The REDTI and MSI: Two New National Climate Impact Indices

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(Manuscript received 12 June 2002, in final form 29 April 2003)

ABSTRACT

Two climate indices that are useful for monitoring the impact of weather and climate on energy usage and crop yields in the United States have been developed at the National Climatic Data Center. The residential energy-demand temperature index (REDTI), which is based on total population-weighted heating and cooling degree days in the contiguous United States, provides quantitative information on the impact of seasonal temperatures on residential energy demand. The moisture stress index (MSI) is based on the effect of severe to catastrophic drought (Palmer Z index values ≤ -2) or catastrophic wetness ($Z \geq +5$) on crop productivity within two crop-growing regions (corn and soybeans). Using climate data that extends into the late nineteenth century and operational updates of near-real-time data, the indices provide information that places the impact of weather and climate on energy-supply and crop-production sectors of the economy during the most recent season into historical perspective.

1. Introduction

Weather is frequently used to explain seasonal and year-to-year changes in economic performance. For example, the U.S. Department of Commerce's Bureau of Economic Analysis estimates that 42% of the U.S. gross domestic product is climate sensitive (National Research Council 1998). The impact of weather and climate on the economy may be significant, but the explanations are often subjective and many times are based on perceptions rather than on clear observational evidence. This paper takes some initial steps to address this deficiency by identifying and quantifying the relationship between climate anomalies and two economic sectors: residential energy usage, and corn and soybean yield.

Climate-impact indicators are an appropriate tool because they provide useful objective information to users whose activities require them to manage climate risks and opportunities. For example, such climate-based indices could aid in assessments of economic losses from weather extremes for government and business interests (Changnon and Hewings 2001) and could provide insight from historical trends of temperature and precipitation to foreshadow the impacts of climate fluctuation and change on modern-day economic and agricultural systems (Easterling and Kates 1995).

The National Climatic Data Center (NCDC), a center in the National Oceanic and Atmospheric Administration/National Environmental Satellite, Data, and Information Service (NOAA/NESDIS), has a long history of providing climate information relevant to the economy and society as a whole. Indices such as the Palmer drought indices and heating, cooling, and growing degree days are examples of the operational dissemination of this kind of climate information. In addition, NCDC has developed indices that combine a number of factors to give a more coherent picture of the climate. The climate extremes index and greenhouse response index are research indices that combine a number of measures (e.g., percent area of the United States in severe drought or wetness, or percent area with extreme temperatures) to produce index time series to show climatic behavior over the twentieth century (Karl et al. 1996). NCDC's operational national climate-impact indices are available on the Internet as of the time of writing (http://www.ncdc.noaa.gov/oa/climate/research/cie/cie.html).

As part of an ongoing program to understand better the impact of weather and climate on vital socioeconomic sectors, two new indices have been developed that provide information related to crop yield and energy usage. The crop moisture stress index (MSI) reflects the influence of severe drought and catastrophic wetness on annual crop yield for corn and soybeans, and the resi-

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dential energy-demand temperature index (REDTI) provides quantitative information on the impact of seasonal temperatures on residential energy demand. These indices have been developed to provide an assessment of the expected impacts of historical climate variability on current agricultural productivity and energy utilization patterns. They were developed using readily available data so that they can be easily applied on a global basis. This paper discusses the development of the MSI and REDTI.

2. Data

The climate division database (Guttman and Quayle 1996) is used for the operational computation of the MSI and REDTI. This database consists of monthly mean temperature, precipitation, degree days, and drought indices for 344 climate divisions in the contiguous United States. It is spatially and temporally complete from January 1895 to the present, and the data are computed operationally by NCDC on a near-real-time basis.

The divisional temperature and precipitation values were calculated by averaging the corresponding station observations within each division beginning in January 1931 and were calculated from a regression analysis (of statewide values generated by averaging station observations within each state) for prior to 1931 (Guttman and Quayle 1996). Divisional values for heating and cooling degree days (HDD and CDD, respectively) [base 18.3°C (65°F)] were derived from the divisional temperature data by using a statistical algorithm developed by Thom (1954a,b, 1966), and the drought indices were computed from monthly divisional temperature and precipitation using the Palmer method (Palmer 1965).

Individual stations may suffer from inhomogeneities because of missing data, station moves, and changes in instrumentation and observation time. In addition, stations open and close over time. Effects of these inhomogeneities are minimized in the climate division database through the process of averaging all available NOAA station data within a division and by applying a time of observation adjustment factor to the temperature data (Karl et al. 1986).

