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# A SHIFT IN WINTER SEASON TIMING IN THE NORTHERN PLAINS OF THE USA AS INDICATED BY TEMPORAL ANALYSIS OF HEATING DEGREE DAYS

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ABSTRACT

The temporal distribution of monthly heating degree days (HDD) approximates a bell-shaped curve, usually with a January maximum. The first moment, or centroid, of this distribution can be taken as the midpoint of the heating season. Analysis of seasonal HDD centroids reveals significant inter-decadal trends in the Northern Plains. From 1950 to 1990, the timing of the HDD centroid is observed to have advanced at a rate of 1.6 days per decade, a trend largely explained by cooling in October and warming in March and April. A trend of comparable magnitude (2.2 days per decade), but opposite direction, is observed for the period 1925–1950, and is again primarily associated with temperature trends in autumn and spring. The results suggest that changes in seasonal timing could be a feature of natural climate variability, and that it may be premature to infer an unprecedented climate change from a subtle shift in the timing of the winter season. Copyright © 2000 Royal Meteorological Society.

KEY WORDS: USA Northern Plains; temporal statistics; heating degree days; winter season timing; North Atlantic Oscillation; Pacific–North American; inter-decadal variability

## 1. INTRODUCTION

There is a growing body of evidence that suggests that rising global mean temperatures, attributable to anthropogenic increases in atmospheric $CO_2$ concentrations, may have been accompanied by a change in the timing of the seasons. Keeling *et al.* (1996) showed that since the early 1960s, the annual amplitude of the seasonal $CO_2$ cycle has increased by roughly 20% in Hawaii, and by roughly 40% in the Arctic. These increases have been accompanied by phase advances of about 7 days during the declining phase of the cycle, suggesting a lengthening of the growing season in the northern hemisphere. Thomson (1995) suggests that phase changes in northern hemisphere temperatures since 1940 are no longer coherent with solar variability associated with precession, but are now related to variations in the atmospheric $CO_2$ concentration. Trends in monthly temperatures in the continental US from 1948 to 1988 suggest that the growing season may have lengthened and shifted, with spring coming earlier in the north and in the west (Lettenmaier *et al.*, 1994).

The possibility of a seasonal shift is also suggested by trends in snow cover duration. Hughes and Robinson (1996) observed a trend after 1970 towards longer autumn (September–November, SON) snow cover duration and shorter spring (March–May, MAM) duration in the Great Plains region of the US. These trends were accompanied by decreases in both maximum and minimum temperatures in the autumn, and increases in the spring minimum temperatures. Brown *et al.* (1995) found an increase in annual snow cover temperature sensitivity in the Canadian Prairies and the Great Plains after 1940, and

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attributed this mainly to the spring season. Increased spring temperatures and shorter spring snow cover extent suggest the possibility of a positive feedback, as the presence/absence of snow cover has been shown to significantly influence air temperatures (Walsh *et al.*, 1982; Namias, 1985), and could explain regional temperature anomalies that are not necessarily explained by large-scale, persistent atmospheric forcing, especially in the late winter (Leathers and Robinson, 1993). However, Brown *et al.* (1995) also suggest that the increase in snow cover temperature sensitivity in spring could be associated with the tendency to more positive values of the Pacific–North American (PNA) index after the late 1950s. Climate trends in the central North Pacific have also been linked to an earlier onset of spring in California. Since the late 1940s, winter sea-level pressure over the central North Pacific has shown a downward trend (Trenberth, 1990). As a result, winter wind fields have been displaced southward over the central North Pacific and northward over the west coast of North America, bringing warmer winters to California and an earlier timing of both snowmelt and runoff (Dettinger and Cayan, 1995).

Kalnicky (1987) compared several aspects of seasonality and climate changes over the northern hemisphere mid-latitudes for three periods: 1899–1919, 1920–1952 and 1953–1969. The timing of the transition from summer–autumn, autumn–winter, winter–spring and spring–summer atmospheric circulation regimes appears to differ from one period to another. For example, the autumn–winter transition occurs later in each successive period while the winter–spring transition occurs earlier. Kalnicky's time periods correspond approximately with those defined by Diaz and Quayle (1980) in their study of seasonal temperature and precipitation variations over the US. In a few cases, the change in transition timing coincides with a climate change. For example, over the period 1920–1952, the average time of the summer–autumn transition is 1 September while in the period 1953–1969 the average time is 1 August. Diaz and Quayle's (1980) study identified a significantly cooler autumn over the Southeast for the period 1955–1977 compared with 1921–1954. Although not all changes in transition timing correspond so neatly with a climate change (some are even opposite from what might be expected), these studies demonstrate two things. First, the time of transition from one seasonal circulation regime to the next is variable rather than constant. Second, a persistent trend in the transition time might be reflected in a climate change in one season that is not necessarily observed in other seasons.

This study examines trends in the seasonality of temperatures across the conterminous US since 1895, and identifies several seasonal shifts in the historical record, one of which is discussed in some detail and may be associated with changes in the large-scale atmospheric circulation. In light of some of the aforementioned results relating to snow cover duration, the focus is on the cold-season months of October–April, and so the study is by no means comprehensive. However, it does demonstrate that it may be premature to infer a climate change from changes in seasonality (especially at the continental and regional scales) without some understanding of the natural variability of seasonal timing.

## 2. DATA AND METHODS

The data used are monthly mean temperatures of the climate division data set of the National Climatic Data Center for the years 1895–1996. These data have been corrected for potential biases introduced by differences in observation time (Karl *et al.*, 1986).

Seasonality can be quantified by several methods, such as harmonic analysis (e.g. Harrington *et al.*, 1987) or circular statistics (Dingman, 1993). In this case, an alternative approach was tested and was found to be very practical for the study's purposes. Temporal statistics were presented by Harrington and Cerveny (1988) as a method for the analysis of temporal distributions of climate data, based on a comparison of a variable's frequency distribution in the time dimension to a standard bell-shaped curve through time. Using mean monthly snowfall as an example, they defined the following temporal statistics (amongst others): the first moment, or temporal mean—the average time of the centroid of snowfall accumulation; the second moment, or temporal S.D.—a measure of the mean annual spread of snowfall accumulation about the mean; and the third moment, or temporal skew—a measure of the symmetry of the annual snowfall accumulation. For computational details of these statistics, the reader is directed to Harrington and Cerveny (1988).

