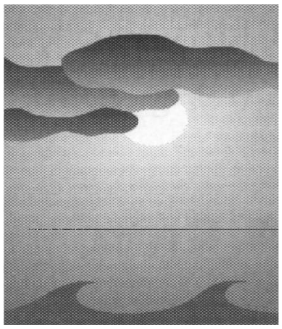
INDICES OF CLIMATE CHANGE FOR THE UNITED STATES



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INDICES OF CLIMATE CHANGE FOR THE UNITED STATES

ABSTRACT

A framework is presented to quantify observed changes in climate within the contiguous United States through the development and analysis of two indices of climate change, a Climate Extremes Index (CEI) and a U.S. Greenhouse Climate Response Index (GCRI). The CEI is based on an aggregate set of conventional climate extreme indicators, and the GCRI is composed of indicators that measure changes in the climate of the U.S. that have been projected to occur as a result of increased emissions of greenhouse gases.

The CEI supports the notion that the climate of the U.S. has become more extreme in recent decades, yet the magnitude and persistence of the changes are not now large enough to conclude that the increase in extremes could not have arisen from a quasi-stationary climate. Nonetheless, if impacts due to extreme events rise exponentially with the index, then the increase is indeed quite significant in a practical sense. Similarly, the Twentieth Century increase in U.S. GCRI is consistent with the expected sign of change due to an enhanced greenhouse effect. The increase is unlikely to have arisen due to chance alone (about a 5 to 10% chance). Still, the increase of the GCRI is not large enough to unequivocally reject the possibility that the increase in the GCRI may have resulted from other factors including natural climate variability, and the similarity in the sign of the change of the GCRI and model projections says little about the sensitivity of the climate system to the greenhouse effect. Both indices increased rather abruptly during the 1970s, at a time of major circulation changes over the Pacific Ocean and North America.

1. Introduction

Has the climate changed significantly during the century that is about to end? And if so, in what ways and by how much? Climatologists are struggling to answer such questions, not only for scientific interests, but also for policy makers (IPCC, 1995) and the public at large. Answers to these questions are fundamental to developing confidence about global and regional projections of climate into the next Century. Such confidence is important not only to scientists concerned with issues of climate sensitivity to anthropogenic and natural climate forcings and feedbacks, but to policy makers, non-specialists, and the general public. They all require comprehensive, but intuitive information that allows them to understand the scientific basis for confidence, or lack thereof, in present understanding of the climate system.

In this article our primary focus relates to the problem of summarizing and presenting a complex set of multivariate, multidimensional changes such that they can be readily comprehended and used in policy decisions made by non-specialists in the field. We selected the contiguous United States as the focus of analysis. The reasons are: 1) it is of special concern to U.S. citizens and U.S. policy makers, 2) the changes of climate within the U.S. have not been given extensive coverage in inter-governmental or national reports focused on climate change assessments (IPCC, 1990,1992; NRC, 1992), 3) the errors and systematic biases of the data from the U.S. have been well studied (Karl et al.,1986; Karl and Williams, 1987; Karl et al., 1988; Quayle et al. 1991; Karl et al. 1993a; Karl et al. 1993b; Groisman and Easterling, 1994), and 4) the climate records are of sufficient length such that high frequency climate variability is less likely to obscure low frequency climate variations and changes.

2. Data

Twentieth Century changes and variation of precipitation with monthly resolution can be calculated from the National Climatic Data Center’s climate division data base (Guttman and Quayle, 1995). This data set consists of thousands of first order and cooperative weather observing sites across the country, but only a fraction of these are continued through 1994. Although there are likely to be precipitation measurement biases at each of these stations (Karl et al., 1993a,b; Groisman and Easterling, 1994), mainly in the form of solid precipitation under-catch, the time-varying biases are likely to be considerably smaller because in this data base most of the sites have had rather consistent instrumentation, e.g., standard eight inch unshielded gauges. Moreover, comparisons with other data sets (Karl et al., 1993a; Groisman and Easterling, 1994) depict only small differences in precipitation trends. Nonetheless, Legates (1995) argues that during months with both liquid and solid precipitation, a systematic change in the ratio of liquid to solid precipitation could introduce an undetected time-varying bias. More work remains to fully assess the significance of this potential bias, but related streamflow data (Lins and Michaels, 1994; Lettenmaier, 1994) would suggest that such a bias is unlikely to adversely affect this assessment of precipitation trends during the Twentieth Century.

A common tool used to quantify long-term moisture anomalies in the U.S. is the Palmer Drought Severity Index or PDSI. The PDSI categorizes moisture conditions in increasing order of intensity as near-normal; mild to moderate; severe; or extreme for drought or wetness. The PDSI is affected by both long-term moisture shortages and excesses, and by variability of temperature-driven evaporation from soils and transpiration (release of water vapor) from plants. Since warmer conditions are capable of evaporating more water from the earth's surface, both temperature and precipitation affect the drought index, but temperature anomalies are less a factor than direct changes in precipitation. The NCDC climate division precipitation and temperature data base are used to calculate the PDSI (Karl, 1986).

Twentieth Century changes of mean maximum and minimum temperature with monthly resolution are calculated from the U.S. Historical Climatology Network [HCN](Karl et al., 1990). This data base has over 1200 stations with many stations beginning in the late Nineteenth or early Twentieth Centuries. Over 600 continuous well-distributed observing sites across the U.S. were selected based on the number of potential discontinuities (any change in instrument siting, location, or instrument type), the consistency of the trends with nearby stations, the percent of missing data, and the width of the confidence interval of the adjustment applied to the data and the record length (Karl et al., 1990). Each station used was adjusted: *a priorí* adjustments included observing time biases (Karl et al., 1986), urban heat island effects (Karl et al., 1988), and the bias introduced by the introduction of the maximum-minimum thermistor and its instrument shelter (Quayle et al., 1991); *a posteriorí* adjustments included station and instrument changes (Karl and Williams, 1987).

Daily changes of precipitation were derived from a subset (131) of the HCN stations with supplemental non-HCN stations in the West where coverage was sparse. The supplemental stations were selected outside of urban areas and have consistent observing times, whereas stations in the HCN had a limited number of random (not systematic) changes in observing times (Hughes et al., 1992).

3. Statistical methods

For each indicator or index[1] we test the hypothesis that the magnitude of the observed trend is a by-product of a quasi-stationary climate. The term quasi-stationary is used to reflect the notion that over very long time scales (thousands of years) no climate regime is likely to be stationary. The alternate hypothesis is that the observed trend represents a changing climate. Each time series is fit to an autoregressive moving average (ARMA) model of maximum order 4 (Box and Jenkins, 1976). Such a model can account for a wide variety of stationary (and apparent non-stationary) processes (Priestly, 1981), including periodicities, persistent fluctuations, quasi-periodicities, etc. The model can be written in the form:

$$(1)\quad Y_t = \sum_{i=1}^{p} \phi_i Y_{t-1} + \sum_{j=1}^{q} \theta_j a_{t-j} + a_t,$$

where Y_t is the value of the time series at time *t*; ϕ_i is the *i*th autoregressive (AR) coefficient; θ_j is the *j*th moving average (MA) coefficient; and a_t is random noise at time *t*. The order of the model is expressed as p,q and represented as ARMA (p,q). The distribution of a_t is normal with mean zero and standard deviation σ_a (i.e., the standard deviation of the random noise).