3. Methods

a. REDTI

The REDTI is based on population-weighted HDDs and CDDs. The use of population weighting in averaging degree days across the United States results in a national degree-day average that more closely reflects temperature deviations in heavily populated areas of the country. The close association between residential energy demand and degree days (Quayle and Diaz 1980; Changnon and Hewings 2001) makes the REDTI a valuable tool for explaining year-to-year fluctuations in energy demand for residential heating and cooling. Population weighting is based on census figures from 2000 for the 344 climate divisions applied throughout the period of record. Therefore, a REDTI time series portrays the historical variability of the temperature-related energy demand as it would have been if one assumes that present-day population density and energy utilization patterns had existed throughout the historical record.

Household data were analyzed to determine if they would provide a more accurate REDTI by recomputing the REDTI time series using the number of households as weights instead of population weighting. The results were virtually identical to the time series computed using population as weights. Correlation coefficients computed between the household- and population-weighted REDTI were very high (0.9994 was the lowest monthly or seasonal value). As a consequence, it was decided to follow the common practice of using population to weight the degree days instead of number of households.

The REDTI is calculated on a seasonal basis, using the sum of population-weighted HDDs and CDDs, to provide retrospective information on the impact of seasonal temperatures on residential energy demand from 1895 to the present. To simplify year-to-year comparisons, the index is linearly scaled from 0 to 100. An index of 100 is assigned to the year with the greatest population-weighted degree-day average, and the year with the smallest degree-day average receives an index of 0. Annual updates may result in a rescaling of the index values.

To determine how well the index captures year-to-year changes in energy demand, the REDTI was correlated with U.S. residential energy consumption for the period of 1980–2000/01. National residential energy-consumption values were supplied by the U.S. Energy Information Agency and are composed of residential coal, natural gas, petroleum, and electricity (excluding electricity losses) usage. At the time of this analysis, these data were available from 1973 through the winter of 2001, but the data from the 1970s were omitted from the analysis for the following reason. The latter half of the 1970s was a period of dramatic change in energy conservation methods, high energy prices, and changing demand patterns, resulting in a decline of energy use, and the subsequent two decades experienced an increase in energy use in large part because of economic and population growth (C. Allen, U.S. Department of Energy, 2001, personal communication). This energy use pattern occurred in all four seasons and is illustrated for winter in Fig. 1.

The effects of the increasing trend in residential energy consumption since 1980 were removed by linearly detrending the energy-consumption time series prior to the correlation analysis. Because other factors, such as the effects of generally increasing U.S. temperatures, are also removed from the detrended energy-consump-

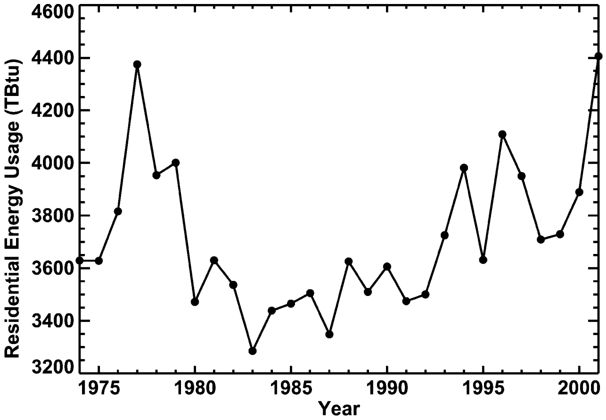

FIG. 1. United States national residential energy usage, for winter (DJF) 1973–2001. Energy sources include primary and electricity sources. Primary sources consist of coal, natural gas, and petroleum.

tion time series, the REDTI was also detrended for the correlation analysis. Seasonal correlations were 0.75 for winter [December–January–February (DJF)], 0.86 for spring (March–April–May), 0.77 for summer [June–July–August (JJA)], and 0.70 for autumn (September–October–November). Statistical significance was substantially better than 0.001 in all seasons. (Significance was determined with a one-tailed t test because there was an a priori expectation of a positive relationship.)

b. MSI

Past attempts to relate annual crop yield to national measures of drought severity, such as percent area of the contiguous United States that is experiencing severe drought or wet conditions, have produced poor results (Changnon and Hewings 2001). These low correlations result from the low signal-to-noise relationship inherent in such national indices; that is, each major crop (the ''signal'') is concentrated in certain U.S. regions (Easterling and Kates 1995), whereas a national percent area index covers the entire United States, which includes non-crop-growing regions (the ''noise''). The new index presented here focuses on the crop signal by considering only the crop region.

