Using Equatorial Pacific Sea Surface Temperature Anomalies to Forecast Seasonal Energy Demand in Four U.S. Regions: An Applied Climate Research Experience for Undergraduate Meteorology Students

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ABSTRACT

The El Niño–Southern Oscillation (ENSO) phenomenon explains some of the interannual climate variability in many tropical and midlatitude regions. It is important in developing more accurate seasonal climate forecasts and thus in aiding long-range weather-sensitive decision making in various sectors.

The degree to which ENSO information could forecast one of three classes of seasonal cooling degree days (CDD) and heating degree days (HDD) was examined using 1) the magnitude of the ENSO event during a given season, 2) the preseason rate of change of sea surface temperature (SSTs) (December–May for summers and June–October for winters), and 3) the effects of strong winter ENSO events on future seasons. All three ENSO-related indices were based on monthly equatorial Pacific SST anomalies in the Niño-3.4 region. Regional probabilities of each HDD/CDD category (above, average, and below) were determined for each ENSO predictive index. The highest probability of experiencing an HDD/CDD anomaly occurs with strong preseason SST trends. When presummer SST cooling occurs, the northeast and midcontinent experience above-average CDD (80% and 75%, respectively). Other interesting relationships were found between strong winter ENSO events and ensuing HDD/CDD anomalies. These results suggest that utility-based decision makers who can utilize enhanced climate information may reap benefits during particular years by integrating the ENSO information into their models. This study was part of a special student training experiment conducted at Northern Illinois University.

1. Introduction

Deregulation of the natural gas (in the early 1990s) and electricity (in 1997) energy markets, and the success of the 1997/98 “long-lead” winter temperature forecast is changing how power utility decision makers view the use of climate information and seasonal forecasts (Changnon et al. 1995; Climate Prediction Center 1998). Furthermore, those organizations concerned about the weather’s impact on future pricing of energy commodities have enlisted specialists to aid them with interpreting and enhancing the climate fore-

casts and information that they use in their decision models (Davis 1998). Their interests include understanding current and forecasted weather and climate trends in the United States and around the world. Developing this knowledge and incorporating it into decisions requires much communication between weather-sensitive decision makers and applied climatologists (Changnon 1998).

The El Niño–Southern Oscillation (ENSO) phenomenon is associated with a considerable degree of interannual climate variability in various regions of the Tropics and midlatitudes (Glantz et al. 1991). Previous research (Ropelewski and Halpert 1986; Yarnal and Diaz 1986; Ropelewski and Halpert 1987; Trenberth et al. 1988; Kiladis and Diaz 1989; Glantz et al. 1991) has identified seasonal temperature and precipitation anomalies associated with El Niños [above-average sea surface temperatures (SSTs) in the equatorial Pacific] and La Niñas (below-average SSTs). In recent years the Climate Prediction Center (CPC) of the National Oceanic and Atmospheric Administration (NOAA) and others have realized the

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FIG. 1. Location of the four regions and the 19 cities used in the study.

importance of the ENSO phenomenon in developing seasonal predictions (Climate Prediction Center 1998). However, potential users often request that the probability forecasts provided by the CPC be interpreted to fit their needs and enhanced by developing climate profiles based on analogs of previous similar ENSO experiences.

This study was part of a special student training experiment conducted at Northern Illinois University (Changnon 1998). The topics chosen for study in this program are selected by cooperating user groups (private and public sector weather-sensitive organizations). Any given study has limiting dimensions, which include 1) developing an answer (product) addressing the user's selected problem within a 4-month period and 2) using undergraduate (senior level) students to conduct the research under faculty guidance. By its nature, this program aims to train students how to address real-world applied climatological problems. Hence, the dimensions of the program limit the amount of in-depth fundamental research that can be accomplished, given the time limits and level of educational training of those involved.

