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CLIMATE IMPACT INDICES FOR THE ECONOMY UTILIZED BY NCDC'S CLIMATE MONITORING BRANCH

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1. INTRODUCTION

Forty-two percent of the U.S. Gross Domestic Product is climate-sensitive, according to the Department of Commerce's Bureau of Economic Analysis (National Research Council, 1998). Weather is frequently used to explain seasonal and year-to-year changes in economic performance, but the explanations are often subjective and many times based on perceptions rather than clear observational evidence.

Indices of leading climate indicators of impacts can provide useful objective information to users whose activities require them to manage climate risks and opportunities. Such climate-based indices could aid in assessments of economic losses due to weather extremes for government and business interests (Changnon and Hewings, 2001) and provide insight from historical trends to foreshadow the impacts of climate fluctuation and change (Easterling and Kates, 1995).

The National Climatic Data Center (NCDC), a center in the National Oceanic and Atmospheric Administration's (NOAA) National Environmental Satellite, Data, and Information Service (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 have played an important role in the 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 as a whole. The Climate Extremes Index (CEI) and Greenhouse Response Index (GRI) both combine a number of measures (e.g., percent area of U.S. in severe drought or wetness, or percent area with extreme temperatures) to produce index time series to show climatic behavior over the 20th century (Karl *et al.*, 1996).

As part of an ongoing program to better understand the impact of weather and climate on vital socio-economic 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 Residential Energy Demand Temperature Index (REDTI) provides quantitative information on the impact of seasonal temperatures on residential energy demand. These indices have been 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 indices.

2. DATA

The climate division data base (Guttman and Quayle, 1996) is used for the operational computation of the MSI and REDTI indices. This data base 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 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 from a regression analysis (of statewide values generated by averaging station observations within each state) prior to 1931 (Guttman and Quayle, 1996). Divisional heating and cooling degree day (HDD and CDD, respectively) values (base 18.3 °C [65 °F]) were derived from the divisional temperature data using a statistical algorithm developed by Thom (1954a, 1954b, 1966) and the drought indices were computed from monthly divisional temperature and precipitation using the Palmer methodology (Palmer, 1965).

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

3. METHODOLOGY

3.1 RESIDENTIAL ENERGY DEMAND TEMPERATURE INDEX (REDTI)

The REDTI is based on population weighted HDDs and CDDs. The use of population weighting in averaging degree days across the nation 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 (Diaz and Quayle, 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 2000 census figures for the 344 climate divisions

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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 assuming present day population density and energy utilization patterns were in effect.)

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 while 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 residential energy consumption for the period 1980-2000/01. National residential energy consumption values were supplied by the Energy Information Agency and are comprised 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 because the latter half of the 1970's was a period of dramatic change in energy conservation methods, high energy prices, and changing demand patterns, this decade was omitted from the analysis. The increase in energy use during the subsequent two decades (Figure 1) was due, in large part, to economic and population growth (Chuck Allen, Department of Energy, personal communication, 2001).

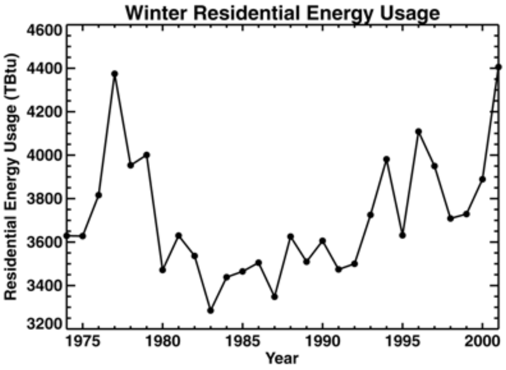

Figure 1. U.S. national energy usage, winter (December-February), 1973-2001.

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 consumption time series, the REDTI was also detrended for the correlation analysis. Seasonal correlations were 0.75 for winter (DJF), 0.86 for spring (MAM), 0.77 for summer (JJA), and 0.70 for fall (SON). Statistical significance was substantially better than 0.001 in all seasons. (Significance was determined with a one-tailed t-test since there was an *a priori* expectation of a positive relationship).