The MSI for corn and soybean crops is a measure of the effects of drought and catastrophic wetness on national crop yield and is calculated through the use of a drought index (the Palmer Z index) reference and annual 10-yr-average crop productivity weights within each U.S. climate division. The monthly Z index was chosen instead of the weekly crop moisture index (Palmer 1968) because the CMI is not temporally complete and is available back only to 1973. The MSI is a special case of total moisture stress (TMS), which is either a lack or an overabundance of soil moisture during critical phases of the crop growth and development cycle. TMS affects average crop yield, particularly when moisture stress occurs in the most highly productive crop-growing areas. As will be shown later, soil moisture conditions in July and August were found to be the best indicators of average crop yield for corn and soybeans. Thus, the MSI is the July–August TMS.

Calculations of the MSI are based on 1) the extent of severe-to-catastrophic drought (Z index value ≤ -2) or catastrophic wetness (Z index $\geq +5$) within the crop-growing regions and 2) the average annual crop productivity of each climate division within the crop-growing regions. Productivity refers to the total amount of crop produced, whereas yield is production per land unit. Weights based on divisional crop productivity values instead of divisional yield values were used in calculating the MSI because the highly productive areas of the United States have a greater impact on the average national yield than those areas that traditionally produce fewer bushels or pounds of a particular crop, even though they may have high yields. Of interest is that the index, although calculated using average productivity values within individual climate divisions, is more closely related to historical national crop yield (for nonirrigated acreage) than productivity because of the impact that year-to-year changes in acreage-planting practices have on nationally averaged productivity.

The U.S. Department of Agriculture (USDA) crop productivity numbers within each climate division for the period of 1991–2000 were averaged into divisional mean annual crop productivity values. Irrigated acreage was excluded from all calculations because irrigation reduces the impact of moisture stress from dry spells. Midwest crops are primarily rain fed; irrigation practices are more widespread in the plains states, particularly in the crop-growing regions farthest west. Figure 2 shows the 10-yr-average crop productivity values within the corn-growing region. The pattern for soybeans (Fig. 3) is similar. These 10-yr divisional mean annual crop-productivity weights were applied throughout the period of record. Therefore, an MSI time series portrays the century-scale historical variability of the moisture stress for the present-day crop-growing area. Actual historical changes of where the crop was grown are not taken into account.

In developing the MSI, values of TMS were calculated for all months of the year even though the occurrence of drought during some months of the year would not be expected to affect crop productivity. In cases for which no climate division within the crop-growing region has a Z index value ≤ -2 or $\geq +5$, the TMS is equal to zero. For months in which more than one climate division within the crop-growing region has Z index values ≤ -2 or $\geq +5$, the TMS value for the month is weighted by the average crop-productivity values in the affected climate divisions. It is not surprising that the largest TMS values result when widespread drought or catastrophic wetness occurs in the most productive areas of the crop-growing region.