This particular study aimed to discern the relationship between recent (1952–96) El Niño and La Niña events, and winter and summer energy demands in four important energy markets east of the Rockies (northeast, midcontinent, Texas triangle, and southeast). The commodities expert who served as the user interface on the project (J. B. Davis 1998, unpublished

manuscript) chose these markets because of the large amounts of energy used in each. Both the magnitude of the SST anomalies (differences from the monthly mean SST values for the Niño-3.4 region) and the SST trend (changes in SST anomalies, December–May for summers and June–October for winters) were examined to find the strongest relationships between these ENSO characteristics and 1) winter (December–February) heating degree days (HDD) and 2) summer (June–August) cooling degree days (CDD). Both seasonal HDD and CDD totals were determined by calculating the difference between the daily mean temperature and 65°F (those days with means > 65°F in the summer and less than 65°F in the winter) and summing the daily differences for the season. These ENSO-related predictive tools, which used current and forecasted SST anomalies, were developed to aid those making operational decisions at utilities. This information could be applied by utility decision makers to understand when and where to expect energy surpluses and deficits and to optimize economic decisions.

2. Data and approach

This study used first-order weather stations in each region that had high-quality, long-term records. Because seasonal temperature conditions vary very little within the four climate regions, a small sample of high-quality stations was selected for each area. The 19 stations chosen represent the larger cities in each region and were considered to be the locations where the greatest demand for heating and cooling occurs (Fig. 1). Data were obtained from the Midwestern Climate Center's MICIS system (Reinke et al. 1996). Seasonal CDD and HDD totals were determined for summers and winters, respectively, over a 45-yr period (1952–96).

For each station, the 45 winter HDD totals and summer CDD totals were ranked and separated into three groups: 15 above average (A is top third of each distribution), 15 near average (N is middle third of each distribution), and 15 below average (B is lower third of each distribution). Thus, a warm winter would be associated with below-average HDD, while a warm summer would expect above-average CDD. For each winter and summer in the 45-yr period, regional totals (number of A, N, and B) were determined by summing the values from the stations in each region. These regional totals were then summed for all years in each ENSO category and expressed as the probability of A, N, and B.

TABLE 1. ENSO classification of summers and winters for 1952–96 period.

Summer	ENSO Event	Winter	ENSO Event
1952	Non	1952/53	Pre–El Niño
1953	El Niño	1953/54	Post–El Niño
1954	La Niña	1954/55	La Niña
1955	La Niña	1955/56	Strong La Niña
1956	La Niña	1956/57	Post–La Niña
1957	El Niño	1957/58	Strong El Niño
1958	El Niño	1958/59	Non
1959	Non	1959/60	Non
1960	Non	1960/61	Non
1961	Non	1961/62	Non
1962	Non	1962/63	Non
1963	El Niño	1963/64	El Niño
1964	La Niña	1964/65	La Niña
1965	El Niño	1965/66	Strong El Niño
1966	El Niño	1966/67	Non
1967	Non	1967/68	Non
1968	Pre–El Niño	1968/69	El Niño
1969	El Niño	1969/70	El Niño
1970	La Niña	1970/71	Strong La Niña
1971	La Niña	1971/72	La Niña
1972	El Niño	1972/73	Strong El Niño
1973	La Niña	1973/74	Strong La Niña
1974	La Niña	1974/75	La Niña
1975	La Niña	1975/76	La Niña
1976	Pre–El Niño	1976/77	El Niño
1977	El Niño	1977/78	El Niño
1978	Non	1978/79	Non
1979	Pre–El Niño	1979/80	El Niño
1980	Post–El Niño	1980/81	Non
1981	Non	1981/82	Non
1982	El Niño	1982/83	Strong El Niño
1983	El Niño	1983/84	Non
1984	Pre–La Niña	1984/85	La Niña
1985	La Niña	1985/86	Non
1986	Pre–El Niño	1986/87	El Niño
1987	El Niño	1987/88	Strong El Niño
1988	La Niña	1988/89	Strong La Niña
1989	La Niña	1989/90	Non
1990	Non	1990/91	Pre–El Niño
1991	El Niño	1991/92	Strong El Niña
1992	El Niño	1992/93	Pre–El Niño
1993	El Niño	1993/94	Post–El Niño
1994	El Niño	1994/95	El Niño
1995	Pre–La Niña	1995/96	La Niña
1996	Non	1996/97	Non

The ENSO-related dataset used in this study was monthly equatorial Pacific SST anomalies determined for the Niño-3.4 region (5°N–5°S, 120°–170°W) from the Climate Prediction Center (Climate Prediction Center 1998). Based on prior research (Trenberth

TABLE 2. Number of ENSO events in each category for summers in 1952–96 period. Those not considered in Table 3, because of small sample sizes, are in italics and underlined.