 

In this study, the method was applied as follows. First, because the distribution of monthly temperatures throughout the cold season is an inverted bell-shaped curve, monthly heating degree day (HDD) totals were computed from the monthly mean temperatures using the standard threshold of 65°F (18.33°C). In the vast majority of the divisions, at least one summer month has a zero HDD total, thus giving the heating season a distinct beginning and end which makes interpretation of the temporal statistics more meaningful. Second, the temporal statistics of the monthly HDD were computed for each 'heating year' (1 July–30 June) in the 1895–1996 period. Trends in the temporal statistics over this period were then examined. An initial concern was that the monthly data would not provide enough temporal resolution. Therefore, a small number of experiments were conducted with daily data, at time increments of 10, 20 and 30 days (some comparisons are presented in a later section). The resolution was found to affect the statistics, but not their long-term trends. As it is the trends with which we are concerned here, the monthly data were considered to be adequate for purpose of this study.

Interpretation of trends in the temporal statistics can by illustrated using Figure 1. Figure 1(a) shows the result of a change in the centroid only. In this case, the temporal distribution is simply shifted in time without any change in shape. The change in the centroid from a value of 7 (15 January) to 6.5 (1 January) corresponds with more HDD early in the season (i.e. relatively cooler conditions) and fewer HDD later in the season (i.e. relatively warmer conditions). Figure 1(b) shows the result of a change in the temporal S.D. A smaller value of this statistic indicates a greater concentration of the HDD around the mean, i.e. around the middle of January. Figure 1(c) illustrates temporal skew. A value of zero indicates a symmetrical distribution. A positive value indicates more of the HDD accumulated in the first half of the season. A negative value indicates more of the HDD accumulated in the second half of the season.

Significant trends were identified by means of the non-parametric Kendall's tau statistic (Kendall, 1938; Hirsch *et al.*, 1982), as applied by Dettinger and Cayan (1995). The statistic identifies monotonic trends in data, although it cannot distinguish between continuous trends and step changes. Another problem with such a measure of trend is that the results can be fairly sensitive to the period of record used

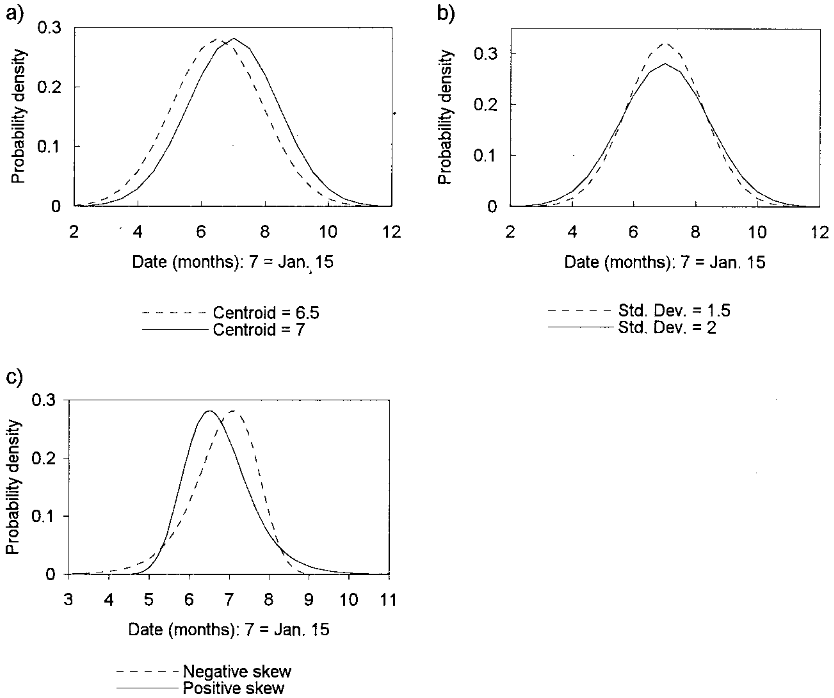


Figure 1. Comparisons of probability density functions for values of temporal statistics. (a) Centroid: comparison of value of 7 (15 January) with value of 6.5 (1 January). (b) Second moment: comparison of value of 2 months with value of 1.5 months. (c) Third moment: comparison of positive and negative skew for centroid of 7 (15 January)

 

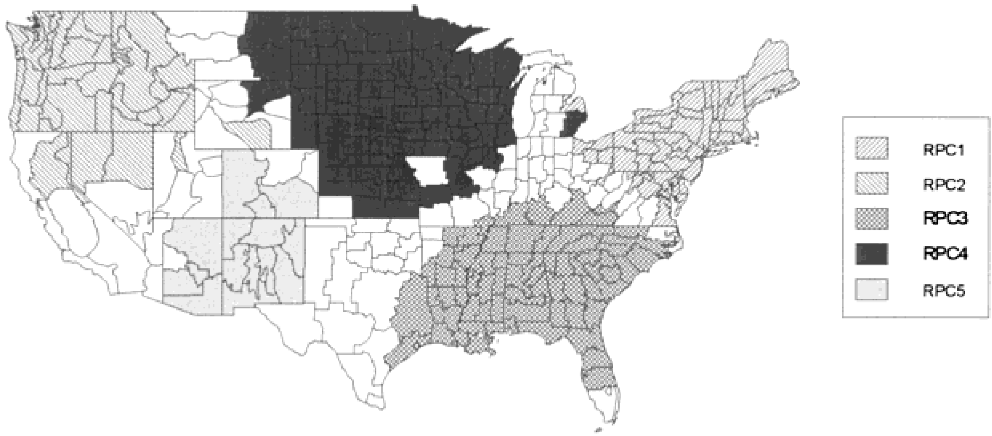


Figure 2. Regions of coherent temperature variability as indicated by rotated principal component analysis (PCA) of divisional temperatures, 1895–1996

