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Efforts to improve predictions of urban winter heating anomalies using various climate indices

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Meteorologists who work in the energy commodities market continue to investigate ways to enhance predictions of seasonal temperature anomalies using oceanic/atmospheric indices. This study examines the relationship of three climate indices – ENSO (El Niño/Southern Oscillation), PNA (Pacific North American) and NAO (North Atlantic Oscillation) – to heating degree day (HDD) totals accumulated in 11 cities in the Midwest and northeastern United States, to determine which, if any, has predictive power. The data covers the 48-year period between 1951/52 and 1998/99, and focuses on two periods either side of 1 January (i.e. the winter months of October–December and January–April). The index most strongly related to the HDD anomalies during both winter periods was NAO. NAO values were negative for cold (above-average HDD) anomalies occurring prior to and after 1 January, while the NAO values were generally positive during warm (below-average HDD) anomalies. During cold anomalies, the PNA values were generally positive in the three months before 1 January and negative afterwards, indicating that different atmospheric teleconnection patterns cause similar temperature anomalies in these regions. The relationship between the equatorial Pacific sea-surface temperatures (SST) data and temperature anomalies was the weakest. Confidence in these relationships increased when the extreme HDD anomaly years were examined. These results indicated that the relationships of climate indices to HDD anomalies exist and that these would be useful in developing and improving seasonal predictions for business applications.

1. Introduction

How cold is the winter going to be? What is causing this winter to be so cold or warm? These kinds of questions, often the subject of daily comment by the general public, take on much greater significance for the power utility companies who today must deal with the economic pressures arising from the deregulation of electricity and natural gas (Weiss, 1982; Brown & Murphy, 1987; Changnon *et al.*, 1995, Changnon *et al.*, 1999; Changnon *et al.*, 2000). Recent research has linked ENSO to winter precipitation and temperature anomalies in parts of the United States (Barnston *et al.*, 1999; Russo *et al.*, 1999). In addition, because of the increased demand on electricity, heating oil and natural gas during cold winters, meteorologists involved with advising those who trade these commodities have realised the need to better understand the factors that contribute to winter temperature anomalies and the importance of more accurate seasonal forecasts. Decision-makers in commodity firms and utilities now have a better grasp of the physical relationship between oceanic conditions and continental weather outcomes (Changnon, 2000).

Salomon Smith Barney is a worldwide commodities firm that employs meteorologists to advise traders on activities primarily in agricultural and energy sectors. As part of their daily, as well as long-term, research activities these meteorologists develop seasonal forecasts tailored for the commodity groups they serve. Through their communication with utility decision-makers they have learned how economically sensitive these organisations are to the occurrence of winter temperature extremes (either warm or cold) in these areas (Russo *et al.*, 1999). They have also learned that decision-makers in the energy industry need information on winter temperature anomalies for two parts of the winter, that prior to 1 January and that thereafter. This is because (a) most energy use for heating occurs in the northern regions of the United States from October through April; and (b) both meteorologists and utility decision-makers continually incorporate new information (based on climate indices and other non-weather factors (Changnon *et al.*, 2000)) and, if necessary, modify their decisions at winter's midpoint. Discovering important linkages between climate indices and temperature anomalies during these two cold season periods could improve outlooks and thus help those companies facing multi-month operational decisions (e.g. purchasing/selling additional natural gas) and planning decisions (e.g. plant maintenance schedules).

A great wealth of information has been accumulated about the following three climate indices and their impact on US seasonal climate (Horel & Wallace, 1981; Ropelewski & Halpert, 1987; Kiladis & Diaz, 1989; Hurrel, 1995; Kousky & Bell, 2000):

(a) ENSO (El Niño/Southern Oscillation).
(b) PNA (Pacific North American pattern).
(c) NAO (North Atlantic Oscillation).