ENSO event	Summer	Winter
Pre–El Niño	4	3
Strong El Niño	<u>0</u>	6
El Niño	16	8
Post–El Niño	<u>1</u>	<u>2</u>
Non-ENSO	10	14
Pre–La Niña	<u>2</u>	<u>0</u>
Strong La Niña	<u>0</u>	4
La Niña	12	7
Post–La Niña	<u>0</u>	<u>1</u>

1997), a 5-month running mean of SST anomalies was used to classify ENSO events into nine categories: pre–El Niño, strong El Niño, El Niño, post–El Niño, non-ENSO, pre–La Niña, strong La Niña, La Niña, and post–La Niña, for the winter (December–February) and summer (June–August) seasons. El Niño events occurred when the 5-month running mean was greater than or equal to +0.4°C for at least six consecutive months (Trenberth 1997), while La Niña events occurred when the 5-month running mean was less than or equal to –0.4°C for at least six consecutive months. Preevents were arbitrarily defined as ENSO events that began between 1 February and 31 March for winter seasons and between 1 August and 31 October for summer seasons. For example, the 1952/53 winter is classified as a pre–El Niño because the El Niño event did not start until March 1953. Postevents were arbitrarily defined as ENSO events that ended between 1 April and 31 May for summer seasons, and between 1 September and 30 November for winter seasons. An example of a post–El Niño is the summer of 1980 when the 1979/80 El Niño ended in April 1980. Strong ENSO events occurred when the 5-month running mean of SST anomaly was greater than or equal to ±1.5°C for at least one winter or summer month. Non-ENSO events were defined by an SST anomaly less than +0.4°C and greater than –0.4°C. If both the precriteria and postcriteria were met (e.g., summer 1976: post–La Niña and pre–El Niño) the event was given the “pre” designation because it started during a summer month. However, if an event received either a “pre” or “post” *and* if either the El Niño or La Niña criterion was met (e.g., summer 1974: pre–La Niña and La Niña) the event was given either the respective

TABLE 3a. Winter HDD and summer CDD probabilities during ENSO events for the northeast. A dash is used to represent sample sizes too small to determine useful conclusions.

ENSO event	Winter HDD			Summer CDD		
	A	N	B	A	N	B
Pre-El Niño	0%	17%	83%	6%	67%	27%
Strong El Niño	3%	44%	53%	-	-	-
El Niño	54%	31%	15%	37%	25%	38%
Post-El Niño	-	-	-	-	-	-
Non-ENSO	56%	30%	14%	25%	40%	35%
Pre-La Niña	-	-	-	-	-	-
La Niña	14%	47%	39%	32%	36%	32%
Strong La Niña	21%	38%	41%	-	-	-
Post-La Niña	-	-	-	-	-	-

El Niño or La Niña designation. These were the only examples when more than one criterion was met for the same season.

Summer preseason SST trends were determined by subtracting the December SST value from the following May SST value. For example, a presummer warming would be represented by a positive value. Winter pre-season SST trends were determined by subtracting the June SST value from the November SST value. The presummer and prewinter trends were each ranked. Regional HDD/CDD probabilities were determined for the six greatest presummer and prewinter SST trends (warming and cooling) identified during the 45-yr period. Based on comments made by the company contact (J. B. Davis 1998, unpublished manuscript) and because the samples were generally small, no tests to determine significance were conducted.

3. Results

a. Relationship of ENSO class and seasonal CDD/HDD categories

Data about current and forecasted SST conditions are available through a number of sources, including NOAA's Climate Prediction Center. Real-time and/or future decisions can be made based on present or expected ENSO conditions. The ENSO-related model predicted the probabilities of each CDD/HDD anomaly (A, N, and B) based on analogs of previous (1952–96) ENSO events.

Initially, each summer and winter was classified into an ENSO category based on the criteria described earlier (Table 1). The breakdown into category varies for each season (Table 2). For winters, the category with the highest number was non-ENSO, while the El Niños occurred most frequently in summers during this 45-yr period. In both seasons El Niño-related

TABLE 3b. Same as in Table 3a but for the midcontinent.