(Lettenmaier *et al*., 1994); thus, the following approach was taken. In order to organize the analysis around some regional framework, the divisional standardized monthly temperatures were subjected to a principal component analysis (PCA). Examination of eigenvalues from the unrotated solution suggested retention of the first five components, together explaining 85% of the total variance. A subsequent Varimax rotation identified five distinct regions of coherent variability (Figure 2—divisions with loading values of less than 0.7 were unassigned to any region). From each region, the ten climate divisions with the highest PC loadings were taken for the next step of the analysis. For each division, monthly HDD totals were computed from the monthly temperatures, and the temporal statistics computed for each heating degree season from 1896 to 1996. The temporal statistics were averaged over the ten divisions to give one representative time series of each statistic for each region. For each time series, Kendall's tau (and the corresponding $Z$ test statistic) was then computed using moving windows of 20, 30 and 40 years in length. Time series plots of the $Z$ test statistic were used to identify periods of trends significant at a level of 0.05 or better.

## 3. RESULTS

### *3.1. Temporal statistics*

Time series of the HDD temporal statistics for each of the regions indicated in Figure 2 are illustrated in Figures 3 and 4. In each of these figures, the statistics have been averaged over the ten highest loading divisions on the corresponding rotated PC, and the solid line indicates the 9-year running mean. Figure 3 shows that the centroid of the HDD season does not differ widely among the regions, occurring around or shortly after the middle of January, with a range of approximately 12 days. In region 1 (the Northeast), region 3 (the Southeast) and region 5 (the Southwest), no long-term trends are evident, but multi-decadal variations are suggested for region 2 (the Northwest) and region 4 (the Northern Plains).

The second moment (Figure 4) is a measure of the spread of the HDD about the centroid, i.e. the length of the HDD season. Not surprisingly, the lowest values of the second moment are found in the Southeast. Multi-decadal variations are suggested for the Northwest, but no such trends are evident in the other regions.

The third moment (not shown) is a measure of the symmetry of the HDD season. In all regions except the Northeast, there is a tendency for positive skew, especially in the Northwest and the Southwest. Examination of monthly HDD totals for some Northwest divisions suggested that the positive skew is associated with an abrupt commencement of the heating season in late autumn, combined with a more

 

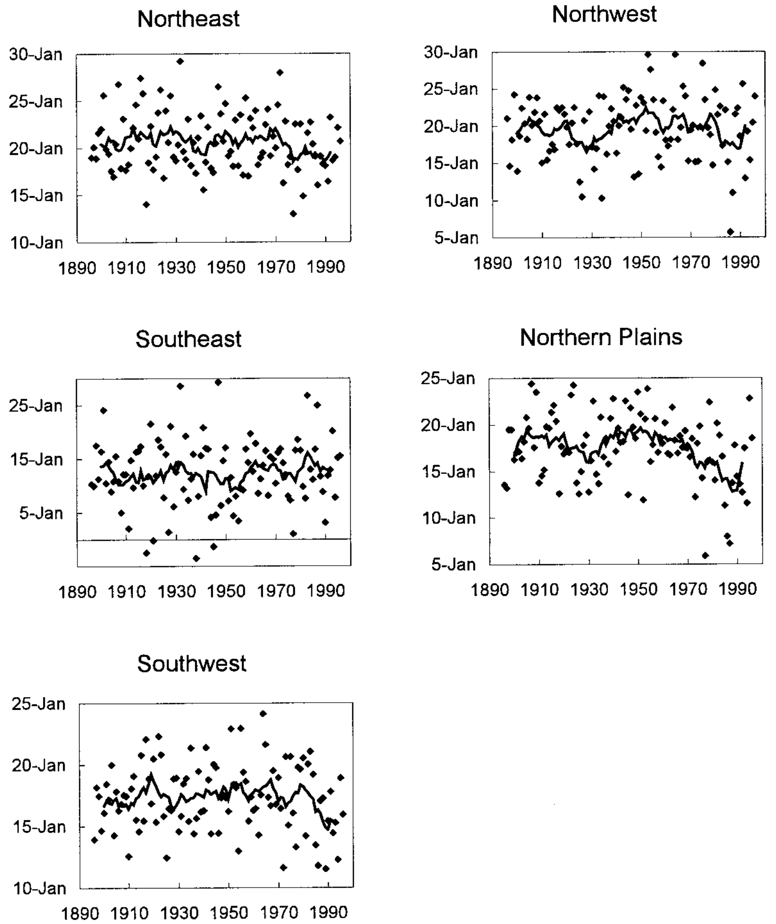


Figure 3. Long-term trends in date of centroid of seasonal HDD accumulation. Solid line is 9-year running mean

drawn-out conclusion of the heating season which extends into the early summer. This suggests the possibility of an ocean influence that may warrant further investigation in a subsequent study.

### *3.2. Analysis windows*

In order to identify a suitable time window for analysis, Kendall's tau was computed for moving windows of 20, 30 and 40 years in length. For each value of Kendall's tau, corresponding values of the standard normal variate test statistic ($Z$) were also computed. The threshold magnitude value for 95% confidence is approximately 2. Thus, by plotting the $Z$ scores versus time, the time windows for which trends are statistically significant can be easily identified. $Z$ scores for the HDD centroid in the Northern Plains are shown in Figure 5 as an example. The downward trend in the latter half of the record turns out to be significant for most 30-year windows after the late 1940s, and for all 40-year windows after 1940. Also indicated is a significant upward trend of 20–30 years in length, beginning in the mid-1920s. Some trends were identified for the other regions and are indicated in Table I. However, this paper will focus on the apparent trends in the HDD centroid in the Northern Plains. These are of particular interest because of the trends in snow cover duration discussed in the 'Introduction'. Based on Figure 5, two analysis windows were selected for further examination: first, the downward trend from 1950 to 1990; and second, the upward trend from 1925 to 1950. Because of data limitations prior to 1950, the analysis for the 1950–1990 window is more extensive and, hence, these results are presented first. The results for the 1925–1950 window are then presented for comparison.