Equatorial Pacific sea-surface temperatures (SST) have been used to classify the different phases of the ENSO phenomena (Trenberth, 1997). Positive (above average) SSTs associated with El Niños generally increase the strength of the subtropical jet stream in the northern hemisphere winter causing the southern tier of the United States to be cooler and wetter than average, while the northern tier of states are generally drier and warmer than average (Kousky & Bell, 2000). Negative (below average) SSTs associated with La Niñas are generally associated with wetter and cooler conditions in the Pacific Northwest and warmer than average conditions in the eastern United States. Although the PNA is often linked to ocean/atmosphere interactions in the equatorial Pacific it is generally characterised by tropospheric geopotential height anomalies measured at four centres located from the mid-Pacific to the eastern United States. When the PNA is positive there is a strong ridge over western Canada and a trough (colder than average temperatures) over the eastern United States (Wallace & Gutzler, 1981); these atmospheric anomalies are reversed when the PNA is negative – the ridge lies over the eastern United States and the trough over western Canada. The phases of the NAO are classified by examining the sea-level pressure differences between the Icelandic Low and the Azores High. A positive NAO is associated with a strong Icelandic low and a predominately zonal flow across the North Atlantic, and is linked to warmer than average winter temperatures in the eastern United States (Wallace & Gutzler, 1981). A negative NAO is generally associated with an atmospheric circulation pattern that is more meridional and is often related to colder-than-average winters in the eastern United States (Robinson & Henderson-Sellers, 1999).

This study seeks to build on previous research findings by closely examining the relationships between these indices and temperature anomalies in the two parts of the cold (heating) season and for two parts of the United States – the Midwest and Northeast. Relationships were assessed using data for a 48-year period (1951/52–1998/99. Because of the interest in understanding when seasonal temperature extremes (either cold or warm) might occur in these two regions, the study examines smaller samples of years, which represent the extremes in the temperature distributions, to determine if the relationships changed as the anomaly changed. If a good relationship existed between any or all indices and the winter temperature anomalies, it would increase the confidence of utility decision-makers in the use of seasonal temperature forecasts.

2. Data and approach

The study uses long-term (48-year) temperature data, as measured at first-order weather stations located in or near large metropolitan regions of the Midwest (Chicago, Cleveland, Columbus, Detroit, and Indianapolis) and the Northeast (Boston, Buffalo, New York, Philadelphia, Pittsburgh, and Washington D.C.). Instrument changes at these stations have occurred at least twice during the period of study. Most recently, during the mid-1990s, the Automated Station Observing System (ASOS) was implemented. Although some change in observed temperatures (≤1 °F) has been identified with the new temperature sensors at some stations (McKee *et al.*, 1995; Kauffman, 2000), an evaluation of the 48-year temperature record at these 11 stations using double mass curves did not indicate significant changes.

Monthly heating degree day (HDD) units were computed for each location for the 48-year period from 1951/52 through 1998/99. To meet users' interests, the HDD values were ascertained for two cold season periods: early (1 October to 31 December) and late (1 January to 30 April). For each city, the HDD anomaly (difference from the 48-year mean) was determined for each season during the 48 years. These city HDD anomalies in each region were averaged. The 48 regional HDD anomalies were ranked for each season, then divided into three equal categories: 16 above average, 16 near average, and 16 below average. A season with a mean temperature in the upper third of the distribution was associated with below average HDD, and a cold season (lower third of the mean temperature distribution) with above average HDD. In the Northeast the early season anomalies ranged from –101 to +167 HDD during the 48-year period, while the anomalies for the late season ranged from –120 to +102 HDD. In the Midwest the HDD anomaly ranges for the two periods were –131 to +209 (early) and –165 to +173 (late).