3.2 MOISTURE STRESS INDEX (MSI)

Past attempts to relate annual crop yield to national measures of drought severity, such as percent area of the contiguous U.S. 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, i.e., each major crop (the ‘signal’) is concentrated in certain U.S. regions (Easterling and Kates, 1995), while a national percent area index covers the entire nation which includes non-crop growing regions (the ‘noise’). The new index presented here focuses in 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 average crop productivity values within each U.S. climate division. The monthly Z Index was chosen instead of the weekly Crop Moisture Index (CMI) (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 over-abundance 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 $ +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. Crop productivity values were used in calculating the MSI instead of divisional yield values because the highly productive areas of the U.S. have a greater impact on the average national yield than those areas that traditionally produce fewer bushels or pounds of a particular crop. Interestingly, the index, although calculated using average productivity values within individual climate divisions, is more closely related to historical national crop yield (for non-irrigated acreage) than productivity due to the impact that year-to-year changes in acreage planting practices can have on nationally averaged productivity.

USDA crop productivity numbers within each climate division for the period 1991-2000 were averaged into mean crop productivity values. Irrigated acreage was excluded from all calculations because irrigation reduces the impact of moisture stress due to dry spells. Midwest crops are primarily rain fed while irrigation practices are more widespread in the Plains states, particularly in the crop growing regions farthest west. Figure 2 shows the 10-year average crop productivity values within the corn growing region. The pattern for soybeans (Figure 3) is similar. (These ten-year mean crop productivity weights were applied throughout the period of record. Therefore, an MSI time series portrays the 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.)

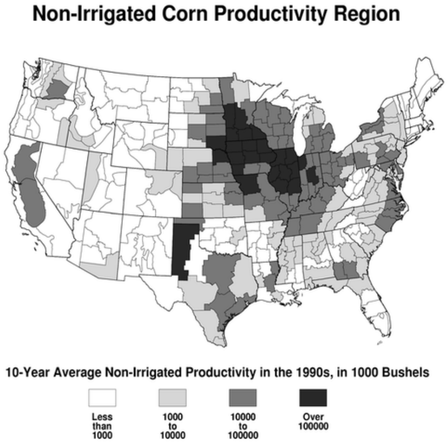

Figure 2. Non-irrigated productivity within corn growing region by climate division (based on 1991-2000 average).

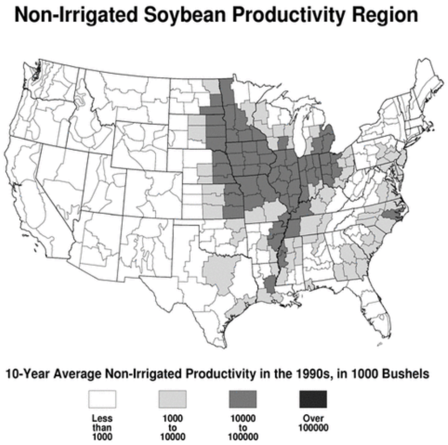

Figure 3. Non-irrigated productivity within soybean growing region by climate division (based on 1991-2000 average).

In developing the MSI, although the occurrence of drought during some months of the year would not be expected to impact crop productivity, values of TMS were calculated for all months of the year. In cases for which no climate division within the crop growing region has a Z index value # -2 or $ +5, the TMS equals zero. For months in which more than one climate division within the crop growing region has Z index values # -2 or $ +5, the TMS value for the month is weighted by the average crop productivity values in the affected climate divisions. Not surprisingly 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 growing 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 through September, the reproductive (pollination and grain filling) season from July to August, and the harvest season from October to November (B. Rippey, USDA, personal communication, 2001). 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 1970-2000. The crop yield time series were linearly detrended before correlations were calculated to remove the effect of improvements in crop science, technology, etc. that have occurred over the years. Because trends due to improving crop technology could not be separated from trends due to other factors such as climate change, the crop stress indices were also detrended. Correlations were calculated for the period 1970-2000, instead of the full 101-year period (Figure 4), as this was a period of high productivity and large year-to-year fluctuations in crop yield. 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], so the MSI time series begin in 1900.)