 

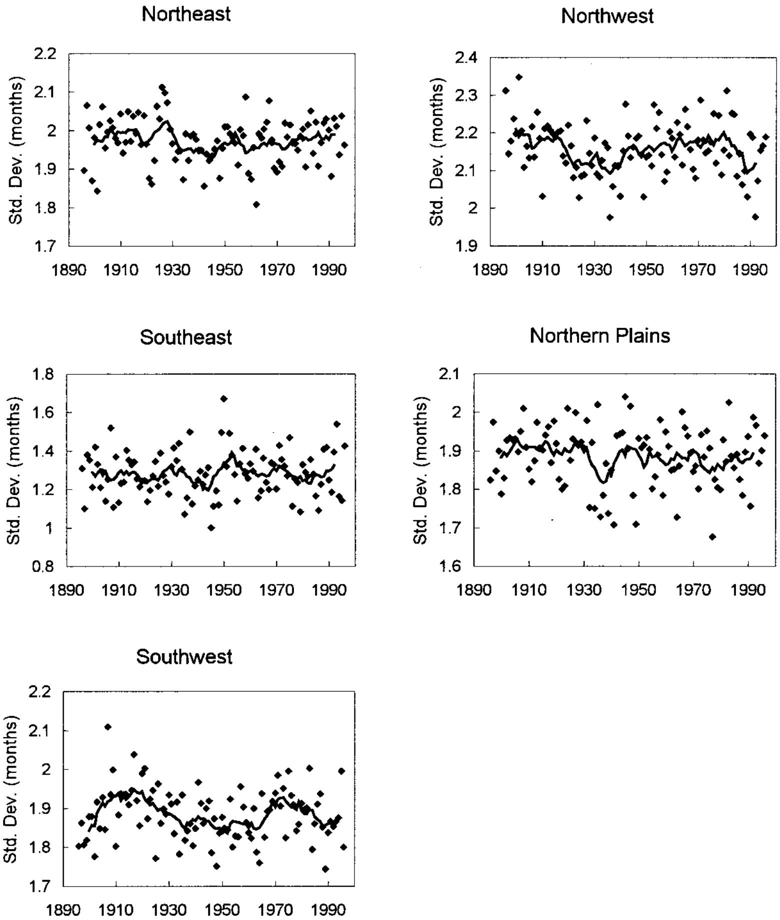


Figure 4. Long-term trends in temporal S.D. (second moment) of seasonal HDD accumulation. Solid line is 9-year running mean

### 3.3. *Window 1: 1950–1990*

*3.3.1. Patterns of trends.* Trends in the temporal statistics over this time window were computed for all the climate divisions. Divisions with significant trends are indicated in Figure 6. Also shown are significant trends in total HDD.

Significant trends in total HDD are observed only in the extreme northern Plains, the northern Rockies and the Pacific coast (negative), and in scattered divisions across the rest of the country (positive). The significant negative trends in the HDD centroid cover a wide region of the Northern Plains and extend into some divisions of the northern Rockies. Significant trends in the second moment are scattered rather than being areally coherent, as is the case of the third moment. Thus, the trend in the centroid in the Northern Plains can for the most part be examined without consideration of trends in the other statistics, although some overlap is acknowledged. Significant trends in monthly mean temperatures are shown in Figure 7. In the Northern Plains, the most areally coherent trends are seen in the months of March and April both of which show a warming trend. Cooling is observed in October, although the areas of significance are not contiguous. Apart from a string of northern divisions that show a significant warming in January, the remaining months show no trends in the Northern Plains region. In the Southeast region, the warming trend of November and the cooling trend of January are interesting and have been identified in other investigations (e.g. Lettenmaier *et al.*, 1994), but they will not be examined at this time.

The time series of standardized monthly temperature, averaged for the ten highest-loading divisions on rotated principal component (RPC) 4 (Figure 8), show that some important variations are obscured if

 

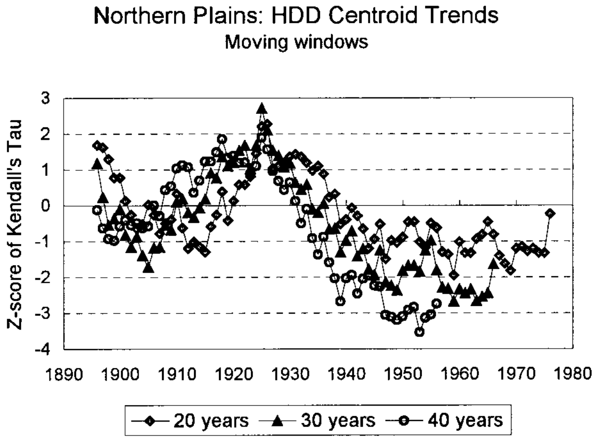


Figure 5. *Z* scores corresponding to computed values of Kendall's tau as a measure of HDD centroid trends based on moving windows of 20, 30 and 40 years in length. The threshold magnitude for 0.05 significance level is approximately 2

only monotonic trends are considered. The time series shown are 9-year moving averages. The cooling trend of October and the warming trends of March and April are immediately evident, and these trends appear to bracket those of the months in between. November also shows a cooling trend, although this is not as marked as October. February and January show warming trends after 1970 and 1980, respectively.

*3.3.2. Magnitude of HDD centroid trend.* Estimates of magnitudes of the trend in the timing of the HDD centroid were obtained for two stations (Fargo, ND and Minneapolis, MN), using daily Summary of the Day temperature data. Daily data were used so that the temporal statistics could be computed based on intervals of 10, 20 and 30 days in length and the results compared. Figure 9 shows the results obtained for Fargo. The computed values of the second and third moments appear to be independent of the temporal resolution, but this is clearly not the case for the centroid, which advances in time as the time increment decreases. However, the traces of the three time series are virtually identical and correlations among them exceed 0.98 in each case.