The climate indices used to identify concurrent relationships between regional HDD anomalies and oceanic/atmospheric teleconnections included equatorial Pacific SST associated with ENSO, NAO, and PNA. The monthly equatorial Pacific SST data were obtained for the El Niño 3.4 region. Monthly anomalies were computed to remove the seasonal cycle in that region. Thus, an anomaly of +0.49 °C would indicate that, for a particular month, SSTs were nearly half a degree warmer than the average value based on a 48-year average. The 48 seasonal SST anomalies for the early season ranged from –1.7 °C to +2.9 °C, while those for the late period ranged from –1.3 °C to +2.2 °C. For the other two climate indices, NAO and PNA, monthly values were averaged for the early and late seasons. The 48 seasonal NAO anomalies for the early period ranged from –1.5 to +1.5, while those for the late period ranged from –1.2 to +1.2. The PNA anomalies ranged from –1.1 to +1.7 (early) and –1.3 to +1.6 (late). For each of the three indices, anomalies were classified into three groups: above average (+), average (0), and below average (–). Owing to the nature of the data, few years in each sample experienced the mean value (0).

The initial analyses examined the statistical strength of relationship between regional HDD anomalies and climate index anomalies using data for all 48 years. Regression analysis provided correlation coefficients that indicated: (a) strength of the relationship, and (b) whether the two variables were positively or negatively related. The student's t-test statistic was used to determine whether the correlation coefficients were significantly different than zero at the 5% level. A second analysis determined the distribution of years by climate index anomaly (+, 0, or –) for each regional extreme HDD group (16 and 8 above-average and below-average categories), and is displayed in climate-relationship matrices. The objective was to determine whether the relationships changed as the sample size decreased and when only the extreme winter conditions were considered.

3. Results

3.1. Analyses using all 48 years

Regression analyses of the 48-year data set indicated that the strongest relationships were between regional HDD anomalies and NAO (Table 1) where the correlation coefficients were significant at the 5% level. For the Northeast, the early and late season correlation coefficients were somewhat higher than those found for the Midwest. This slightly higher correlation in the Northeast may be related to the proximity of the region to location of the NAO. In both regions and both seasons the relationships were negative (below-average NAO values related to above-average HDD values), as shown in Figure 1.

The relationship of PNA anomalies to HDD anomalies was not as strong as those found for NAO (Table 1) when considering all 48 years. The r-values for both regions were higher (and significant at the 5% level) during the 'early winter' period (Figure 2). Interestingly, the relationship between the PNA anomaly and HDD anomaly switched from positive in the early period (above-average PNA values related to above-average HDD values) to negative in the late period (above-average PNA values related to below-average HDD values), as seen in Figure 3. The relationship between PNA and HDD anomalies was similar in both regions.

Table 1. *Correlation coefficients based on relationships between climate indices (NAO, PNA and SST) and HDD anomalies for the 48 years (1951/52 through 1998/99). 'Early' indicates the October–December period; 'Late' indicates the January–April period.*

Region and relationship	Correlation coefficients
Midwest	
Early NAO vs. HDD	–0.37
Late NAO vs. HDD	–0.47
Early PNA vs. HDD	+0.40
Late PNA vs. HDD	–0.13
Early SST vs. HDD	+0.04
Late SST vs. HDD	+0.11
Northeast	
Early NAO vs. HDD	–0.40
Late NAO vs. HDD	–0.51
Early PNA vs. HDD	+0.38
Late PNA vs. HDD	–0.13
Early SST vs. HDD	+0.03
Late SST vs. HDD	+0.09