When p and q are zero the model represents a white noise or uncorrelated serial process. ARMA (0,q) models can be characterized as having finite persistence, i.e., the random noise in the model persists for exactly q observations. By comparison ARMA (p,0) models can be characterized as having infinite, but geometrically decaying persistence of the random noise component. Karl (1988) contains more details on the climatological applications of this model.

The Bayesian Information Criterion (BIC) was used to select the appropriate order of the model (Katz, 1982). The BIC balances the goodness of fit against the complexity (the order) of the model. The model with the smallest BIC is preferred. The sensitivity of our results is tested by also considering the model with the second smallest BIC. Models were constrained such that $p+q \le 4$, with higher order models tested only if BIC reached a minimum at model order 4. This assumption is consistent with the notion that highly complex statistical models are likely

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[1] An index is defined as an aggregate of a set of indicators.

to overfit the observations (i.e. attach too much significance to the noise within the data).

The trend is removed from each time series prior to fitting the model. This is necessary because our interest will be in using the model to simulate a stationary process and compare this to the observed trends. Once the appropriate model is identified for each indicator or index, the trend of the observed time series is compared with trends calculated from 1000 Monte Carlo simulations from generated time series of an ARMA model. Each time series has the same number of discrete values as does the observed indicator or index of interest. The fraction of time the observed trend exceeds those calculated from the simulated series is used as a measure of the statistical significance of the observed trend.

Numerous indicators are considered, and although we provide estimates of their statistical significance, their interpretation can sometimes become difficult. This is because as more and more indicators are analyzed it is likely that some will contain unusual trends simply due to chance. This is one of the prime motivations for developing an index which integrates a variety of climate change indicators.

4. Background

Area-averaged total precipitation has varied from decade-to-decade (Fig. 1). This area-averaged value is derived from area-weighting the total annual precipitation from each of the 344 climate divisions across the U.S. Although there is an absence of a monotonically increasing trend, after about 1970 precipitation has tended to remain above the Twentieth Century mean, and has averaged about 5% more than in the previous 70 years. Such an increase hints at a change in climate. Formal statistical analysis suggests that the change is unusual, but still there is about a 10% chance that such a change could arise from a quasi-stationary climate without any real long-term changes. The end-of-century increase is mainly due to

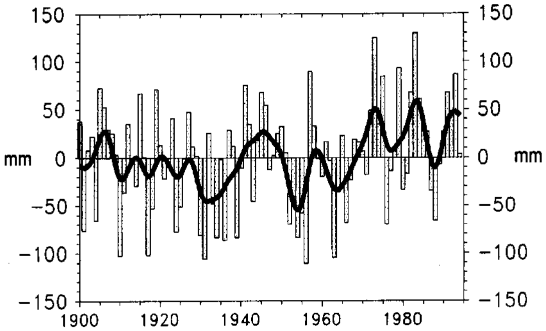


Fig. 1 Departures from the long-term mean of area-average annual precipitation over the conterminous United States. The smooth curve on this and subsequent plots is generated from a nine point binomial filter of the annual values. The data end in 1994 for this and subsequent figures.

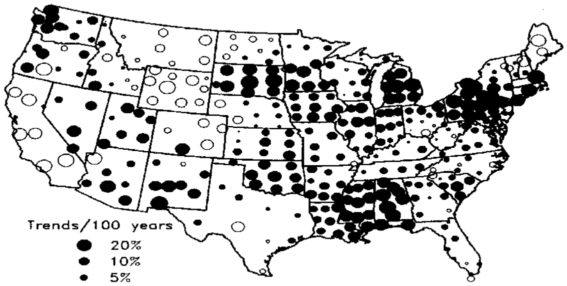


Fig. 2 Precipitation trends (1900-94 converted to percent per century) centered within state climatic divisions are reflected by the diameter of the circle centered within each climatic division. Solid circles represent increases and open circles, decreases.

increases during the second half of each year, particularly during the autumn. On a regional basis (Fig. 2) we see that the increase is widespread within the U.S., and local increases of nearly 20% are not uncommon. The increase is not apparent everywhere however, as some states like California, Montana, Wyoming, North Dakota, Maine, New Hampshire, Vermont, and parts of the southeast have had decreases in annual precipitation. As is the case with precipitation, mean temperatures across the U.S. have not monotonically increased during the present century (Fig. 3), although a linear trend equates to a rise of about 0.4°C/100yr. Such a simple interpretation of mean temperature change in the U.S. would be a gross oversimplification. The record reveals a sharp rise in temperature during the 1930s and a modest cooling from the 1950s to the 1970s, at which time the temperature increased, and has since remained as high as some of the high temperatures recorded during the major droughts of the 1930s. However, the more recent warmth is accompanied by relatively high amounts of precipitation, unlike the dry 1930s. Although U.S. temperatures have substantially increased, the increase by itself is neither large enough, nor temporally consistent enough, to completely dismiss the notion (around 1 chance in 20) that the change may have arisen due to purely random natural variations.

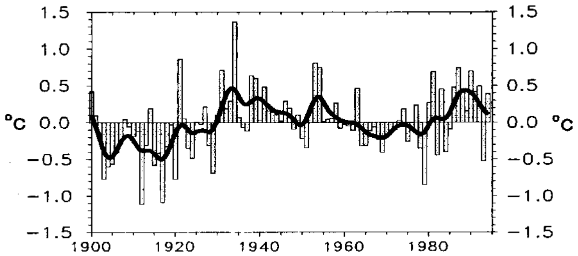


Fig.3.Same as Fig. 1 exxcept for mean temperature in °C.

The increase in annual temperatures after the 1970s is mainly the result of significant increases of temperature during the first six months of the year (winter and spring). Temperatures during summer and autumn have changed little after dropping from the warm 1930s.

On a regional basis the areas north and west of an arc from Virginia through Illinois to Texas contribute most to the increase of annual average nationwide temperatures (Fig. 4), while the southeast shows mostly cooling. There has been a tendency for smaller temperature increases to be coincident with the larger positive trends of precipitation and associated circulation changes (Trenberth and Hurrell, 1994).

5. Indicators of climate change for the U.S.

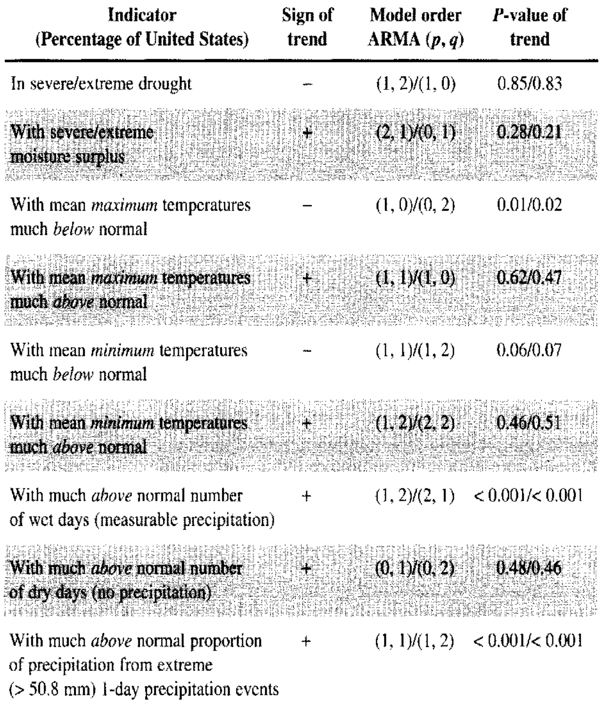
Twentieth Century changes in a variety of climate indicators that represent various aspects of climate are presented in the next two subsections. Each indicator has been selected based on its reliability, length of record, updateability, and its relevance to changes in climate extremes or projected climate responses due to increasing anthropogenic greenhouse gases.

a) Extremes

An important aspect of climate extremes relates to extreme droughts and moisture surpluses. To characterize long-term variations of drought or wetness it is possible to calculate the proportion of the U.S. under conditions with severe and extreme (which we simply characterize as "severe") drought or moisture surplus, as defined by the Palmer Drought Severity Index (PDSI). Considerable decadal variability of drought and wetness is revealed (Fig. 5). The droughts of the 1930s and 1950s stand out in the upper curve as remarkable events. During 1934, the worst year, on average nearly 50% of the country was in severe drought; even the spring and summer drought of 1988 is dwarfed by comparison. Since about 1970 however, more of the country has tended to remain excessively wet: over 30% of the country has experienced a severe moisture surplus for at least one year in each of the past three decades.