Estimates of trend magnitudes from 1950 to 1990 were obtained by regression of the HDD centroid values against the numerical value of the year. The regression slopes were then converted into units of

Table I. Trends significant at the 95% confidence level as indicated by Kendall's tau with moving window analysis period

| Region | Statistic | Trend | Window |
|---|---|---|---|
| Northeast | Second moment | – | 1915–1945 |
| Northeast | Second moment | + | 1940–1970 |
| Northwest | Centroid | + | 1925–1955 |
| Northwest | Second moment | – | 1900–1940 |
| Northwest | Second moment | + | 1935–1965 |
| Northwest | Second moment | – | 1965–1990 |
| Northwest | Third moment | + | 1965–1995 |
| Northern Plains | Centroid | + | 1925–1950 |
| Northern Plains | Centroid | – | 1950–1990 |
| Southwest | Centroid | – | 1955–1995 |
| Southwest | Second moment | – | 1915–1955 |
| Southwest | Second moment | + | 1945–1985 |
| Southwest | Third moment | + | 1955–1995 |

 

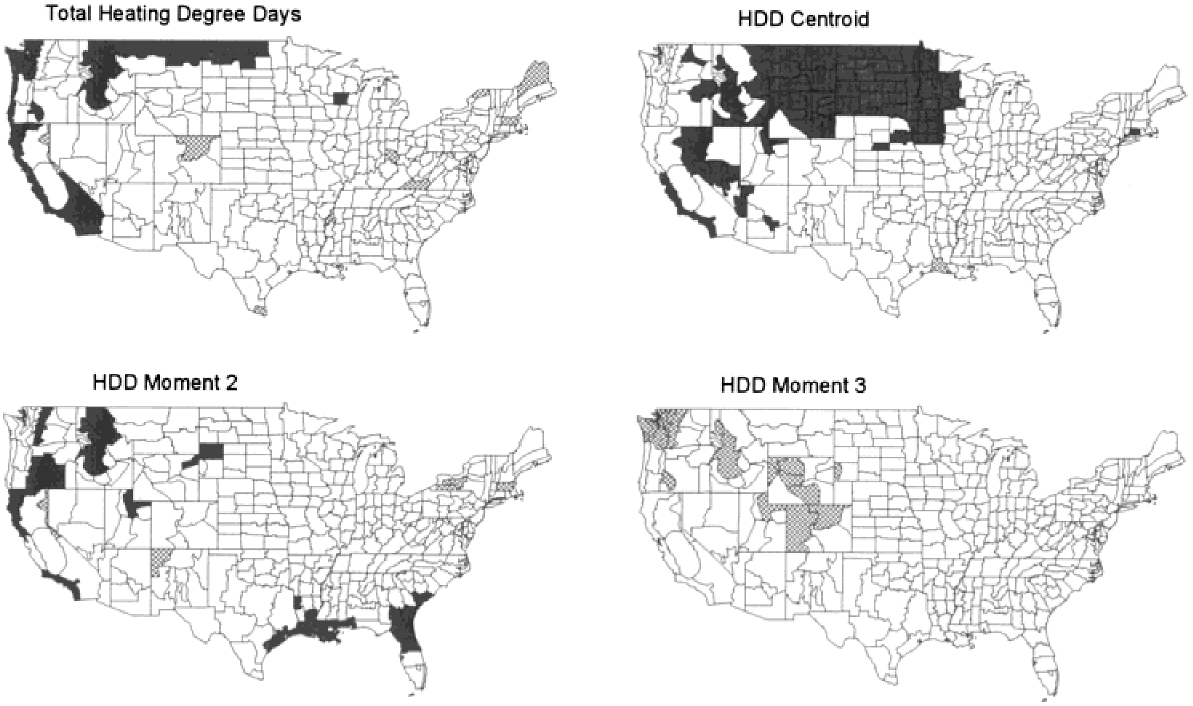


Figure 6. Trends in HDD statistics as indicated by Kendall's tau, 1950–1990. Solid shading = negative trend significant at 0.05 level; cross-hatching = positive trend significant at 0.05 level

days/decade for ease of interpretation. From 1950 to 1990, on average, the timing of the HDD centroid advanced by between 1.3 and 1.7 days per decade. Over the period 1965–1990, the trend is somewhere in the range of 1.7–2.2 days per decade. Corresponding estimates of the trends obtained from the regionally-averaged HDD centroid values are in good agreement, with advances of 1.6 days/year from 1950 to 1990 and 2.0 days/year from 1965 to 1990.

*3.3.3. Associations with atmospheric circulation*. Monthly values of the PNA and North Atlantic Oscillation (NAO) teleconnection indices for the years 1950–1996 were obtained from the Climate Prediction Center (formerly the Climate Analysis Center) of the National Center for Environmental Prediction (NCEP). Month-by-month correlations of these values with the Northern Plains monthly temperature time series were computed and are given in Table II.

Significant associations between temperature and the PNA pattern are observed in the second half of the cold season. The temperature–NAO association is most significant during the shoulder months of October, March and April. Neither pattern is of significance in November or December. Smoothed time

Table II. Spearman correlation coefficients of Northern Plains monthly temperature versus monthly indices of PNA and NAO patterns (significance level in parentheses)

| | Temperature versus PNA | Temperature versus NAO |
|---|---|---|
| October | NS | 0.43 (0.002) |
| November | NS | NS |
| December | NS | NS |
| January | 0.35 (0.017) | NS |
| February | 0.33 (0.022) | 0.31 (0.035) |
| March | 0.50 (0.000) | 0.51 (0.000) |
| April | 0.31 (0.031) | 0.47 (0.001) |

 

series (9-year running means) of the PNA and NAO indices for the months October, January, February, March and April are shown in Figure 10. The October NAO index shows a downward trend until the late 1970s, which corresponds with the general downward trend of the October temperature. In March, both indices clearly show an upward trend that corresponds with the warming observed over the Northern