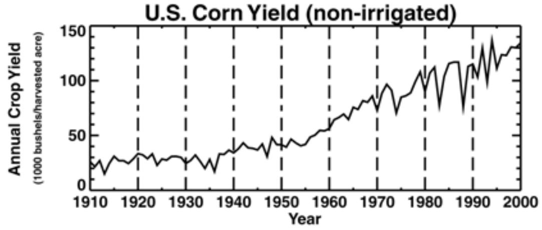

Figure 4. Annual U.S. crop yield for corn, 1910-2000.

During development of the MSI, variations of the index (TMS) were evaluated using a variety of minimum drought and wetness thresholds (e.g., Z Index # -2, # -3, etc. and Z Index $ +2.5, $ 3.5, etc.). There wasn’t an adverse effect of excessive moisture on crop yield until the Z Index was > +5. Evaluation of the monthly correlations of the detrended index with detrended annual crop yield for each variation showed that the TMS based on the Z Index values of # -2 and $ +5 best reflected the year to year changes in crop yield. Table 1 shows the monthly 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, personal communication, 2001). To determine if some combination of months could explain more variance in crop yield, the crop stress indices were calculated over the July-August two-month period and other combinations of the highly correlated growing season months, e.g., 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 since there was initially no expectation of a particular sign of response on a month to month basis.

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-tail 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

Crop yield statistics were available for much of the 20th century, allowing us to verify the validity of this index against an independent period of data. We employed crop yield data from 1910-1969 (for corn) and 1927-1969 (for soybeans) for the purposes of cross-validation. These periods are 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 compared to 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, e.g., other climatic parameters, such as temperature extremes (Easterling and Kates, 1995), or non-climatic factors. This is important to note since the verification in this case provides a lower boundary estimate to the validity of the index as a predictor. Another reason to suppose that the verification statistics here 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 'predicting' crop yield for the verification period.

4. RESULTS

The U.S. national summer (June-August) REDTI for the last 107 years is plotted in Figure 5. This time series clearly shows the impact of the severe heat waves of the 1930's and 1950's. Several summers during the turn of the century and in the 1980's and 1990's also 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 occurred in 1992 and the largest in 1934. The REDTI value for summer 2001 was 53, which ranked as the 39th largest value in the 1895-2001 record. By contrast, the area-averaged national temperature gave this 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 (December-February) REDTI is plotted in Figure 6. The unprecedented back-to-back cold winters of the late 1970's were characterized by extremely high REDTI values, with 1977, 1978, and 1979 ranking as the fourth, sixth, and third, respectively, highest energy-demand winters in the 106-year record. The extremes were 1918 (highest) and 1932 (lowest). The 2000-2001 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 21st highest.

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

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 to 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.

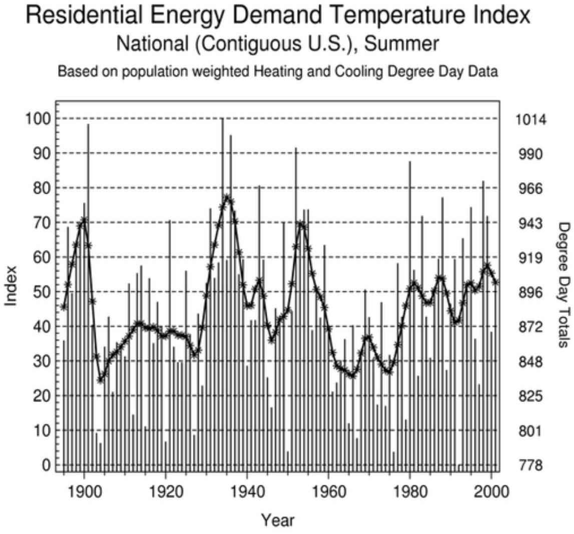

Figure 5. U.S. national summer (June-August) REDTI for 1895-2001.