The catastrophic summertime flooding of the Mississippi River and its tributaries during 1993 is an obvious example of these severe moisture surplus events, but Table 1 indicates that there is still a good chance (about 25%) that the trend toward increased frequency of severe moisture

Table 1. Estimated statistical significance based on the best (left) and second best (right) ARMA models for various indicators related to climate extremes. The hypothesis tested is that trends this century are not stationary.



Indicator (Percentage of United States)	Sign of trend	Model order ARMA (p, q)	P-value of trend
In severe/extreme drought	–	(1, 2)/(1, 0)	0.85/0.83
With severe/extreme moisture surplus	**+**	**(2, 1)/(0, 1)**	**0.28/0.21**
With mean *maximum* temperatures much *below* normal	–	(1, 0)/(0, 2)	0.01/0.02
With mean *maximum* temperatures much *above* normal	**+**	**(1, 1)/(1, 0)**	**0.62/0.47**
With mean *minimum* temperatures much *below* normal	–	(1, 1)/(1, 2)	0.06/0.07
With mean *minimum* temperatures much *above* normal	**+**	**(1, 2)/(2, 2)**	**0.46/0.51**
With much *above* normal number of wet days (measurable precipitation)	+	(1, 2)/(2, 1)	< 0.001/< 0.001
With much *above* normal number of dry days (no precipitation)	**+**	**(0, 1)/(0, 2)**	**0.48/0.46**
With much *above* normal proportion of precipitation from extreme (> 50.8 mm) 1-day precipitation events	+	(1, 1)/(1, 2)	< 0.001/< 0.001

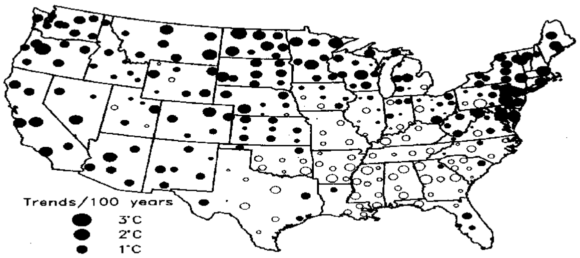


Fig. 4. Same as Fig. 2 except for mean temperature $[^{\circ}C(100\ yr)^{-1}]$. Closed circles represent warming and open circles cooling.

has arisen from a quasi-stationary climate with exponentially decaying persistence.

The national effects of a long-term moisture deficit or surplus are generally proportional to the areal coverage in either severe drought or in severe moisture surplus. If we consider the sum of the proportion of the country in either of these severe categories no systematic trends are evident in the present century, although during the past few decades, there has been a tendency for a greater portion of the country to be either in severe drought or severe moisture excess.

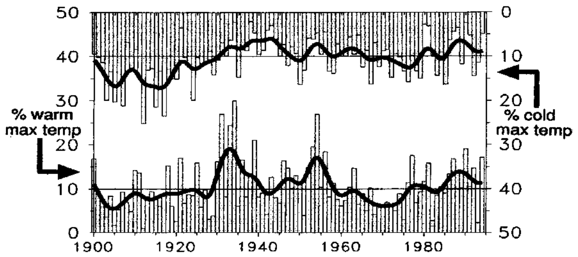


Fig. 6.Percentage of the conterminous U.S. area with much above normal (bottom curve,left scale) or much below normal (top curve, right scale) monthly mean maximum (max) temperatures.

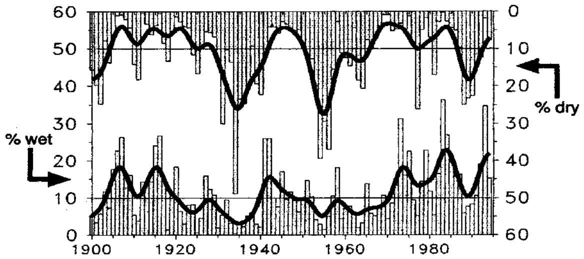


Fig. 5. Percentage of the conterminous U.S. area in severe moisture surplus (bottom curve,left scale) and in severe drought (top curve, right scale).

As with drought and excessive moisture, portions of the country can be extremely cold at the same time that others are unusually warm. This is actually a fairly common occurrence because the conterminous U.S. very roughly spans half the average longitudinal extent of a stationary Rossby wave, e.g, the Pacific North American teleconnection pattern, thus placing one part of the country in southerly flow and the other in northerly flow. This leads to an average national temperature that is near-normal. Hence, we focus on temperature indicators that can capture changes in unusually cold or warm weather, even when average national temperatures are near normal. Also, abnormally high daytime maximum temperatures can occur while nighttime temperatures remain below normal (this is not usually the case however), or vice-versa. Moreover, an increase (decrease) of temperature can be asymmetric in the tails of the distribution. For example, the warmth of the 1930s is better reflected by the area of the

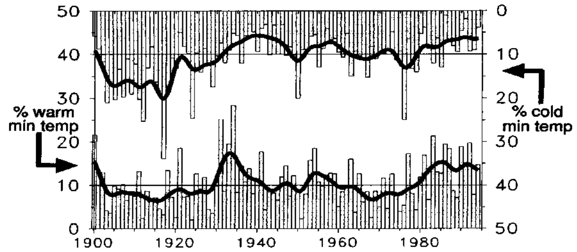


Fig.7.Same as Fig. 6 except for minimum (min) temperature.

country affected by much above normal[2] annual daily maximum temperatures (Fig. 6) compared with the percent of the country affected by much above normal annual minimum temperatures (Fig. 7). Fig. 7 also shows that the proportion of the U.S. with much below normal mean annual daily minimum temperatures has been sustained at low levels since the late 1970s with only 5 to 10% chance that the overall decrease in area affected by these conditions would occur in a stationary climate (Table 1). This is in contrast to only a 1 to 2% chance for much below normal conditions the maximum temperature (Fig. 6; Table 1). The recent increase of the minimum temperature relative to maximum temperature has been directly related to an observed increase in cloud amount over the past several decades (Plantico et al., 1990).

The fraction of the country with anomalous mean monthly maximum <u>or</u> minimum temperatures, has changed little during the Twentieth Century. The tendency for a larger area of the U.S. to have much below normal temperatures in the early part of the century has been balanced by the opposite category of much above normal temperatures in the last few decades.

An analysis of changes in extremes would be incomplete without consideration of changes in daily precipitation events. The proportion of the country with a much greater than normal number of wet days (Fig. 8) has increased much more than would be expected in a stationary climate (Table 1). This is especially apparent between 1910 and 1940 and after about 1970. The latter increase bears some similarity to the increase of total precipitation over the U.S. (Fig. 1). Meanwhile the proportion of the U.S. with a much greater than normal number of dry days has shown little overall change. Occasionally, for certain areas and times of the year, there are too few wet days in a given month to establish an upper ten percentile. These areas are not included.