Soil moisture conditions in months outside the grow-

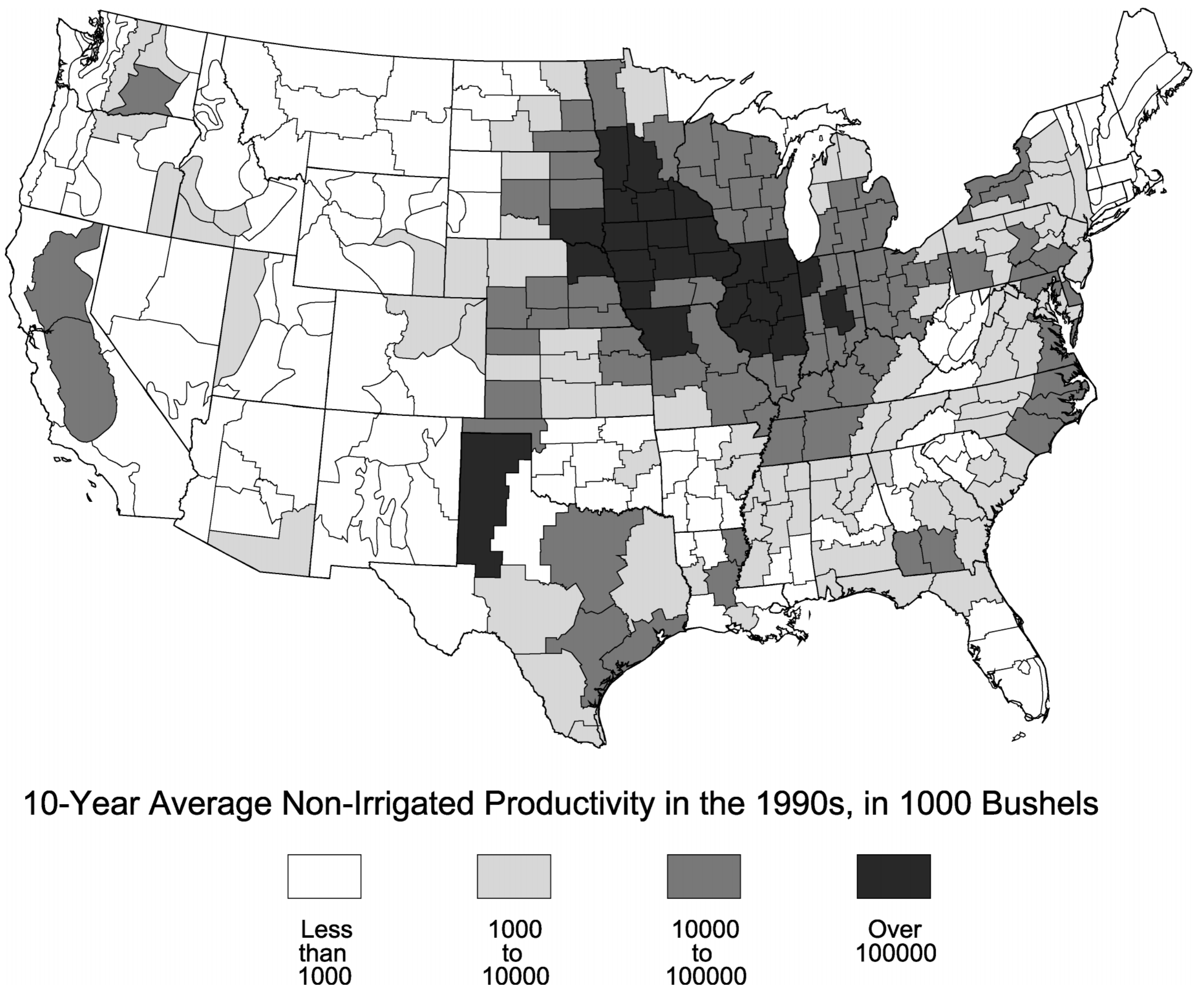

FIG. 2. Corn productivity (from nonirrigated regions) by climate division (based on 1991–2000 average).

ing season should naturally have less impact on crop yield than those months that are part of the growing season. It is also known that some months of the growing season are more critical to the final success of the harvest than others. For corn and soybeans, the growing season generally runs from May to September, the reproductive (pollination and grain filling) season runs from July to August, and the harvest season runs from October to November (B. Rippey, USDA, 2001, personal communication). To determine the months in which the MSI was a better indicator of the success of the year's crop, the monthly index values were correlated with the annual crop yield for the period of 1970–2000. The crop yield time series were linearly detrended before correlations were calculated to remove the effect of improvements in crop science, technology, and so on that have occurred over the years. Because trends from improving crop technology could not be separated from trends caused by other factors such as climate change, the crop stress indices were also detrended. Correlations were calculated for the period of 1970–2000, instead of the full 91-yr corn yield data period (Fig. 4), because this was a period of high productivity and large year-to-year fluctuations in crop yield, and it was desirable to reserve some portion of the record to cross validate or verify the index. [Although *Z*-index values are available back to 1895, the Palmer model requires four or five years for the indices to reflect actual rather than initial conditions (Guttman 1991), and so the MSI time series begin in 1900.]

During development of the MSI, variations of the index (TMS) were evaluated using a variety of minimum drought and wetness thresholds (*Z* index ≤ -2, ≤ -3, etc., and *Z* index $\geq +2.5$, ≥ 3.5, etc.). Excessive moisture did not adversely affect crop yields until the *Z* index exceeded $+5$. Evaluation of the monthly correlations of the detrended index with detrended annual crop yield for each variation showed that the TMS based on *Z*-index values of ≤ -2 and $\geq +5$ best reflected the year-to-year changes in crop yield. Table 1 shows the monthly