ENSO event	Winter HDD			Summer CDD		
	A	N	B	A	N	B
Pre-El Niño	0%	7%	93%	7%	47%	46%
Strong El Niño	3%	50%	47%	-	-	-
El Niño	55%	23%	22%	33%	28%	39%
Post-El Niño	-	-	-	-	-	-
Non-ENSO	57%	27%	16%	24%	36%	40%
Pre-La Niña	-	-	-	-	-	-
La Niña	20%	57%	23%	42%	35%	23%
Strong La Niña	5%	55%	40%	-	-	-
Post-La Niña	-	-	-	-	-	-

events occurred more than La Niña events. Based on the ENSO classifications, strong El Niños and La Niñas only occurred in winters. Categories with less than three samples, such as post-La Niña, were not evaluated due to small sample size.

For the four regions, the regional probabilities for the three HDD/CDD categories were determined for each ENSO class (Tables 3a–d). In the winter during a pre-El Niño event, all four regions experience average to below-average HDD. In the summer during a pre-El Niño event, the northeast has a greater probability (67%) of average CDD [than below (27%) or above CDD (6%)], while the midcontinent, Texas triangle, and southeast regions have greater probabilities of average to below-average CDD. During the six strong El Niño events, the northeast and midcontinent experienced a greater probability of average to below-average HDD, whereas the Texas triangle and southeast experienced a greater probability of average to above-average HDD. For the eight El Niño events, all four regions experienced average to above-average HDD, a reversal in the northern two regions from what is seen in strong El Niños. During a summer experiencing an El Niño event, only the Texas triangle showed a relationship of average to above-average CDD, while other regions show no relationship.

During the 14 non-ENSO winters, all four regions experienced a greater probability of average to above-average HDD. During the 10 non-ENSO summers, the northeast and midcontinent regions had greater chances of average to below-average CDD, while the Texas triangle experienced a higher probability of average CDD, and the southeast experienced average to above-average CDD.

During the seven La Niña winters, the northeast, Texas triangle, and southeast regions experienced a higher

TABLE 3c. Same as in Table 3a but for the Texas triangle.

ENSO event	Winter HDD			Summer CDD		
	A	N	B	A	N	B
Pre-El Niño	0%	56%	44%	0%	0%	100%
Strong El Niño	56%	28%	16%	-	-	-
El Niño	38%	38%	24%	47%	33%	20%
Post-El Niño	-	-	-	-	-	-
Non-ENSO	57%	29%	14%	27%	43%	30%
Pre-La Niña	-	-	-	-	-	-
La Niña	10%	43%	47%	25%	33%	42%
Strong La Niña	0%	33%	67%	-	-	-
Post-La Niña	-	-	-	-	-	-

TABLE 3d. Same as in Table 3a but for the southeast.

ENSO event	Winter HDD			Summer CDD		
	A	N	B	A	N	B
Pre-El Niño	0%	13%	87%	20%	20%	60%
Strong El Niño	33%	43%	24%	-	-	-
El Niño	63%	25%	12%	38%	33%	29%
Post-El Niño	-	-	-	-	-	-
Non-ENSO	49%	34%	17%	38%	36%	26%
Pre-La Niña	-	-	-	-	-	-
La Niña	15%	48%	37%	23%	35%	42%
Strong La Niña	0%	40%	60%	-	-	-
Post-La Niña	-	-	-	-	-	-

TABLE 4. The six greatest presummer SST warmings and coolings, and prewinter SST coolings in degrees Celsius.