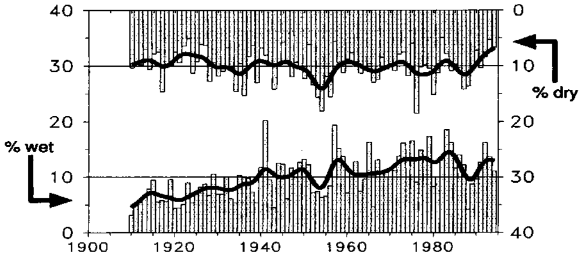


Fig.8.Percentage of the conterminous U.S. area with the number of wet days much above normal (bottom curve,left scale) or number of dry days much above normal(top curve,right scale).

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[2] Defined as within the upper ten percent or upper decile of all annual values.

The proportion of the country that has had a much greater than normal amount of precipitation derived from extremely heavy (>50.8mm or 2 inches) 1-day precipitation events (Fig. 9) can be reliably calculated at least back to 1910. Similar to Fig. 8, in some regions and for certain months of the year, 1-day precipitation events exceeding 50.8mm never occur e.g., the West in summer. These areas and months of the year are not included in the indicator. It is clear (Fig. 9) that during the present century there has been a steady increase in the area of the U.S. affected by extreme precipitation events. It is unlikely (less than 1 chance in 1000) that such a large change could occur in a quasi-stationary climate (Table 1).

Other measures of high frequency extreme events were also considered, such as the frequency of heat waves and cold waves, freezes, strong winds, tropical cyclones, etc., but not included in the CEI at this time. With appropriate data, these additional measures could easily be used, but existing data sets require considerably more attention with respect to homogeneity. Even today however, the frequency of daily temperature above a given threshold cannot be reliably calculated for large portions of the USA. Proper adjustments for changing observing times at daily resolutions have not been developed. Fortunately, there is a high correlation between much below (or above) normal conditions and cold waves (heat waves) that last several days. The duration, intensity, and areal extent of tropical and extratropical cyclones also require more homogeneity assessment, as do the frequencies of tornadoes and hail.

b. Greenhouse response

Efforts to detect the effects of greenhouse gas warming are best studied through global analyses (Karl, 1993). Such analyses have been made and assessed in both intergovernmental (IPCC, 1990; 1992; 1995) and national reports (NRC, 1992). All of these commissioned assessments have concluded that observed changes in global climate are not yet sufficiently large to be ascribed unequivocally to anthropogenic increases of greenhouse gases; although they also suggest that the anthropogenic greenhouse effect is the most probable cause for the global temperature increase of nearly 0.5°C during the past

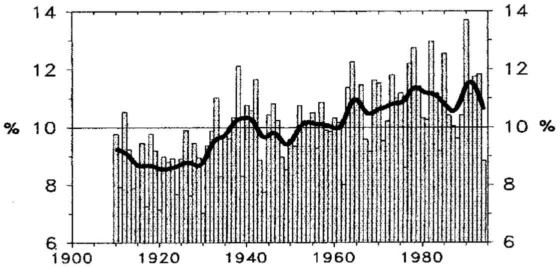

Fig.9.Percentage of the conterminous U.S. area with a much above normal proportion of total annual precipitation from 1-day extreme(more than 2 in. Or 50.8mm) events.

100 or so years. The question arises however, whether there is any evidence to suggest that the expected effects of anticipated greenhouse warming are already affecting the climate of the United States. A number of projections have been made that are expected to affect large continental regions in the mid-to-high latitudes, such as the USA (IPCC, 1990; 1992; 1995). These changes, in rough order of confidence in the projections (IPCC, 1990; 1992; 1995) include:

- An increase of mean surface temperature.
- An increase in precipitation, primarily in the cold season.
- More severe and longer lasting droughts, especially during the warm season (May-Sep.).
- A small, but significantly greater increase of nighttime temperature compared with daytime temperature.
- A greater portion of precipitation derived from heavy convective rainfall (showers or thundershowers) compared with gentler, longer-lasting rainfalls.
- A decrease in the day-to-day variability of temperature.

The increase in the mean temperature is a fundamental characteristic of all model simulations with enhanced greenhouse gases, with the daily minimum temperature increasing about 10% more than the maximum. Another primary climate response to increased greenhouse gases relates to an intensified hydrologic cycle. As a result, cold season precipitation generally increases in the mid-to-high latitudes as a warmer atmosphere is capable of maintaining greater amounts of water vapor condensed as precipitation in migrating cyclones. During summer, increased surface temperatures lead to greater evaporation and with only small changes in precipitation in some areas; and more frequent and severe droughts. An increase in convective precipitation, resulting in more intense rainfalls (not necessarily more overall rain) is also a characteristic of a stronger hydrologic cycle. The projected reduction in the day-to-day temperature variability in a warmer climate is consistent with the reduced day-to-day variability of temperature in the summer versus the winter and in the tropics compared to mid and high latitudes. Warmer sea-surface temperatures could be expected to increase the severity and/or frequency of hurricanes affecting the United States and adjacent waters. However, the natural variability of hurricanes is so great (Karl et al., 1995) and model projections so uncertain that even century-scale changes are not reliable indicators of greenhouse warming.

Table 2. Same as Table 1 except indicators are related to projected large-scale changes associated with an enhanced greenhouse effect. The hypotheses tested are that trends this century are not stationary and are positive. Here, T_{mx} is the mean maximum temperature and T_{mn} the minimum.

Indicator (Percentage of United States)	**Sign of trend**	**Model order ARMA (*p*, *q*)**	***P*-value of trend**
With much *above* normal mean temperatures ($0.525{*}T_{mx} + 0.475{*}T_{mn}$)	+	(1, 2)/(1, 1)	0.27/0.21
With much *above* normal precipitation during the cold season (Oct. through Apr.)	**+**	**(1, 0)/(0, 1)**	**0.01/0.01**
In extreme/severe drought during the warm season (May through Sept.)	+	(1, 0)/(1, 1)	0.45/0.42
With much *above* normal proportion of precipitation from extreme (> 50.8 mm) 1-day precipitation events	**+**	**(1, 1)/(1, 2)**	**< 0.001/< 0.001**
With much *below* normal day-to-day temperature differences	+	(1, 1)/(2, 1)	0.14/0.12

The projected changes have been captured in five climate indicators as listed in Table 2. One of these, the increasing proportion of the country with extreme 1-day precipitation events has also been considered as related to changes in extremes (Table 1). In addition to the increase in the area affected by much above normal mean temperatures (Fig. 4) and the proportion of the U.S. affected by extreme precipitation events, the percent of the U.S. affected by much above normal cold season precipitation has significantly increased since 1970 (Table 2 and Fig. 10). In contrast, the proportion of the country affected by extreme and severe warm season droughts reflects little overall trend, but considerable decadal variability (Fig. 11).