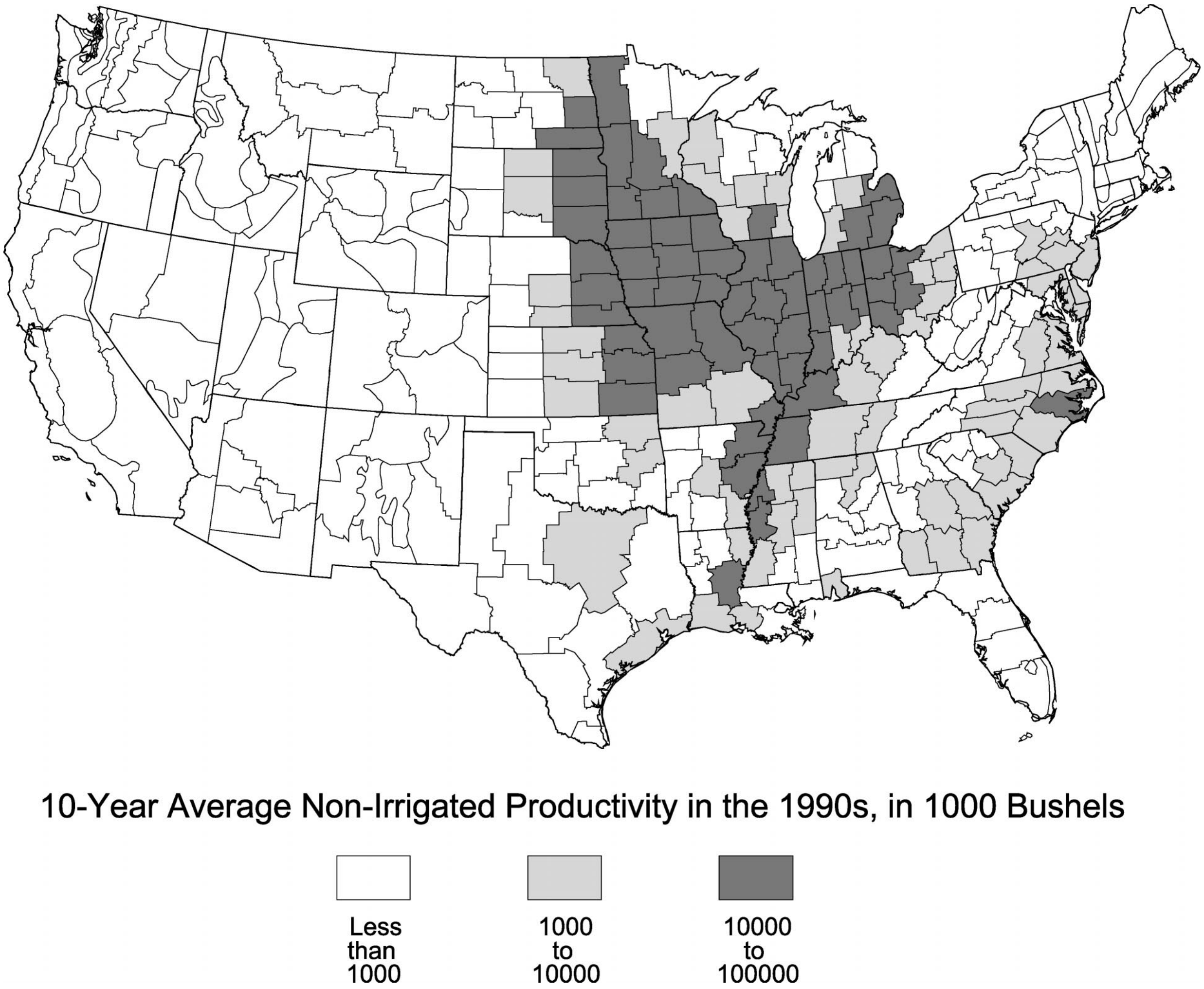

FIG. 3. Soybean productivity (from nonirrigated regions) by climate division (based on 1991–2000 average).

and seasonal correlations for crop yield (for corn and soybean) with the TMS.

The strong correlations in July and August are consistent with the understanding that conditions during the reproductive season (July and August for corn and soybeans) are most critical in determining the outcome of a crop-growing season (B. Rippey, USDA, 2001, personal communication). To determine whether the index in some combination of months could explain more variance in crop yield, the crop stress indices were calculated over the July–August 2-month period and other combinations of the highly correlated growing-season months, for example, June–August and May–September. Correlations for the July–August TMS were found to be more highly correlated than any single month or other combination of months (see Table 1). The strong correlations (-0.78 and -0.73 for corn and soybeans, respectively), as well as the understanding that conditions during July and August are critical to the success of the crop growing season, led us to base the MSI on the July–August average TMS. The statistical significance of both of these correlations is better than 0.0001 with a two-tailed *t* test. A two-tailed test was necessary in this case because there was initially no expectation of a particular sign of response on a month-to-month basis.