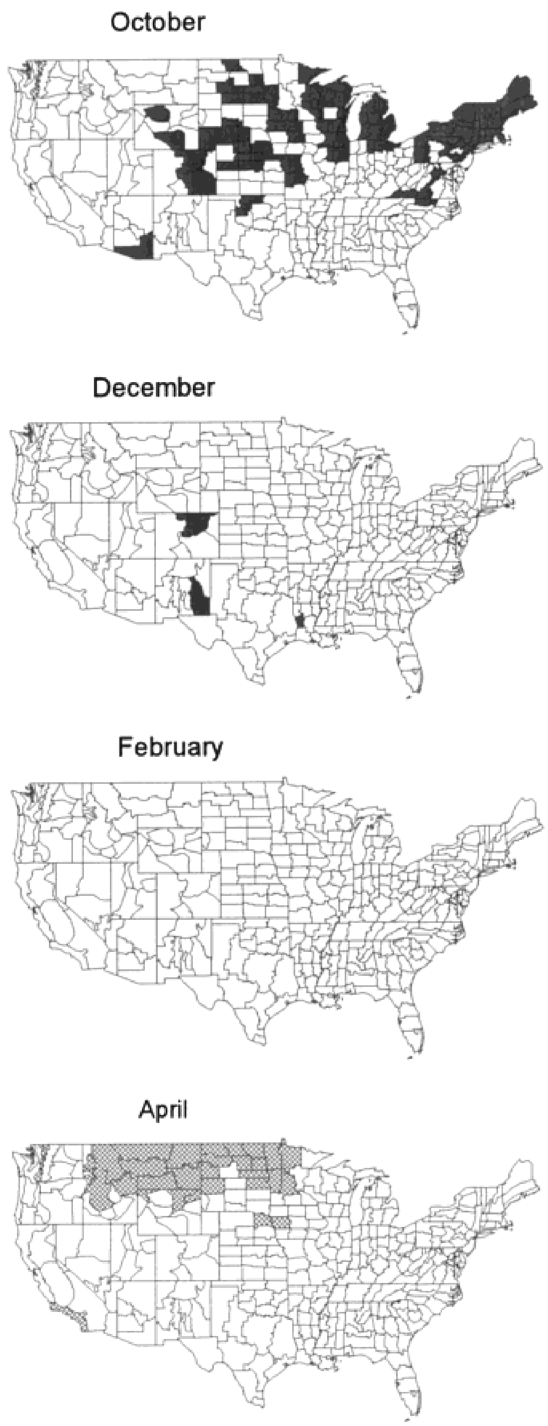


Figure 7. Significant trends in monthly temperatures, 1950–1990. Legend is as given in Figure 6

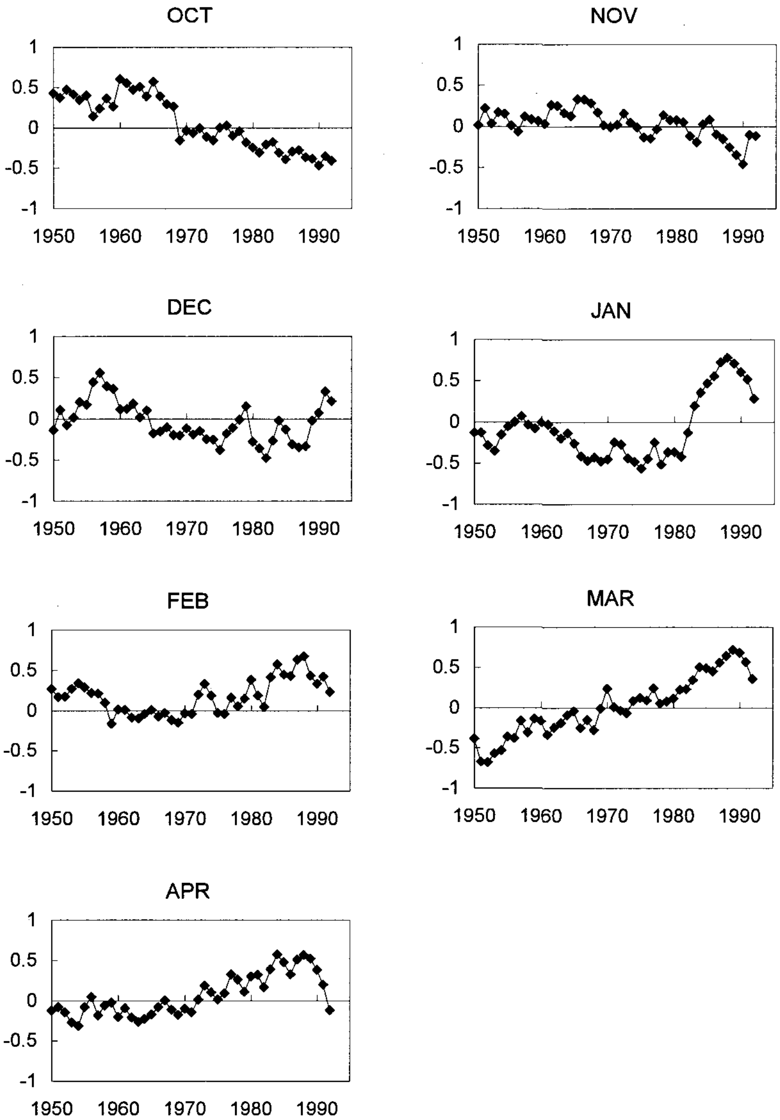


Figure 8. Smoothed (9-year running means) monthly temperature indices for the Northern Plains. Temperature values are standardized with reference to the 1895–1996 period of record

Plains in this month. Trends in April values of the indices do not bear much resemblance to the trend of April temperature, however, and the same can largely be said for January and February. Comparison of trends in the NAO index values for January, February and March, however, is interesting (Figure 11). The NAO index shows a general upward trend in all 3 months after 1970. Prior to 1970, March is the first month to see an upturn, followed successively by February and January. The same lagged sequence is observed in the monthly temperature series of Figure 8, although the timing of the upturns do not coincide neatly with those for the NAO index.