Changes in high frequency temperature variability can be reflected in the day-to-day changes of temperature calculated as the absolute value of the difference in temperature from day *i* to day *i*+1. Trends in the proportion of the U.S. with much above (below) normal day-to-day temperature change for the present century indicate that there has been a rather steady and significant decline (increase) in the area affected by these abnormally high (low) day-to-day differences of temperature. The reduction in

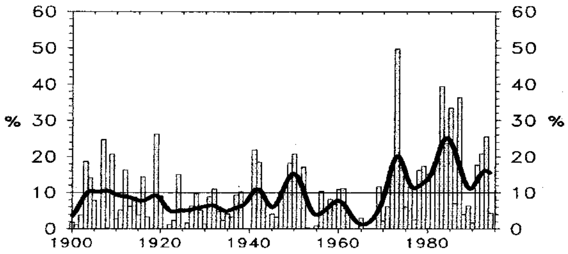

Fig.10.Percentage of the conterminous U.S. area with much above normal cold season (Oct.through Apr.) precipitation.

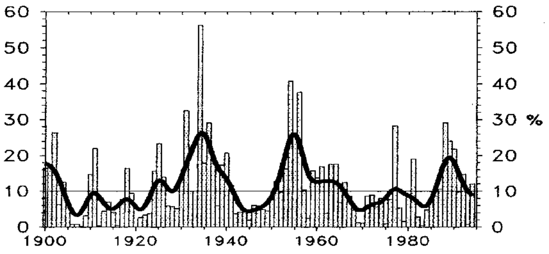

Fig.11.Percentage of the conterminous U.S. area in sever or extreme drought during the warm season (May through Sep.).

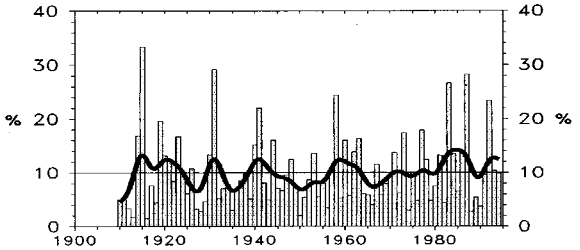

Fig.12.Percentage of the conterminous U.S. area with much below normal day-to-day temperature differences.

day-to-day temperature variability is not as apparent in the much below normal category of day-to-day temperature differences (Fig. 12), but still has a positive trend (Table 2), and relatively small P-values.

6. Climate Change Indices

It should be clear by now that not only is it difficult to assimilate the broad spectrum of changes in various indicators as related to the U.S. climate, but conveying this information to policy-makers and the general public is a formidable task. For these reasons an index that combines a number of climate indicators as related to a specific aspect of climate change can provide a convenient tool to summarize the state (and changing state) of the climate. To be useful it must have a clear meaning, a moderately long history, and continuity into the future. It should not smooth out potentially important aspects of climate change in the name of intended simplification. Two types of indices have been developed. The first is aimed at assessing changes and variations of climate extremes, and is most relevant to gauging the potential impact of long-term climate variations and changes on natural and man-made systems in the U.S. The other focuses on changes that have been projected to occur in the U.S. from anthropogenic increases in greenhouse gases.

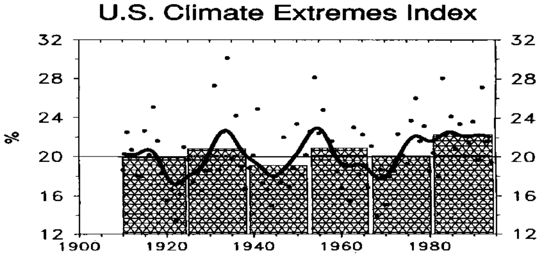

Fig. 13. An annual U.S. Climate Extremes Index. Dots represent annual values, the smooth curve is a 21-point binomial filter, and the bars represent 14-year averages.

a) A climate extremes index

The U.S. Climate Extremes Index (CEI) is the annual arithmetic average of the following five indicators of the percent of the conterminous U.S. area:

(1) The sum of:
  a) Percent of the U.S. with maximum temperatures much below normal.
  b) Percent of the U.S. with maximum temperatures much above normal.
(2) The sum of:
  a) Percent of the U.S. with minimum temperatures much below normal.
  b) Percent of the U.S. with minimum temperatures much above normal.
(3) The sum of:

a) Percent of the U.S. in severe drought (equivalent to the lower ten percentile) based on the PDSI.

b) Percent of the U.S. with severe moisture surplus (equivalent to the upper ten percentile) based on the PDSI.

(4) Twice the value of:

the percent of the U.S. with a much greater than normal proportion of precipitation derived from extreme (more than 2 inches or 50.8 mm) 1-day precipitation events.

(5) The sum of:

a) Percent of the U.S. with much greater than normal number of days with precipitation.

b) Percent of the U.S. with greater than normal number of days without precipitation.

In each case, we define much above (below) normal or extreme conditions as those falling in the upper (lower) tenth percentile of the local, century-long period of record. In any given year each of the five indicators has an expected value of 20% in that 10% of all observed values should fall, in the long-term average, in each tenth percentile, and there are two such sets in each indicator. An extremely high value in any one of the five indicators does not exclude extremely high values for the others. In fact, for the maximum and minimum temperature indicators (1 and 2 listed above) there is usually, but not always, a close correspondence between the two. The fourth indicator, related to extreme precipitation events, has an opposite phase that cannot be considered extreme: The fraction of the country with a much below normal percentage of annual precipitation derived from extreme (i.e., zero) 1-day precipitation amounts. Hence, the fourth indicator is multiplied by twice its value to give it an expected value of 20%, comparable to the other indicators. Overall, the CEI gives slightly more weight to precipitation extremes than to extremes of temperature. A value of 0% for the CEI, the lower limit, indicates that no portion of the country was subject to any of the extremes of temperature or precipitation considered in the index. In contrast, a value of 100% (or more, considering the nature of indicator 4) would mean the entire country had extreme conditions throughout the year for each of the five indicators, a virtually impossible scenario. The long-term variation or change of this index represents the tendency for extremes of climate to either decrease, increase, or remain the same. Although we focus on an annual CEI and do not produce a ‘seasonal’ CEI, which may be more appropriate for some impact studies or to explore the processes leading to changes and variations in the index, the CEI is constructed such that seasonal values can easily be calculated.

The century-long record of the CEI depicted in Fig. 13 demonstrates that the climate of the U.S. in this period has included large decadal fluctuations of climate extremes. Since about 1976, the time when the atmospheric circulation over the Pacific and North America underwent a significant change (Trenberth, 1990; Trenberth and Hurrell, 1994), the CEI has averaged about 1.5% higher than the average of the previous 65 years. This is equivalent to a persistent increase of extreme events covering an area somewhat larger than the state of Indiana. Other notable times of extreme climate variations include the 1930s and 1950s, but the more recent spell of extreme climate is of longer duration. This increase in extremes is related primarily to the increase in three precipitation indicators: the frequency of long-term drought severity and moisture excess, the frequency of extreme 1-day precipitation events, and a much greater than normal number of days with precipitation. The increase in climate extremes over the past 15 to 20 years is not, however, of sufficient persistence and magnitude to suggest that the climate really has changed. Such a change, simply due to natural year-to-year variability, is not unexpected (Table 3). Depending on the model selected, the range of P-values extends from 0.10 to 0.21. One could argue that since the impacts or damages associated with extremes go up exponentially, the CEI should be nonlinearly scaled, but the appropriate scaling is uncertain. Clearly, this would further emphasize the significance of the recent increase in extreme events.

Table 3.Same as Table 1 for this century except for indices. The hypotheses tested is that trends of extremes are not stationary; trends in the greenhouse response are not stationary and are positive.