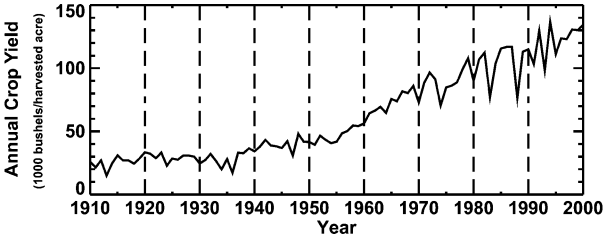

FIG. 4. Annual U.S. crop yield (nonirrigated) for corn, 1910–2000.

Crop yield statistics were available for much of the twentieth century, allowing us to verify the validity of this index against an independent period of data. We employed crop yield data for 1910–69 (for corn) and 1927–69 (for soybeans) for the purposes of cross val-

TABLE 1. Monthly and seasonal correlation analysis between the TMS and annual crop yield (corn and soybeans) for 1970–2000. The correlation coefficient (*r*) and *p* value (2-tailed test) are shown. The sample size is 31 for all correlations.

Month or Season	Corn		Soybeans	
	r	*p* value	*r*	*p* value
Jan	0.11	0.5558	0.10	0.5925
Feb	−0.02	0.9150	0.08	0.6688
Mar	0.33	0.0698	0.24	0.1934
Apr	0.14	0.4526	−0.01	0.9574
May	−0.15	0.4206	−0.05	0.7894
Jun	−0.41	0.0220	−0.41	0.0220
Jul	−0.67	<0.0001	−0.55	0.0013
Aug	−0.44	0.0133	−0.53	0.0022
Sep	−0.09	0.6302	−0.17	0.3606
Oct	−0.10	0.5923	−0.09	0.6302
Nov	0.08	0.6688	−0.09	0.6302
Dec	−0.08	0.6688	−0.26	0.1578
May–Sep	−0.60	0.0004	−0.58	0.0006
Jul–Aug	−0.78	<0.0001	−0.73	<0.0001
Jun–Aug	−0.71	<0.0001	−0.69	<0.0001
Aug–Sep	−0.35	0.0536	−0.46	0.0092

idation. These periods have the longest reliable crop yield data for each crop without overlapping the years used for index development. Verification was achieved by detrending both the yield and the MSI and correlating them over the verification periods. The July–August verification correlation was −0.52 for corn and −0.42 for soybeans. As is evident from comparison with Table 1, the verification correlation values, though still good and with a minimum statistical significance of 0.01, are somewhat reduced when compared with the 1970–2000 development period. One of the possible reasons for this decrease is that the MSI is based solely on moisture extremes. It assumes that exceptional wetness or dryness will result in a lower crop yield. During decades such as the 1960s, there were unusually few moisture extremes in the most productive crop-growing areas, and other factors played a larger role in yield variations, for example, other climatic parameters, such as temperature extremes (Easterling and Kates 1995), or nonclimatic factors. This fact is important to note because the verification in this case provides a lower-boundary estimate of the validity of the index as an estimator of crop yield. Another reason that the verification statistics are an underestimate is that the index is based on present-day crop-producing regions, which may in fact have ‘‘moved’’ over time. Nevertheless, the MSI does a good job of estimating crop yield for the verification period.

4. Results

Summer and winter examples of the REDTI illustrate the historical vulnerability of the energy-supply industry to temperature extremes. The U.S. national summer (JJA) REDTI for the last 107 years is plotted in Fig. 5. This time series clearly shows the impact of the severe heat waves of the 1930s and 1950s. Several summers during the turn of the nineteenth century and in the 1980s and 1990s were characterized by large energy use (assuming modern population density and energy utilization patterns throughout the period), as evidenced by REDTI values of 70 or higher. The lowest REDTI

