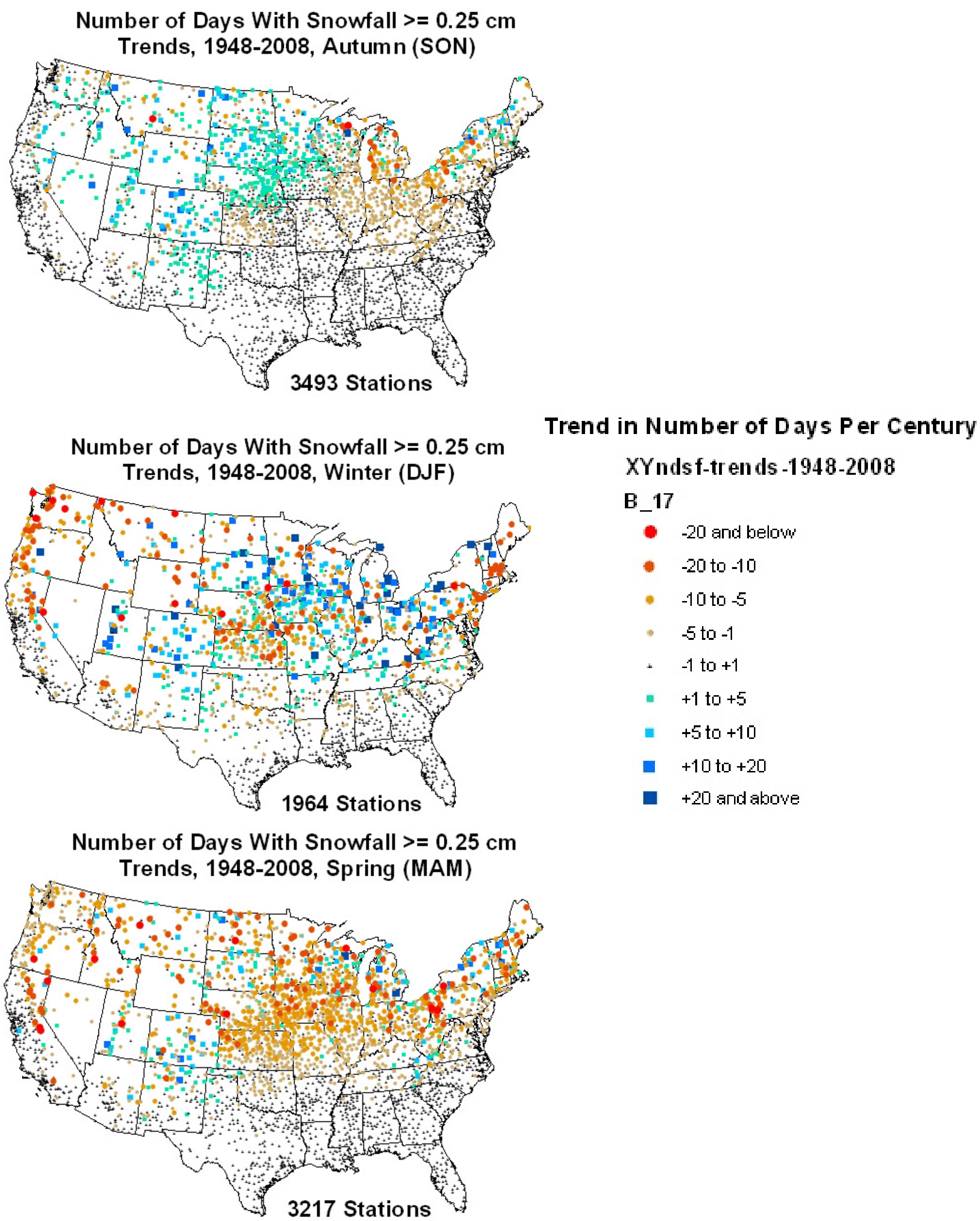

Figure 2. Linear regression trends for number of days with snowfall ≥ 0.254 cm. for autumn, winter, and spring for the period 1948-2008. The number of stations with sufficient non-missing data to compute a trend is indicated for each season.