Indices	Sign of trend	Model order ARMA (p, q)	*P*-value of trend
U.S. Climate Extremes Index	+	(1, 1)/(1, 0)	0.21/0.10
U.S. Greenhouse Response Index (weighted)	+	(1, 2)/(1, 1)	0.08/0.05
U.S. Greenhouse Response Index (unweighted)	+	(1, 1)/(0, 1)	0.04/0.01

b) A U.S. greenhouse climate response index

The U.S. Greenhouse Climate Response Index (GCRI) is composed of a set of anticipated greenhouse climate response indicators. It is intended as a means of early detection and monitoring of anticipated greenhouse-induced climate change as applied to conditions in the U.S. Other anthropogenic influences on climate, such as the cooling effects of sulfate aerosols (Santer et al. 1995; Karl et al., 1995) as well as natural climate change mechanisms, will either enhance or reduce the GCRI. It is worth noting however, that in the U.S. there was a negligible net change of anthropogenic emissions of sulfur dioxide (which can cause sulfate-induced smog) between 1950 and 1993.

The U.S. GCRI is calculated from the annual arithmetic average of the following five indicators of the percent of the conterminous U.S. area:

(1) The percent of the U.S. with much above normal mean temperature (minimum temperature times 0.525, plus maximum temperature times 0.475).
(2) The percent of the U.S. with much above normal precipitation during the months October through April (the cold season).
(3) The percent of the U.S. in extreme or severe drought during the months May through September (the warm season).
(4) The percent of the U.S. with a much greater than normal proportion of Fig. precipitation derived from extreme 1-day precipitation events (exceeding 2 inches or 50.8 mm).
(5) The percent of the U.S. with much below normal day-to-day temperature differences.

Each of these five indicators defines an anticipated response of the U.S. climate related to increases of atmospheric greenhouse gases derived from the IPCC (1990; 1992; 1995). In addition to its role in monitoring for anticipated climate responses another reason for developing a U.S. GCRI relates to additional information obtained from analyzing multiple, mostly independent parameters, each of which is expected to respond to increases of greenhouse gases and/or temperatures. Due to data deficiencies, only mean temperature has been analyzed and related to the greenhouse effect on global space-scales (IPCC, 1992). So, although a “U.S. only” analysis suffers from limited areal extent, by using five mostly independent indicators it complements global greenhouse detection analyses with limited dimensionality in variate selection. The correlation matrix (Table 4) of detrended indicators reveals that most indicators are independent or

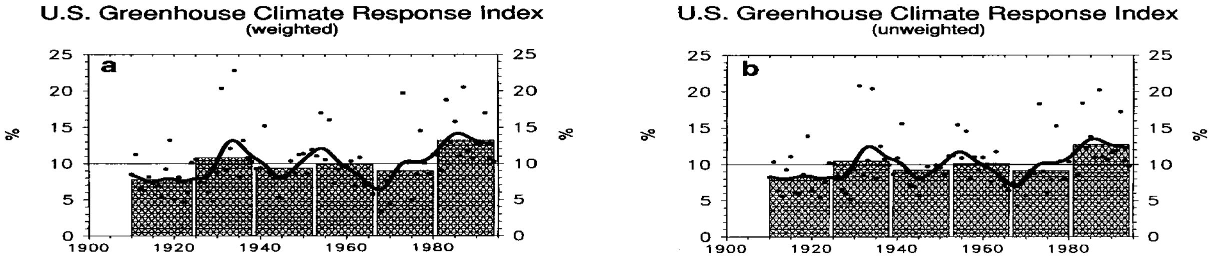

Fig. 14. Same as Fig. 13 except for the annual U.S. Greenhouse Climate Response Index based on greenhouse climate response indicators;(a) weighted and (b) unweighted.

only weakly related with each other. The major exception is the correlation between temperature and drought during the warm season. This latter relationship however, still only explains 36% of the common variance between temperature and warm season drought.

Each indicator has an expected value in any year of 10%. For the first indicator, we use a slightly heavier weight for the minimum temperature compared to the maximum (10% more), consistent with the 10% greater increase in the minimum related to greenhouse forcing (IPCC, 1990; 1992). Each indicator focuses on the upper or lower ten percentile of the distribution to ensure that changes in the indicators reflect events that are often noticed by the general public as well as policy-makers. The choice of an upper or lower decile is based on the expected trend of the quantity under consideration.

A question arises about the appropriate emphasis or *weight* to assign to each of the five indicators. We show both weighted (Fig. 14a) and unweighted (Fig. 14b ---all five indicators equally weighted) versions of the GCRI, and note that differences between the weighted and unweighted versions are relatively minor (Table 3). The weights used reflect our subjective estimate of the relative confidence placed on anticipated greenhouse-induced changes in U.S. climate: a value of 5 for the first indicator (temperature); 4 for precipitation; and 3, 2, and 1 for indicators (3), (4), and (5) respectively. Since the expected value for the GCRI for any given year is 10%, we depict this as a horizontal line in both the weighted and unweighted version of the GCRI, reflecting a time invariant climate.

Based on the overall increase of the GCRI it can be concluded that the changes are consistent with the general trends anticipated from a greenhouse-enhanced climate. Moreover, since 1980 the unweighted and weighted GCRI's have averaged 12.8% and 13.3%, respectively which is 2.8% and 3.3% higher than expected. In terms of relative effect, a change of this magnitude corresponds to an area somewhat greater than the combined areas of Indiana, Illinois, and Ohio. At the same time however, statistical analysis indicates that because the change is neither large enough nor consistent enough through time, it may not be prudent to unequivocally reject the possibility (roughly a 5 to 10% chance) that the increase is a random variation of a stationary climate (Table 3). In order to test the sensitivity of the P-value to the model selected, the full range of ARMA models of orders 1 to 4 were simulated. P-values ranged from 0.01 to 0.20 and 0.01 to 0.09 for the unweighted and weighted version of the GCRI.

7. Discussion and Conclusions

A framework has been developed that can be used by climatologists to express multidimensional changes in an integrated and informative manner. We present two indices composed of specific indicators, a Climate Extremes Index and a Greenhouse Climate Response Index. The content of these indices are unlikely to be totally static. New indicators may be added as our data bases improve, (e.g. winds, hail, tornadoes, etc.) and information increases regarding the details of the climate response to increases in greenhouse gases. Moreover, as other forcings become better understood (e.g., sulfate aerosols), other indices will surely emerge.

At the present time, trends of several indicators stand out most conspicuously. These include the rather steady increase in precipitation derived from extreme 1-day precipitation events; the increase in area affected by much below normal maximum temperatures; the increase of cold season precipitation, and the increased frequency of days with precipitation. Trends in other indicators of climate change are not now sufficiently large or persistent enough to be considered as <u>strongly</u> suggestive of a changing climate. Nonetheless, real changes in climate remain the most likely explanation for the most conspicuous changes. Some of the indicators had seemingly significant changes during the late 1970s and have more or less remained at these levels to the present. Other surface climate change indicators (e.g., proportion of the country affected by extreme or severe warm season drought) reflect the kind of climatic variability that is completely consistent with the premise of a stable or unchanging climate.

It is noteworthy that the increase in temperature across the U.S. is slightly smaller than the global increase of temperature. The increase in minimum temperature relative to the maximum is also reflected in many other countries of the Northern Hemisphere (Karl et al., 1991; 1993c). Worldwide land precipitation has changed little over the Twentieth Century (IPCC, 1995), but this is because high latitude increases have been balanced by low-latitude decreases. By comparison, the change in precipitation in the U.S. is still relatively moderate compared to some of the increases and decreases at other latitudes. Decreases in the day-to-day differences of temperature observed in the U.S. are also apparent in China and Russia, the other large countries analyzed as of this date (Karl and Knight, 1995). The persistent increase in the proportion of precipitation derived from extremely heavy precipitation has not been detected in these countries, although homogeneous records are much shorter. In northeast Australia however, significant increases in extreme precipitation events have been detected by Suppiah and Hennessy (1995).