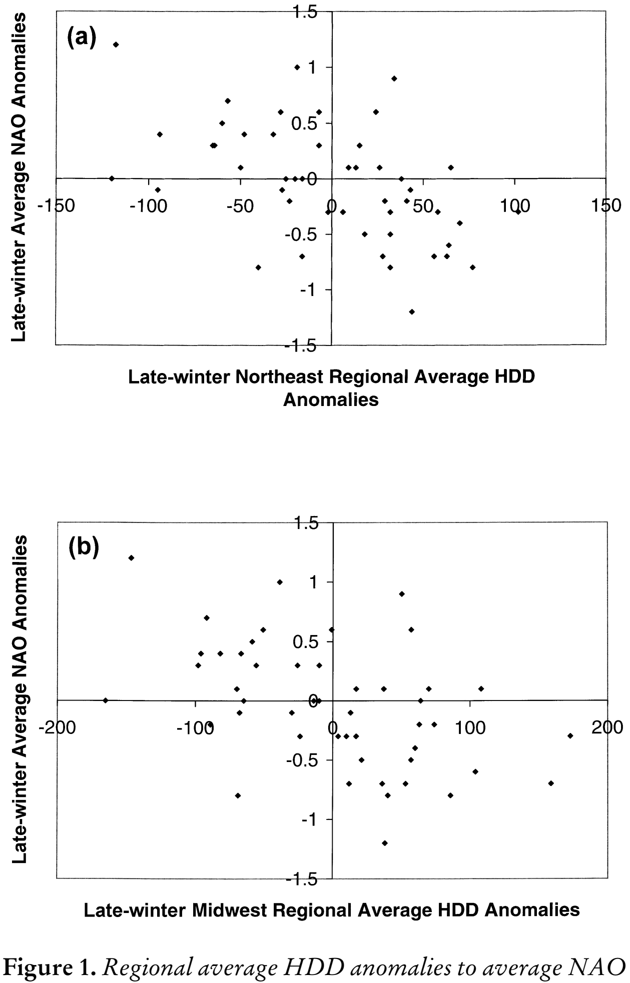

Figure 1. *Regional average HDD anomalies to average NAO anomalies for the late winter period during the 48-year period from 1951/52 through 1998/99 in (a) the Northeast and (b) the Midwest.*

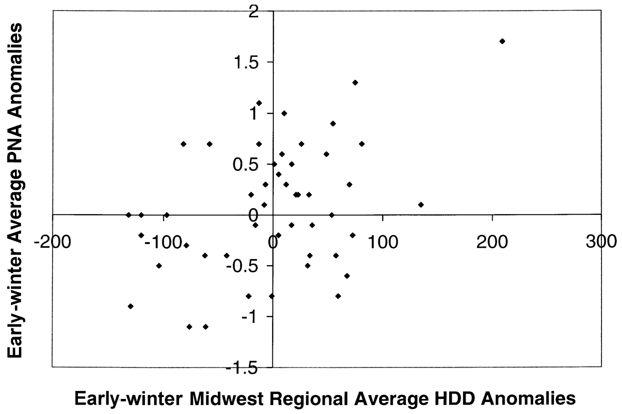

Figure 2. *Regional average HDD anomalies to average PNA anomalies for the early winter period during the 48-year period from 1951/52 through 1998/99 in the Midwest.*

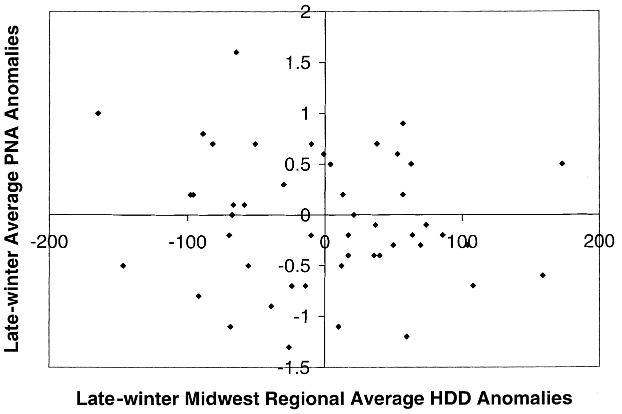

Figure 3. *Regional average HDD anomalies to average PNA anomalies for the late winter period during the 48-year period from 1951/52 through 1998/99 in the Midwest.*

The relationship of equatorial Pacific SST anomalies to regional HDD anomalies over the 48-year period was the weakest of the three indices examined, with r-values between +0.03 and +0.11. These low r-values were expected based on previous research that indicated no significant relationship between ENSO phases and winter temperature anomalies in these two US regions (Ropelewski & Halpert, 1987; Kiladis & Diaz, 1989; Kousky & Bell, 2000).