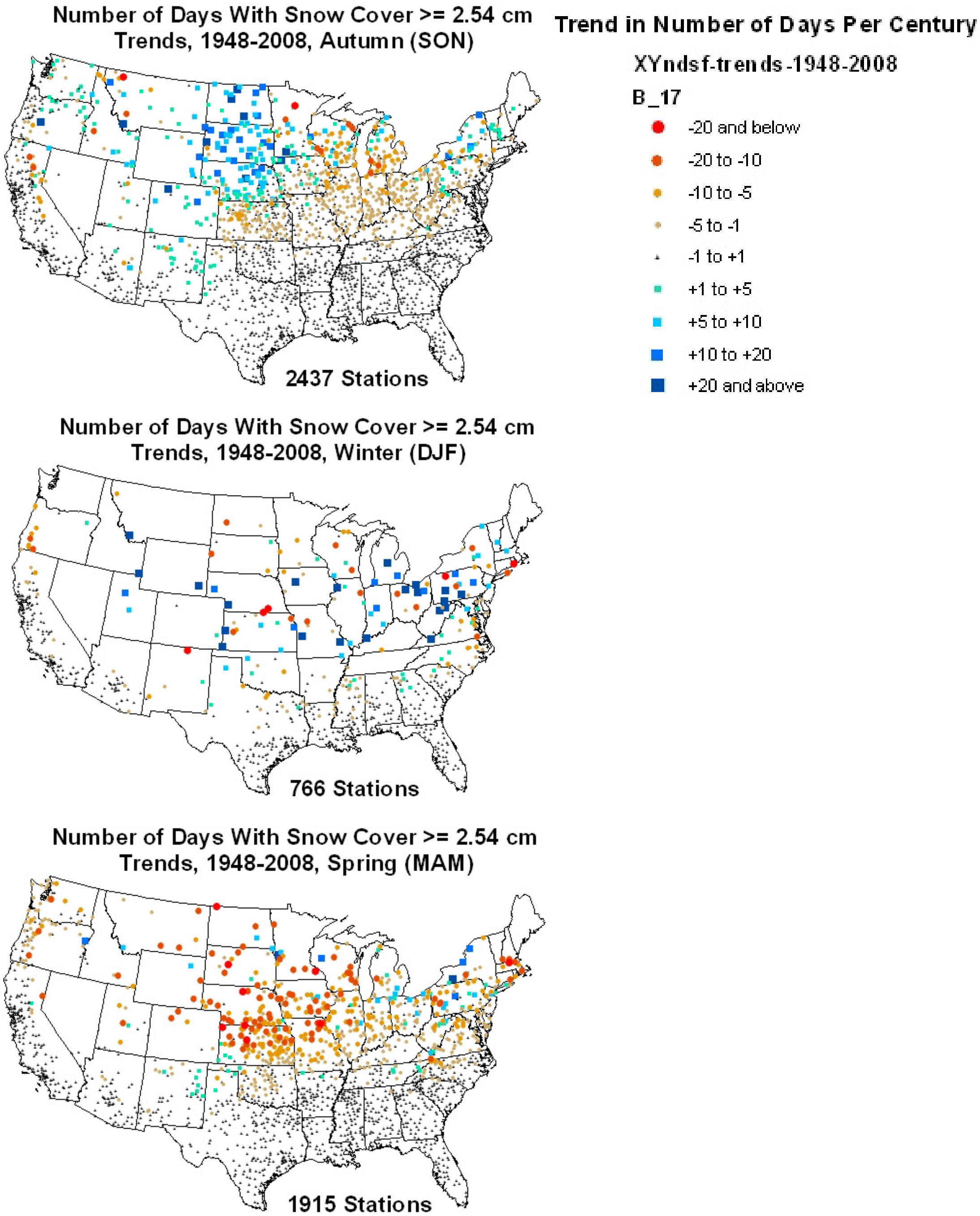

Figure 3. Linear regression trends for number of days with snow cover (snow depth) ≥ 2.54 cm. for autumn, winter, and spring for the period 1948-2008. The number of stations with sufficient non-missing data to compute a trend is indicated for each season.