### *3.4. Window 2: 1925–1950*

This analysis window is not examined in as much detail as the first window, but the results do add some insight to some of the observations of the previous section. Significant trends in total HDD and the second and third moments are observed in only a few scattered divisions, although there is a suggestion

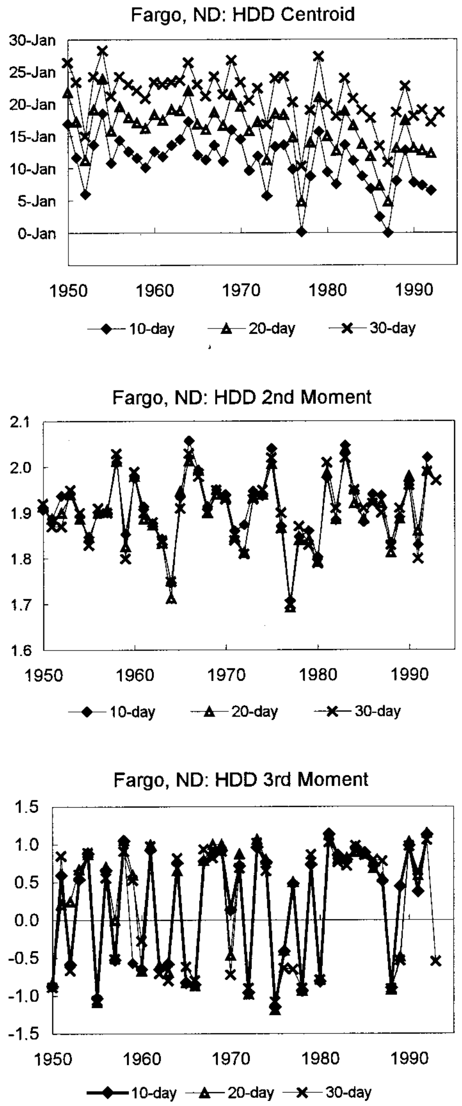


Figure 9. Comparison of temporal statistics based on computation intervals of 10, 20 and 30 days in length

of some areal coherence for the second moment on the Northeast. Positive trends in the timing of the HDD centroid are observed over a large region of the Northern Plains, i.e. the opposite of the 1950–1990 window. The magnitude of the trend was computed by regression of the regionally-averaged HDD centroid values against year, and is 2.2 days/decade. Spatial patterns of monthly temperature trends (not shown) are not as interesting as the 1950–1990 case, however. Significantly negative trends are observed in the Northern Plains in February and March, but significant trends in other months are seen only to the south and the east. The 9-year running means of monthly temperature for the region (Figure 12) show cooling trends for February and March, but also a warming trend for October after 1935 that is not revealed by computation of the monotonic trend statistic. December shows a warming trend until the early 1940s.

As with Window 1, it appears that the change in timing of the HDD centroid is influenced primarily by temperature trends in the shoulder months of October and March that appear to 'bracket' the trends of the months in between. The rate of change of timing is also similar in magnitude.

 

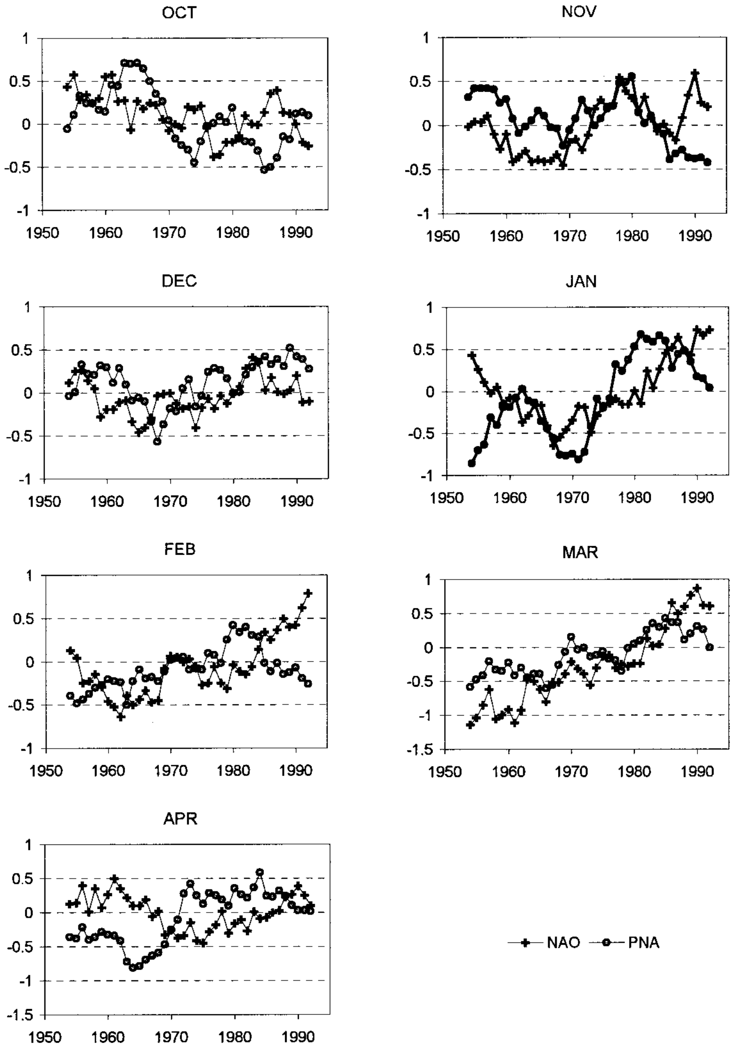


Figure 10. Smoothed (9-year running means) time series of monthly PNA and NAO indices