In the relationships between the three indices and HDD anomalies there was concern that the noise that exists in the near-average part of each distribution may be causing the low correlation values. Because decision-makers in most utility organisations are impacted more by seasonal temperatures out in the tails of the distribution than near its centre (Changnon *et al.*, 1995, Changnon *et al.*, 2000), an examination of the extremes was deemed important.

3.2. Analyses using the 16 warmest and 16 coldest years

In each region the 16 warmest seasons (lowest HDD totals) and 16 coldest seasons (highest HDD totals) were combined and analysed as a group of 32 years. A climate-relationship matrix indicated the number of years (out of 16) in each climate index anomaly type (+, 0, and –) that occurred with cold and warm winters during both early and late periods (Table 2). For example, in the Midwest during cold early periods, 12 of 16 (75%) had negative NAO anomalies, while during late warm periods, 11 of 16 (69%) had positive NAO anomalies. Both the Midwest and Northeast regions experienced negative NAO anomalies during cold (high HDD) seasons and positive NAO anomalies during warm (low HDD) seasons (Figure 4). As before, the PNA relationships associated with a particular winter temperature anomaly reversed from the early to the late period. For example, in the Midwest cold (positive HDD anomalies) early periods were primarily characterised by positive PNA anomalies (Figure 5), while cold late periods were most frequently associated with negative PNA anomalies (Table 2). The pattern was opposite for warm seasons.

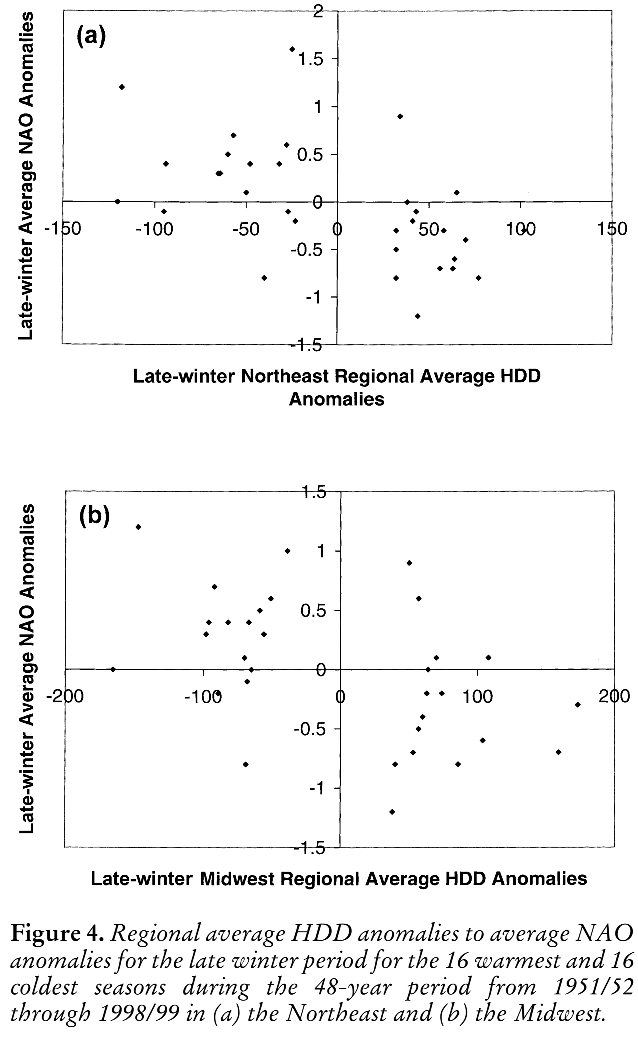

Figure 4. *Regional average HDD anomalies to average NAO anomalies for the late winter period for the 16 warmest and 16 coldest seasons during the 48-year period from 1951/52 through 1998/99 in (a) the Northeast and (b) the Midwest.*