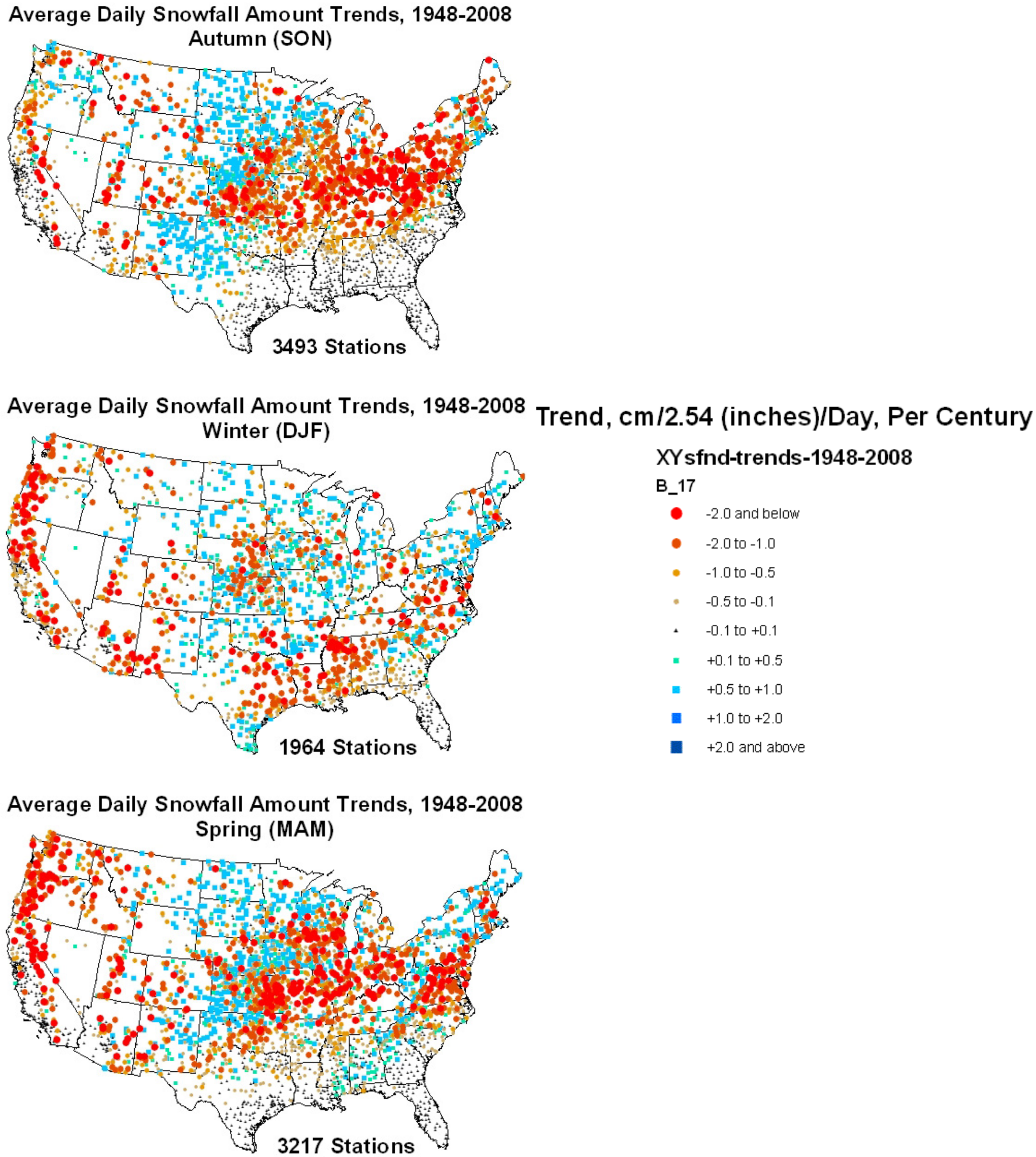

Figure 4. Linear regression trends for average daily snowfall (SF / NDSF) for autumn, winter, and spring for the period 1948-2008. The number of stations with sufficient non-missing data to compute a trend is indicated for each season.