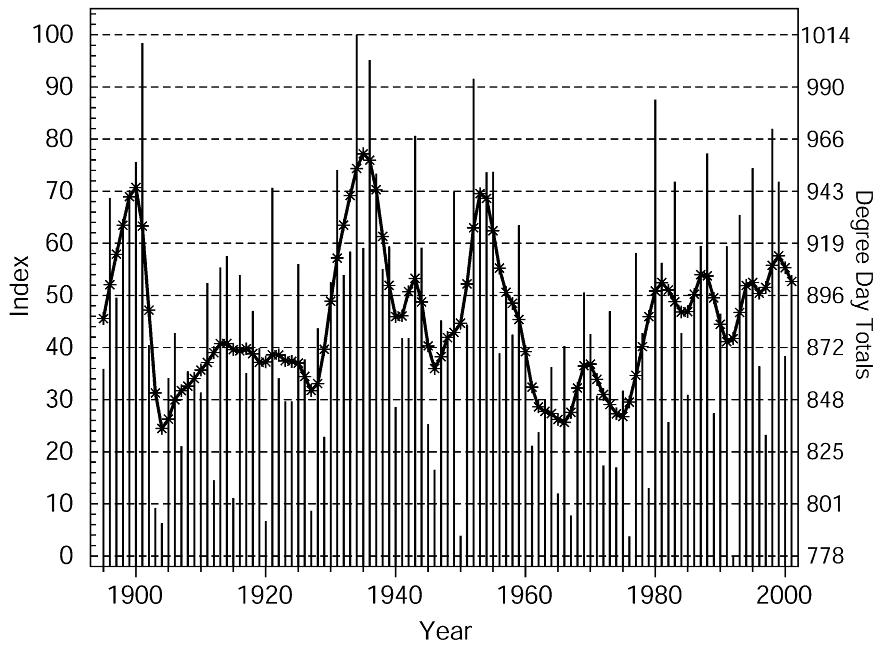

FIG. 5. Contiguous U.S. national summer (JJA) REDTI for 1895–2001, based on population-weighted HDD and CDD data. Vertical bars are annual values; curve is a nine-point binomial filter.

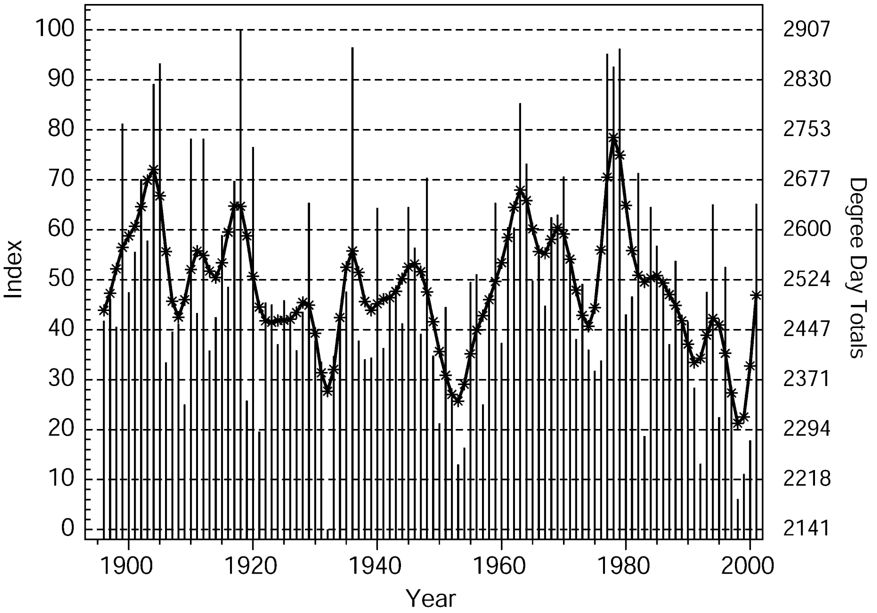

FIG. 6. Same as Fig. 5 but for winter (DJF) REDTI from 1895/96 to 2000/01.

occurred in 1992; the largest REDTI occurred in 1934. The REDTI value for summer of 2001 was 53, which ranked as the 39th largest value in the 1895–2001 record. By contrast, the area-averaged national temperature gave that summer a rank of fifth warmest. This difference in ranks is due to the fact that much of the anomalous warmth was centered in areas with a low population density.

The U.S. national winter (DJF) REDTI is plotted in Fig. 6. The unprecedented back-to-back cold winters of the late 1970s were characterized by extremely high REDTI values, with 1977, 1978, and 1979 ranking as the fourth-, sixth-, and third-highest, respectively, energy-demand winters in the 107-yr record. The extremes were 1918 (highest) and 1932 (lowest). The 2000/01 winter was characterized by an extremely cold (seventh coldest) December, followed by near-normal temperatures during January and February, resulting in a winter REDTI value of 65, or the 21st highest.

The MSI time series for corn (Fig. 7) and soybeans (Fig. 8) have similar temporal features because of the similarities in the crop-growing regions (see Figs. 2 and 3). This index shows the historical vulnerability to moisture stress of these modern crop-producing regions.