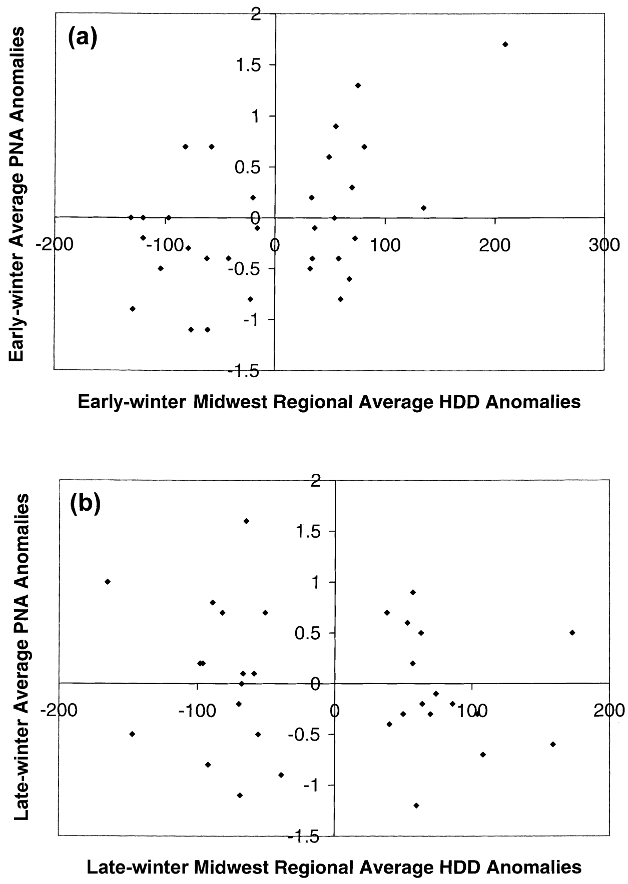

Figure 5. *Regional average HDD anomalies to average PNA anomalies for (a) early and (b) late winter periods for the 16 warmest and 16 coldest seasons during the 48-year period from 1951/52 through 1998/99 in the Midwest.*

For the primary climate index anomaly type (+, 0, or –), the PNA percentages ranged from 50% to 69%, while those found for NAO ranged from 63% to 88%. Equatorial Pacific SST anomalies were not related to HDD anomalies (Figure 6) and generally had the lowest percentages (ranging from 50% to 63%) for the primary anomaly type. However, similar to the NAO and PNA, the primary anomaly type found with SSTs for the late period and HDD anomalies (warm or cold) were similar for the Midwest and Northeast.

3.3. Analyses using the 8 warmest and 8 coldest years

A climate-relationship matrix similar to the one developed for the 32 extreme years was developed for the 16 extreme years (8 warmest and 8 coolest) for each season (Table 3). These samples located at the two ends of the HDD distribution approximate values outside one standard deviation. The number of years for the each anomaly type (+, 0, or –) was determined. For the primary index anomaly type, the percentage of years out of a possible eight, improves to 75% or higher in 7 of the 8 categories for NAO. Remarkably, in the two warm early period categories all 8 seasons were associated with positive NAO values (Figure 7). Similar to the results described for the 32 extreme years, the percentages associated with the primary index anomaly

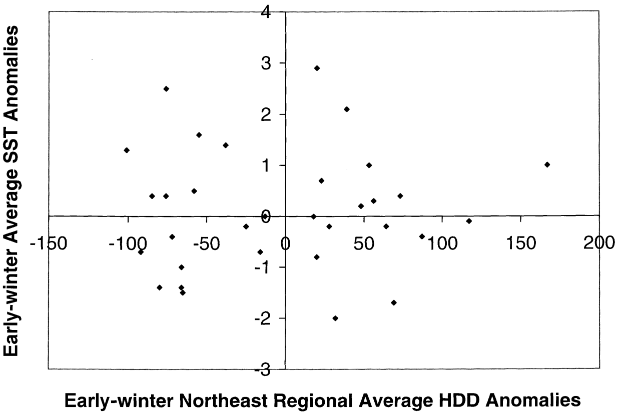

Figure 6. *Regional average HDD anomalies to average equatorial Pacific SST anomalies for the early winter period for the 16 warmest and 16 coldest seasons during the 48-year period from 1951/52 through 1998/99 in the Northeast.*