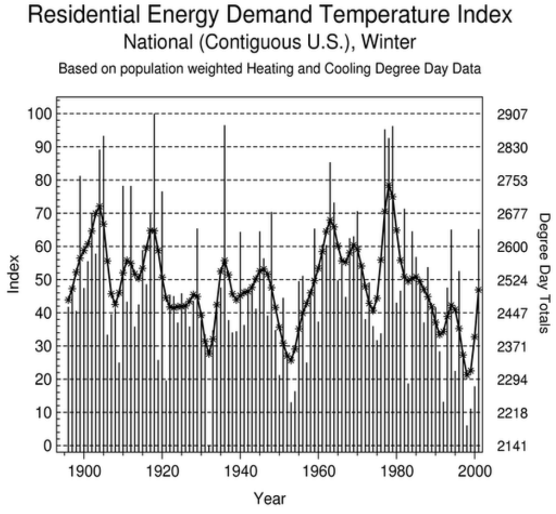

Figure 6. U.S. national winter (December-February) REDTI for 1895-96 to 2000-01.

5. CONCLUSIONS

Indices of leading climate indicators can provide useful information for the 42% of the U.S. economy that is impacted by weather extremes. We have developed two new indices (REDTI and MSI) which 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 two sectors of the economy. The indices were computed for the U.S. but, due to their simple construction, could be extended globally.

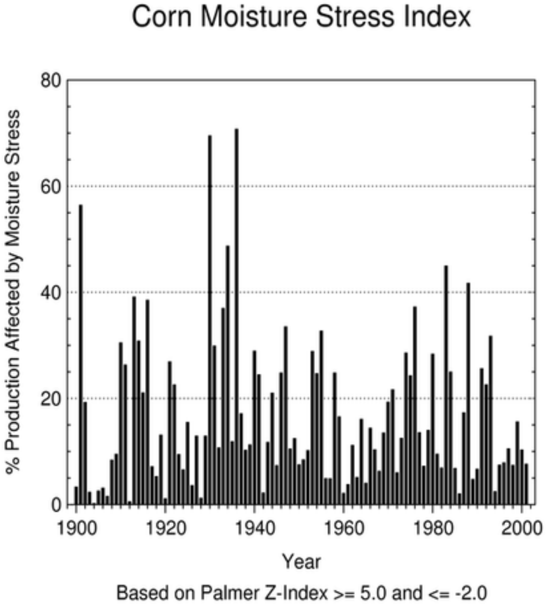

Figure 7. MSI for corn for 1900-2001.

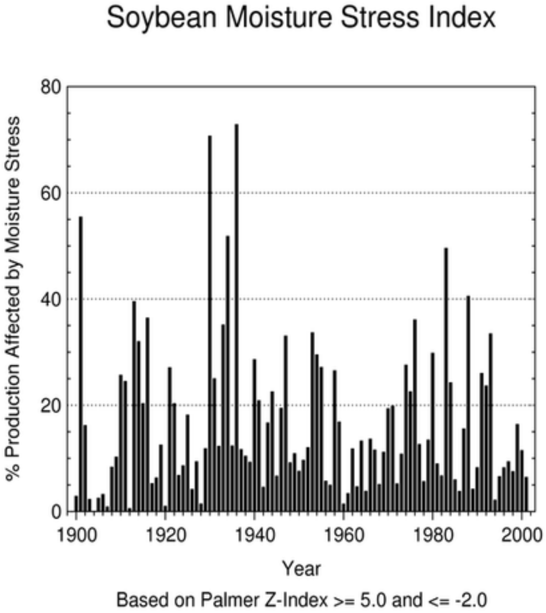

Figure 8. MSI for soybeans for 1900-2001.

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