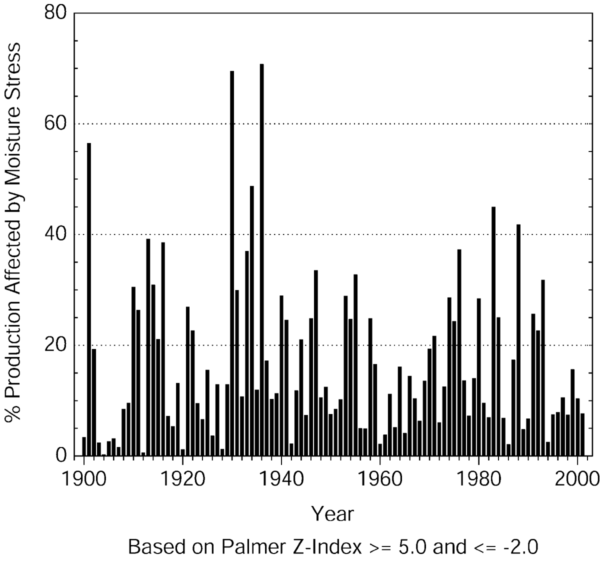

FIG. 7. MSI for corn for 1900–2001.

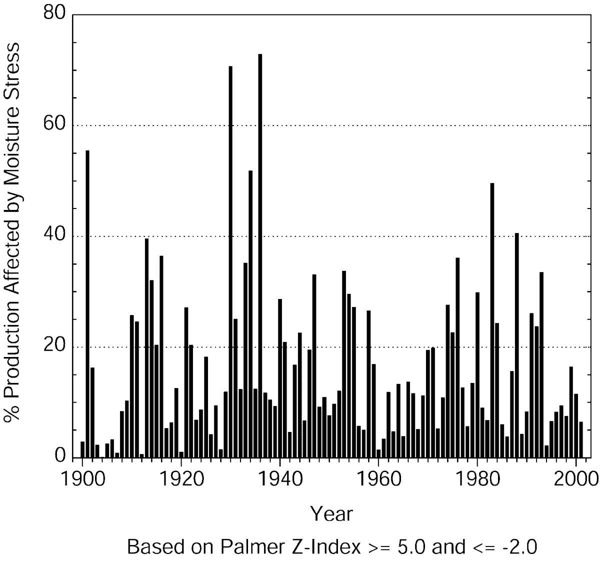

FIG. 8. MSI for soybeans for 1900–2001.

Both corn and soybeans were very highly stressed during 1930 and 1936, when approximately 70% of the (modern) crop productivity was (i.e., would have been) adversely affected. Peaks in the recent record occurred in 1976, 1983, 1988, and 1993, when between about one-third and one-half of the productivity was affected by extreme moisture conditions. The 2001 MSI values indicate that only about 7.7% and 6.5% of corn and soybean productivity, respectively, were affected by adverse moisture conditions during this recent growing season.

Although the MSI was not developed as a predictor index, it often provides a good indication of national crop yields that are consistent with subsequent USDA crop statistics. For example, the 2001 MSI values, which were available in early September, indicate that national crop productivity should not have been adversely affected by climatic conditions. Indeed, the national corn yield for 2001 was 138.2 (in units of 1000 bushels per harvested acre), which was close to the figures for 2000 (136.9), 1999 (133.8), and 1998 (134.4) and above the 1991–2000 average of 125.2. By contrast, the two years since 1970 that had the highest MSI also had the lowest corn yield (81.1 during the wet record El Niño year of 1983, and 84.6 during the drought year of 1988).

5. Conclusions

Climate-impact indicators can provide useful information for the 42% of the U.S. economy that is climate sensitive. We have developed two new indices (REDTI and MSI) that describe the sensitivity of present-day residential heating and cooling energy-use patterns and crop productivity to variations in climate. These indices are strongly correlated, at a high statistical significance level, to residential energy-consumption and crop-yield data. Although index development is ongoing, we are confident that these results provide useful quantitative information in linking climate with these two sectors of the economy. The indices were computed for the United States, but, because of their simple construction, could be extended globally.

The REDTI and MSI provide a quantitative assessment of how past climate variations would have affected present-day energy-use and crop-productivity patterns, respectively, thus giving industry and government managers and planners a tool for determining risk. In doing so, the indices put current conditions into a century-scale historical perspective. Current numerical models produce forecasts from several months to a year into the future, but these forecasts are largely of a statistical or probabilistic nature. The REDTI and MSI are not intended to be used in a predictive sense. However, they potentially could be used with forecast models that output monthly mean temperature and precipitation values on a fine spatial scale to predict the impact of future (the next 1–12 months) climate anomalies on energy demand and agricultural productivity.

Acknowledgments. Partial support was provided by the U.S. DOE Office of Biological and Environmental Research under Interagency Agreement DE-AI02-96ER62276.

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