Table 2. *Number out of 16 seasons (warm and cold) experiencing each anomaly (+, 0, or –) for each climate index (NAO, PNA, and SST) during both seasons (early and late).*

Region, HDD anomaly and season	Number of years in each anomaly type								
	NAO			PNA			SST		
	+	0	–	+	0	–	+	0	–
Midwest									
Cold winters (early period)	4	0	12	8	1	7	7	0	9
Cold winters (late period)	4	1	11	6	0	10	10	1	5
Warm winters (early period)	12	0	4	3	3	10	8	1	7
Warm winters (late period)	11	2	3	9	1	6	9	2	5
Northeast									
Cold winters (early period)	5	0	11	11	1	4	8	1	7
Cold winters (late period)	2	1	13	6	0	10	8	2	6
Warm winters (early period)	14	0	2	6	3	7	7	1	8
Warm winters (late period)	11	1	4	10	1	5	9	2	5

Table 3. *Number out of 8 seasons (warm and cold) experiencing each anomaly (+, 0, or –) for each climate index (NAO, PNA, and SST) during both seasons (early and late).*

Region, HDD anomaly and season	Number of years in each anomaly type								
	NAO			PNA			SST		
	+	0	–	+	0	–	+	0	–
Midwest									
Cold winters (early period)	2	0	6	5	0	3	4	0	4
Cold winters (late period)	2	1	5	1	0	7	4	1	3
Warm winters (early period)	8	0	0	1	3	4	4	0	4
Warm winters (late period)	6	1	1	5	0	3	3	2	3
Northeast									
Cold winters (early period)	2	0	6	6	1	1	4	0	4
Cold winters (late period)	1	0	7	2	0	6	5	1	2
Warm winters (early period)	8	0	0	1	2	5	4	0	4
Warm winters (late period)	6	1	1	4	1	3	4	2	2

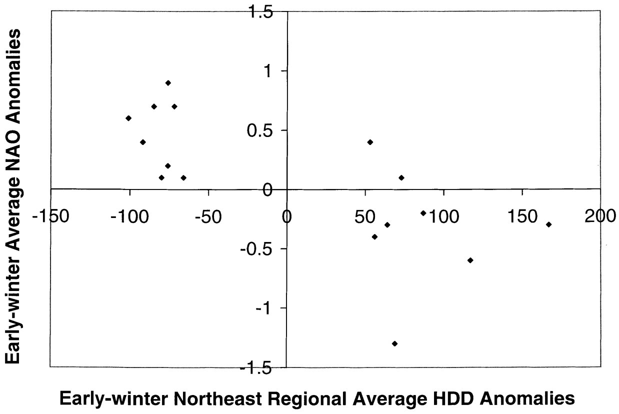

Figure 7. *Regional average HDD anomalies to average NAO anomalies for the early winter period for the 8 warmest and 8 coldest seasons during the 48-year period from 1951/52 through 1998/99 in the Northeast.*