A Climate Extremes Index, defined by an aggregate set of conventional climate extremes indicators, supports the notion that the climate of the U.S. has become more extreme in recent decades, yet the magnitude and persistence of the changes are not now large enough to conclude that the climate has systematically changed to a more extreme state as opposed to fluctuating about a near stable state. Similarly, a U.S. Greenhouse Climate Response Index, composed of indicators that measure the changes of U.S. climate that are expected to follow increased emissions of greenhouse gases, reflects Twentieth Century trends that are consistent with expectations. Moreover, all five indicators reflect trends consistent with greenhouse projections, with two of them reflecting highly significant trends. Still, the rate of change of the GCRI, as with the CEI, is not large enough to unequivocally reject the possibility that the increase in the GCRI may have resulted from other factors including natural climate variability, although this is not a likely explanation (about a 5 to 10% chance). Moreover, the hypothesis tested is simply that the trend in the GCRI is non-zero and positive. The sensitivity of the climate system to anthropogenic greenhouse forcing is not addressed by this test. Nonetheless, by analogy the circumstantial evidence to link greenhouse projected change in the U.S. climate and observed changes may be adequate in a civil court, but not in a criminal conviction (at least one juror would still have reasonable doubts).

Both the CEI and the U.S. GCRI increased rather abruptly during the 1970s (but two-phase regression analysis [Solow, 1987] does not indicate a significant change point in the series), at a time of major circulation changes over the Pacific Ocean and North America. Moreover, since the winter of 1976-77, the frequency and intensity of El Niño Southern Oscillation events have increased relative to previous decades. During these years sea-surface temperatures in the central and eastern equatorial Pacific have remained anomalously warm. Such events have been directly linked to increased precipitation and reduced winter temperatures along the Gulf Coast of the U.S. (Ropelewski and Halpert, 1987; Halpert and Ropelewski, 1992). During the late 70's and into the 1980s (but whether this has continued in the 1990s is less apparent) a large-scale redistribution of atmospheric mass took place in the North Pacific, associated with a change of the jet stream over the North Pacific and North America. There is little doubt that the increase in the indices is at least partially related to these circulation variations, but analyses indicate that it is not a dominant factor. For example, we have calculated the coherence of the Southern Oscillation Index (SOI) with the GCRI, but find no statistically significant relationships. We do find a peak in the co-spectrum that is almost significant (at the 0.10 level, but with only 2 to 3% of the covariance explained) at time scales of 4 to 6 years, the approximate recurrence interval of ENSO events. A weak non-significant relationship is also evident at a 1-year lag with negative values of the SOI leading the GCRI toward higher values. It must be acknowledged that the role of increased anthropogenic greenhouse gas concentrations in such circulation variations is poorly understood. Since the indices are influenced by natural changes and variations that can either add or subtract from any underlying long-term anthropogenic-induced change, it will be important to carefully monitor the indices over the next decade to see if they sustain their incipient trends or return to previous levels. It will also be important to continue improving the indices and the homogeneity of the records that constitute the indices. Such efforts are critical for a better understanding of climate, how it changes, and how these changes can affect our own lives and well being.

8. Acknowledgments

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10. References

Box, G.E.P. and G.M. Jenkins: 1976. The time series analysis: Forecasting and control. Holden-Day, San Francisco. CA. 575 pp.

Groisman, P.Ya., and D.R. Easterling, 1994: Variability and trends of precipitation and snowfall over the United States and Canada. *J. Clim.*, **7**, 184-205.

Guttman, N.G. and R.G. Quayle, 1995: The U.S. Climate Divisions. National Climatic Data Center, Asheville, NC. Submitted *Bull. Amer. Meteor. Soc.,* 28 pp.

Halpert, M.S. and C.F. Ropelewski, 1992: Surface temperature patterns associated with the southern oscillation. *J. Clim.*, **5**, 577-593.

Hughes, P.Y., E.H. Mason, T. R. Karl, and W.A. Brower, 1992: United States Historical Climatology Network Daily Temperature and Precipitation Data. Dept of Energy, Oak Ridge Nat’l Lab., ORNL/CDIAC-50 NDP-42, 55pp. plus Appendices.

IPCC, 1990: Climate Change: The IPCC Scientific Assessment. Intergovernmental Panel on Climate Change, World Meteorological Organization/United Nations Environment Programme. Cambridge University Press, Cambridge, New York, Port Chester, Sydney, Melbourne, 362 pp.

IPCC, 1992: Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment. Intergovernmental Panel on Climate Change, World Meteorological Organization/United Nations Environment Programme. Cambridge University Press, Cambridge, New York, Port Chester, Sydney, Melbourne, 200 pp.

IPCC, 1995: Climate Change 1995: The Second IPCC Scientific Assessment. Intergovernmental Panel on Climate Change, World Meteorological Organization/United Nations Environment Programme. Cambridge University Press, Cambridge, New York, Port Chester, Sydney, Melbourne, In Review.

Karl, T.R., 1993: Missing pieces of the puzzle. Research and Exploration, publication of the *National Geographic Society*, **9**, 234-249.

Karl, T.R., 1988: Multi-year fluctuation of temperature and precipitation: The gray area of climate change. *Climatic Change*, **12**, 179-197.

Karl, T.R., 1986: The sensitivity of the Palmer drought severity index and Palmer’s Z-index to their calibration coefficients including potential evapotranspiration. *J. Climate Appl. Meteor.*, **25**, 77-86.

Karl, T.R., R.W. Knight, D.R. Easterling, and R. G. Quayle, 1995: Trends in U.S. climate during the Twentieth Century. CONSEQUENCES: The Nature and Implications of Environmental Change, **1**, 2-12, (Available through the U.S. Global Change Research Information Office).

Karl, T.R. and R.W. Knight, 1995: Temporal changes in the intensity and frequency of precipitation and the variability of temperature over the U.S.A. and Asia. *Amer. Meteor. Soc.*, Sixth Symposium on Global Change Studies, Dallas, TX.

Karl, T.R., P.Ya. Groisman, R.W. Knight and R.R. Heim, Jr.,1993a: Recent variations of snow cover and snowfall in North America and their relation to precipitation and temperature variations. *J. Clim.* **6**, 1327-1344.

Karl, T.R., R.G. Quayle, and P.Ya. Groisman, 1993b: Detecting climate variations and change: New challenges for observing and data management systems. *J. Clim.,* ***6**,* 1481-1494.

Karl, T.R., P.D. Jones, R.W. Knight, G. Kukla, N. Plummer, V. Razuvaev, K.P. Gallo, J. Lindseay, R.J. Charlson, and T.C. Peterson, 1993c: A new perspective on recent global warming: Asymmetric trends of daily maximum and minimum temperature. *Bull. Amer. Meteor. Soc.*, **74**, 1007-1023.

Karl, T.R., G. Kukla, V. Razuvaev, M. Changery, R. Quayle, R. Heim, Jr., D. Easterling, and C. Fu, 1991: Global warming: Evidence for asymmetric diurnal temperature change. *Geophys. Res. Letter,* **18**, 2253-2256.