Rank	Presummer cooling	Presummer warming	Prewinter cooling
1	-1.35 (1973)	+2.75 (1972)	-2.46 (1983)
2	-1.07 (1988)	+2.73 (1989)	-2.02 (1961)
3	-0.76 (1964)	+2.71 (1965)	-1.89 (1955)
4	-0.65 (1966)	+2.58 (1956)	-1.85 (1995)
5	-0.24 (1983)	+2.52 (1971)	-1.69 (1970)
6	-0.16 (1995)	+2.40 (1976)	-1.68 (1992)

probability of average to below-average HDD, while the midcontinent region had a higher chance of average HDD. The four strong La Niña events occurring during winter were associated with average to below-average HDD in all four regions. In the Texas triangle and southeast regions no above-average HDD winters occurred. There were no clear relationships between summer La Niñas and CDD anomalies for any region.

b. Effect of presummer and prewinter SST trends on seasonal CDD/HDD categories

The six greatest preseason SST trends were determined for winters and summers (Table 4). Because only two prewinter warming events occurred, no results were determined for this category. The influence of the six greatest presummer and prewinter SST trends on CDD and HDD probabilities was determined using analogs (Tables 5a–d). There was a strong relationship between strong preseason SST trends and the ensuing number of winter HDD and summer CDD. After strong presummer warming events, all four regions experienced a greater probability of average to below average CDD. After strong prewinter cooling, the northeast and midcontinent regions had a greater probability of average to above-average HDD, while the Texas triangle and southeast regions experienced a higher percentage of average to below-average HDD. Finally, following strong presummer cooling, the northeast and midcontinent regions experienced above-average CDD, while the Texas triangle and southeast regions had more average to below-average CDD.

c. Effect of strong ENSO events on future CDD/HDD categories

The final analyses dealt with the influence of the strongest winter ENSO events (Table 1) on future CDD and HDD values. A strong relationship between CDD and HDD values following strong winter ENSO

events existed (Tables 6a–d). Following the six strong winter El Niños, the northeast and midcontinent regions experienced a high percentage of above-average summer CDD, while the Texas triangle and southeast regions had average to below-average summer CDD. For winters one year after a strong winter El Niño, there was no strong relationship with HDD in any region except the southeast region where there was an average to below-average HDD bias.

Following the four strong winter La Niñas, the summer CDD for all four regions were average to below average. Furthermore, a strong relationship existed between winters following strong La Niñas by one year. For all four regions it is highly likely that below-average HDD values will be experienced during the winter one year after a strong La Niña.

4. Conclusions

In this applied climate project, the corporate meteorologist was interested in determining whether a relationship between ENSO characteristics defined by equatorial Pacific SST anomalies and regional heating and cooling degree day anomalies existed. Although ENSO does not explain all changes in seasonal weather patterns, it has been shown to be related to variations in precipitation and temperature anomalies across the United States and other regions of the world (Glantz et al. 1991).

The approach was to use analogs of past events to aid in predicting future events. Three different ENSO indices were examined to determine how well ENSO information could forecast regional seasonal CDD and HDD anomalies: 1) the magnitude of the ENSO event during a given season, 2) the preseason rate of change of SST (December–May for summers and June–October for winters), and 3) the effects of the strong winter ENSO events on future seasons.

During winters prior to the start of an El Niño (in February or March) the northeast, midcontinent, and southeast regions experience a below-average number of HDD (83%, 93%, and 87%, respectively). Likewise, during summers prior to the start of an El Niño (in the period from August through October) there is a 100% chance that the Texas triangle will experience below-average CDD. However, due to the small sample size

associated with these ENSO classifications results should be viewed with caution.

The best ENSO tool for predicting summer CDD and winter HDD anomalies was found to be preseason SST trends (i.e., the SST trend in the six months preceding winter or summer). The highest probabilities associated with presummer SST cooling were found in the northeast and midcontinent regions where the ENSO index indicated a high probability of above-average CDD (80% and 75%, respectively). Similarly, there is a 77% probability that the southeast region will experience a below-average number of CDD when SSTs have warmed.

Relationships between strong winter ENSO events and CDD/HDD anomalies also appeared relatively strong. This behavior reflects how strong ENSO events can become the most influential factor contributing to the development of seasonal weather patterns across the United States when compared to other atmospheric phenomena. Summers and winters following strong winter ENSO events have high probabilities of experiencing a summer CDD or winter HDD anomaly. For example, in summers following a strong winter El Niño, the midcontinent has a 60% chance of experiencing above-average CDD, whereas the Texas triangle has a 61% chance of experiencing below-average CDD. Also, during the summer following a strong winter La Niña, all regions experience an average to below-average CDD bias (northeast, 87%; midcontinent, 95%; Texas triangle, 75%; southeast, 80%). Winters following a strong winter La Niña experience a high probability of below-average HDD in all regions (northeast, 67%; midcontinent, 60%; Texas triangle, 67%; southeast, 95%).