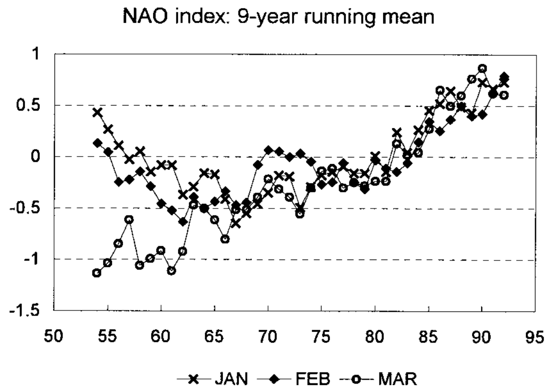


Figure 11. Comparison of trends in NAO index values for January, February and March

 

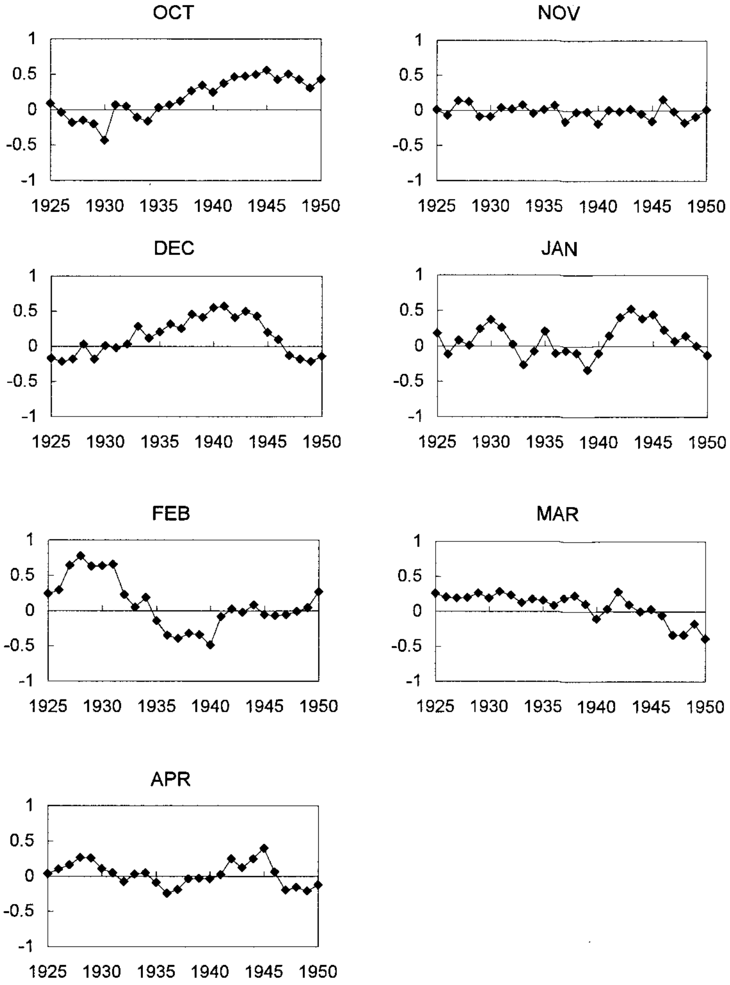


Figure 12. As Figure 8, but for Window 2, 1925–1950

## 4. DISCUSSION AND CONCLUSIONS

In the Northern Plains, significant trends in the timing of the HDD centroid have been identified. From 1925 to 1950, the timing retarded at an average rate of 2.2 days per decade. After 1950, the trend reversed and the timing advanced at a rate of 1.6 days per decade until 1990. Both trends are associated primarily (although not entirely) with temperature trends in the months of October and March. The retarding trend in the earlier time period is associated with warming in October and cooling in March, while the advancing trend of the later period is associated with just the opposite conditions.

The monthly temperature trends since 1950 are consistent with observed decadal trends in snow cover. Hughes and Robinson (1996) found that autumnal snow cover over the US Great Plains increased from the 1950s into the 1970s through the 1990s, while spring snow cover decreased sharply from the 1950s to the 1970s into the 1980s and the early 1990s. Considering North America as a whole, Frei *et al.* (1999) found that November snow cover increased from the 1970s onward, while March snow cover showed a maximum in the 1950s and the 1960s. Frei *et al.* (1999) also observed that March snow cover was less extensive in the first three decades of the century and rose rather quickly in the 1940s and early 1950s, which is consistent with the March temperature trend from 1925 to 1950.

 

Monthly indices of the PNA and NAO teleconnection patterns were available for the later analysis window 1950–1990. Temperature–PNA associations are indicated for the months January–April, while temperature–NAO associations are most significant in the shoulder months of October, March and April. Over the period 1950–1990, trends in the NAO index coincide with the trends of monthly temperature for both October and March, suggesting that the apparent seasonal shift in temperature, which is reflected in the advance of the HDD centroid, could be associated with a long-term trend in the large-scale atmospheric circulation. The PNA index also shows a positive trend that is consistent with increasing temperatures in March. This suggests that the atmosphere drives the March warming, although a snow cover-related feedback could be amplifying what would otherwise be a more modest signal. In April, however, even though temperature–PNA and temperature–NAO correlations are significant (albeit weak), the long-term trends in the indices do not resemble the trend in April temperature. The April warming could be as much a reflection of the early loss of snow cover as it is influenced by the PNA or NAO, while other factors of land–atmosphere interaction, such as soil moisture or earlier greenup, might also be significant. Spring season processes clearly warrant further investigation.

The lagged sequences of upward trends in the NAO index and temperature for the months March, February and January are intriguing, even though they are not well synchronized. The correlation analysis does suggest a linkage between the NAO and the temperature in February and March, but this association could benefit from more rigorous examination. However, even taken separately, both lagged sequences suggest that climate trends (whether or not they are associated with global warming) may not be observed simultaneously, and at the same rate, in all months.

Finally, the results suggest that it may be premature to infer an unprecedented climate change from an apparent seasonal shift, especially at the subcontinental scale. The advance of the timing of the HDD centroid in the Northern Plains from 1950 to 1990 is consistent with other previously cited evidence of a winter seasonal shift. However, this was preceded by a seasonal shift of similar magnitude, and of similar nature, in the opposite direction.

## ACKNOWLEDGEMENTS

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