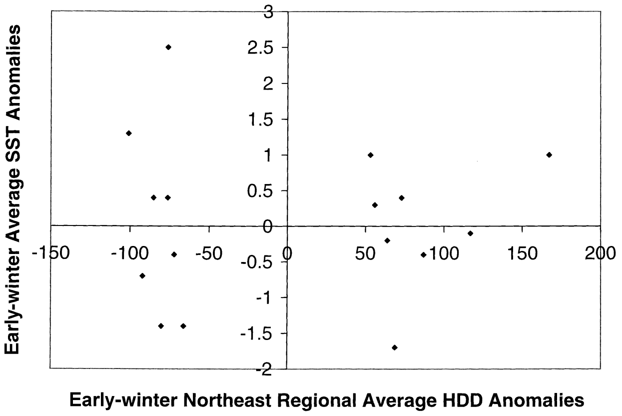

Figure 8. *Regional average HDD anomalies to average equatorial Pacific SST anomalies for the early winter period for the 8 warmest and 8 coldest seasons during the 48-year period from 1951/52 through 1998/99 in the Northeast.*

type were highest for NAO (ranging from 63% to 100%), then PNA (ranging from 50% to 88%), and lowest for equatorial Pacific SST (ranging from 50% to 63%). Although relationships could be discerned when examining NAO or PNA to HDD anomalies, no pattern appeared for SSTs (Figure 8). Except for the SSTs, the primary anomaly type did not change from those found when examining the 32 extreme years.

4. Conclusions

Defining the relationships between three key oceanic/atmospheric indices and heating degree day (HDD) anomalies in the Midwest and Northeast United States was the primary objective of this research. Improved understanding provides meteorologists in the energy commodities market with the opportunity to confirm or modify predictions using updated information, and consequently allows utility decision-makers to make more informed choices.

The study examined two separate parts of the cold season, 'early' (the three months before 1 January) and 'late' (the four months after 1 January), and focused on the 48-year period from 1951/52 through 1998/99. HDD data for 11 sites in the Midwest and Northeast were compared with values of NAO, PNA, and equatorial Pacific SST associated with ENSO. Because the energy sector is highly sensitive to the extreme seasonal climate anomalies, more emphasis was placed on identifying relationships during the 32 extreme winters (both cold and warm) and then on the 16 most extreme winters.

Overall, the relationships between the climate indices and seasonal HDD anomalies were generally similar to those found in previous research (Wallace & Gutzler, 1981; Ropelewski & Halpert, 1987; Kiladis & Diaz, 1989; Hurrel, 1995; Kousky & Bell, 2000). Interestingly, HDD anomalies in both regions were best related to NAO. As the number of years in the HDD sample decreased, the percentages associated with a primary anomaly type (+, 0, or –) improved for both regions and both seasons for NAO and PNA, indicating greater confidence in the relationships at the tails of the HDD distribution. Although a significant amount of attention has focused on the use of ENSO-based seasonal climate forecasts (Changnon, 2000), relationships between SST anomalies and winter HDD anomalies in this part of the United States were found to be weak. The analyses indicated that the two ends of the SST distribution (i.e. El Niños and La Niñas) were not associated with a single HDD anomaly, either cold or warm, in these regions. These results indicate that mid-latitude ocean/atmosphere indices located near North America appear to be more strongly teleconnected to winter temperatures in the Midwest and Northeast than those indices measured in the equatorial Pacific. Overall, the findings were similar for the Midwest and Northeast, suggesting that a latitudinal relationship exists in this broad area of the United States between the three indices and cold season temperature anomalies.

Early periods that were cold (high HDD totals) were characterised by negative NAO anomalies and positive PNA anomalies, whereas late season cold periods were associated with negative NAO and PNA anomalies. Early periods that were warm (low HDD totals) were characterised by positive NAO anomalies and negative PNA anomalies, while late season warm periods were associated with positive NAO and PNA anomalies. The change in the primary PNA anomaly from the pre- to the post-January 1 period, associated with one type of HDD anomaly, was unexpected and not explained in this study. These results will take on added importance for both seasonal temperature forecasters (Weiss, 1982) and utility decision-makers (Changnon *et al.*, 1995; Changnon *et al.*, 2000) when seasonal anomalies of the NAO and PNA can be predicted accurately some months in advance of the cold seasons.

Acknowledgments

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