Although interesting relationships were found between a current or projected ENSO category and regional

TABLE 5a. Winter HDD and summer CDD probabilities following preseason SST trends for the northeast. A dash is used to represent sample sizes too small to determine useful conclusions.

SST trend	Winter HDD			Summer CDD		
	A	N	B	A	N	B
Preseason warming	-	-	-	11%	36%	53%
Preseason cooling	47%	44%	9%	75%	14%	11%

TABLE 5b. Winter HDD and summer CDD probabilities following preseason SST trends for the midcontinent.

SST trend	Winter HDD			Summer CDD		
	A	N	B	A	N	B
Preseason warming	-	-	-	3%	33%	64%
Preseason cooling	50%	37%	13%	80%	20%	0%

TABLE 5c. Winter HDD and summer CDD probabilities following preseason SST trends for the Texas triangle.

SST trend	Winter HDD			Summer CDD		
	A	N	B	A	N	B
Preseason warming	-	-	-	22%	39%	39%
Preseason cooling	17%	28%	55%	17%	28%	55%

TABLE 5d. Winter HDD and summer CDD probabilities following preseason SST trends for the southeast.

SST trend	Winter HDD			Summer CDD		
	A	N	B	A	N	B
Preseason warming	-	-	-	13%	10%	77%
Preseason cooling	23%	50%	27%	30%	30%	40%

TABLE 6a. Winter HDD and summer CDD probabilities following strong winter ENSO events for the northeast.

Strong event	Summer CDD			Winter HDD		
	A	N	B	A	N	B
Strong El Niño	58%	8%	34%	25%	39%	36%
Strong La Niña	13%	20%	67%	0%	33%	67%

TABLE 6b. Winter HDD and summer CDD probabilities following strong winter ENSO events for the midcontinent.

Strong event	Summer CDD			Winter HDD		
	A	N	B	A	N	B
Strong El Niño	60%	10%	30%	33%	27%	40%
Strong La Niña	5%	50%	45%	0%	40%	60%

TABLE 6c. Winter HDD and summer CDD probabilities following strong winter ENSO events for the Texas triangle.

Strong event	Summer CDD			Winter HDD		
	A	N	B	A	N	B
Strong El Niño	6%	33%	61%	39%	28%	33%
Strong La Niña	25%	33%	42%	0%	33%	67%

TABLE 6d. Winter HDD and summer CDD probabilities following strong winter ENSO events for the southeast.

Strong event	Summer CDD			Winter HDD		
	A	N	B	A	N	B
Strong El Niño	26%	37%	37%	23%	27%	50%
Strong La Niña	20%	30%	50%	0%	5%	95%

CDD/HDD anomalies, some unexplained differences also were found. For instance, regional CDD/HDD anomalies associated with strong El Niños were opposite those for weaker El Niños, perhaps indicating the importance of the SST magnitude on the large-

scale atmospheric patterns that become established. Further, the small sample size associated with several ENSO categories limits the confidence that can be placed in the results.

Despite the small sample size (45 yr), the results suggest that power utility decision makers who integrate ENSO information into their decision models may reap some benefits during particular years. More broadly speaking, this study provides an example of how climatologists can readily apply available climate information to aid those who are impacted by seasonal climate phenomena.

An assessment of the project, the initial goals, and the described results indicated that the students, faculty, and the weather-sensitive decision maker from Salomon Smith Barney viewed the experience as a "success." Most importantly, students involved 1) gained an understanding of the problems facing weather-sensitive users, 2) learned how to communicate scientific information in oral and written presentations, and 3) worked together as a team to successfully complete the project. The faculty member (Changnon) became better aware of the ways to enhance available climate information to answer questions for specific users in utilities. The weather-sensitive decision maker realized the benefit from integrating various types of enhanced climate information into long-term seasonal decisions. Results from this project were incorporated into seasonal heating demand predictions for the 1998/99 winter. Based on his efforts as a student in this project, M. Russo was hired by Salomon Smith Barney to assist J. Davis with short- and long-term forecasting activities.

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