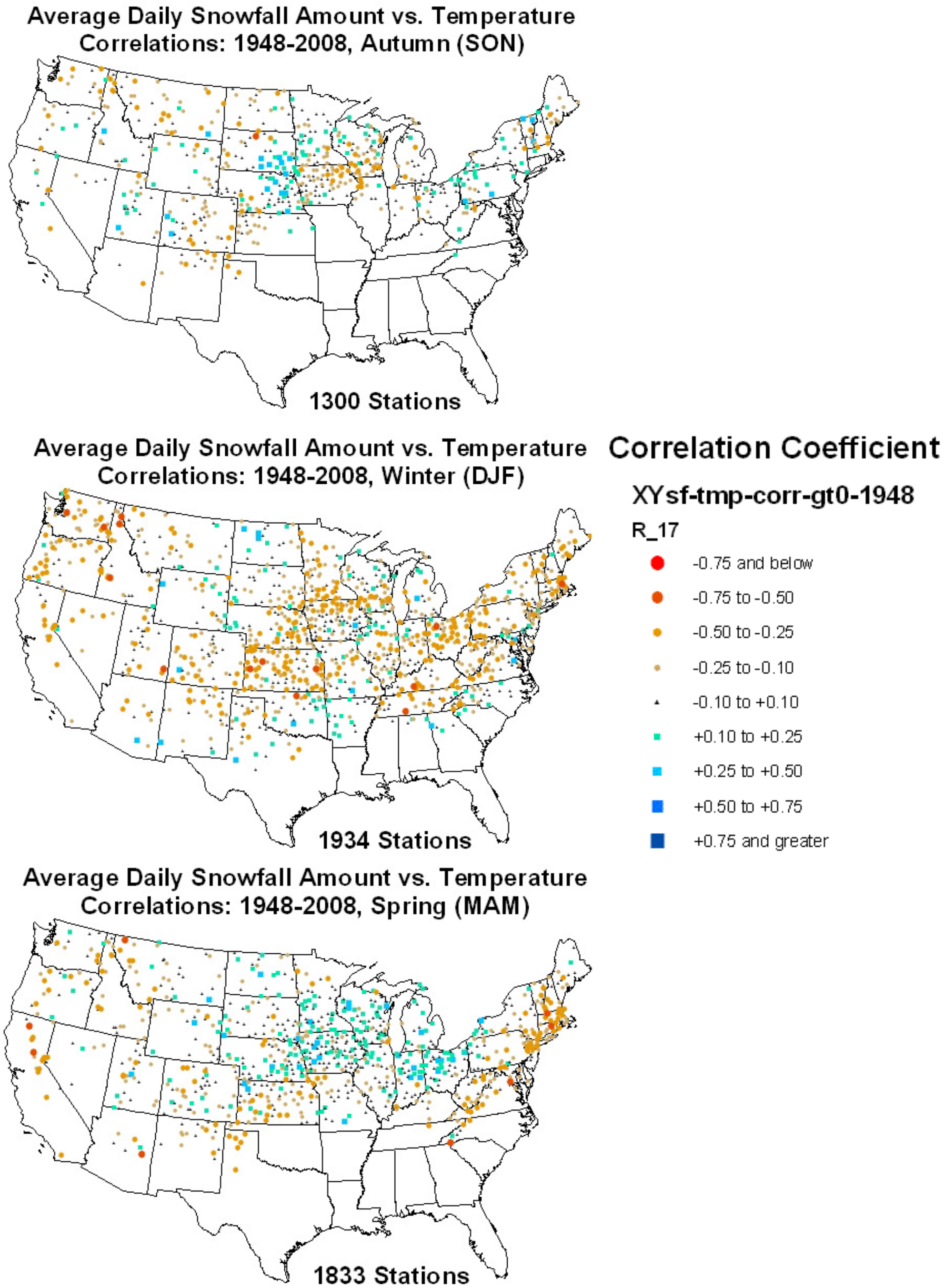

Figure 5. Correlation coefficients for average daily snowfall (SF / NDSF) vs. mean temperature for autumn, winter, and spring for the period 1948-2008. The number of stations with sufficient non-missing data to compute a correlation is indicated for each season.