Karl, T.R., C.N. Williams, Jr., F.T. Quinlan, and T. A Boden, 1990: United States Historical Climatology Network (HCN) Serial Temperature and Precipitation. Dept. of Energy, Oak Ridge Nat'l Lab. ORNL/CDIAC-30, NDP-019/R1 83pp. Plus appendices.

Karl, T.R., H. Diaz, and G. Kukla, 1988: Urbanization: Its detection in the U.S. climate record. *J. Clim.,* **1**, 1099- 1123.

Karl, T.R. and C.N. Williams, 1987: An approach to adjusting climatological time series for discontinuous inhomogeneities. *J. Climate Appl. Meteor.*, **26**, 1744-1763.

Karl, T.R., C.N. Williams, Jr., and P.J. Young, 1986: A model to estimate the time of observation bias associated with monthly mean maximum, minimum, and mean temperatures for the United States. *J. Clim. Appl. Meteor.*, **25**, 145-160.

Katz, R.W.: 1982, Statistical evaluation of climate experiments with general circulation models: A parametric time series modeling approach. *J. Atmos.Sci.* **39**, 1446-1455.

Legates, D.R., 1995: Precipitation measurement biases and climate change detection. *Amer. Meteor. Soc*., Sixth Symposium on Global Change Studies, Dallas, TX.

Lettenmaier, D., E.F. Wood and J.R. Wallis, 1994: Hydro-climatological trends in the continental United States, 1948-88. *J. Clim.*, **7**, 586-607.

Lins, H.F. and P.J. Michaels, 1994: Increasing streamflow in the United States. *EOS*, **75**, 281-286.

NRC, 1992: Policy implications of Greenhouse Warming: Mitigation, Adaptation, and the Science Base. National Academy Press, 918 pp.

Plantico, M.S., T.R. Karl, G. Kukla, and J. Gavin, 1990: Are recent changes of temperature, cloudiness, sunshine, and precipitation across the United States related to rising levels of anthropogenic greenhouse gases? *J. Geophys. Res.*, **95**, 16617-16632.

Priestly, M.B., 1981: Spectral analysis and time series. *Academic Press*, 890 pp.

Quayle, R.G., D.R. Easterling, T.R. Karl, and P.Y. Hughes, 1991: Effects of recent thermometer changes in the cooperative station network. *Bull. Amer. Meteor. Soc.*, **72**, 1718-1723.

Ropelewski, C.F. and M.S. Halpert, 1987: Global and regional scale precipitation patterns associated with the El Niño/Southern Oscillation (ENSO). *Mon. Wea. Rev.*, **115**, 1606-1626.

Santer, B.D. et al., 1995: Towards the detection and attribution of an anthropogenic effect on climate. *Climate Dynamics*. In press.

Solow, A.R., 1987: Testing for climate change: an application of the two-phase regression model. *J. Climate Appl. Meteor.*, **26**, 1401-1405.

Suppiah, R. and K.J. Hennessy, 1995: Trends in the intensity and frequency of heavy rainfall in tropical Australia and links with the southern oscillation. Proceedings of the TOGA95 Conference. April 2-7, 1995, Melbourne, Australia.

Trenberth, K.E., 1990: Recent observed interdecadal climate changes in the Northern Hemisphere. *Bull. Amer. Meteor. Soc.,* ***71****, 988-993.*

Trenberth, K.E., and J.W. Hurrell, 1994: Decadal atmosphere-ocean variations in the Pacific. *Climate Dynamics*, **9**, 303-319.

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Figure 1 Departures from the long-term mean of area-average annual precipitation over the conterminous U.S. The smooth curve on this and subsequent plots is generated from a nine-point binomial filter of the annual values. The data end in 1994 for this and subsequent figures.

Figure 2 Precipitation trends (1900-94 converted to % per Century) centered within state climatic divisions are reflected by the diameter of the circle centered within each climatic division. Solid circles represent increases and open circles decreases.

Figure 3 Same as Figure 1 except for mean temperature in °C.

Figure 4 Same as Figure 2 except for mean temperature (°C/100 yr.). Closed circles represent warming, open circles cooling.

Figure 5 Percent of the conterminous U.S. area in severe moisture surplus (bottom curve, left scale) and in severe drought (top curve, right scale).

Figure 6 Percent of the conterminous U.S. area with much above normal (bottom curve, left scale) or much below normal (top curve, right scale) monthly mean Maximum (Max) temperatures.

Figure 7 Same as Figure 6 except for minimum (Min) temperature.

Figure 8 Percent of the conterminous U.S. area with the number of wet days much above normal (bottom curve, left scale) or number of dry days much above normal (top curve, right scale).

Figure 9 Percent of the conterminous U.S. area with a much above normal proportion of total annual precipitation from 1-day extreme (more than 2 inches or 50.8mm) events.

Figure 10 Percent of the conterminous U.S. area with much above normal cold season (Oct. through Apr.) precipitation.

Figure 11 Percent of the conterminous U.S. area in severe or extreme drought during the warm season (May through Sep.).

Figure 12 Percent of the conterminous U.S. area with much below normal day-to-day temperature differences.

Figure 13 An annual U.S. Climate Extremes Index (CEI). Dots represent annual values, the smooth curve is a 21-point binomial filter, and the bars represent 14-year averages.

Figure 14 Same as Fig. 13 except for the annual U.S. Greenhouse Climate Response Index (GCRI) based on greenhouse climate response indicators; (a) weighted and (b) unweighted.

TABLE 1. Estimated statistical significance based on the best (left) and second best (right) ARMA models for various indicators related to climate extremes. Hypothesis tested is: Trends this century are not stationary.

INDICATOR	Sign of Trend	Model order ARMA (p,q)	P-value of trend*
% of U.S. in severe/extreme drought	-	(1,2/(1,0)	0.85/0.83
% of U.S. with severe/extreme moisture surplus	+	(2,1)/(0,1)	0.28/0.21
% of U.S. with mean maximum temperatures much below normal	-	(1,0)/(0,2)	0.01/0.02
% of U.S. with mean maximum temperatures much above normal	+	(1.1)/(1.0)	0.62/0.47
% of U.S. with mean minimum temperatures much below normal	-	(1,1)/(1,2)	0.06/0.07
% of U.S. with mean minimum temperatures much above normal	+	(1,2)/(2,2)	0.46/0.51
% of U.S. with much above normal number of wet days (measurable precipitation)	+	(1,2)/(2,1)	< 0.001/ < 0.001
% of U.S. with much above normal number of dry days (no precipitation)	+	(0,1)/(0,2)	0.48/0.46
% of U.S. with much above normal proportion of precipitation from extreme (> 50.8mm) 1-day precipitation events	+	(1,1)/(1,2)	< 0.001/ < 0.001

*Probability that the trend is a random realization of a stationary climate.

TABLE 2. Same as Table 1 except indicators are related to projected large-scale changes associated with an enhanced greenhouse effect. Hypotheses tested: Trends this century are not stationary and are positive. T_{mx} is the mean maximum temperature and T_{mn} is the minimum.

INDICATOR	**Sign of Trend**	**Model order ARMA (p,q)**	**P-value of trend**
% of U.S. with much above normal mean temperatures ($0.525*T_{mx} + 0.475 * T_{mn}$)	+	(1,2)/(1,1)	0.27/0.21
% of U.S. with much above normal precipitation during the cold season (Oct. through Apr.)	+	(1,0)/(0,1)	0.01/0.01
% of U.S. in extreme/severe drought during the warm season (May through Sept.)	+	(1,0)/(1,1)	0.45/0.42
% of U.S. with much above normal proportion of precipitation from extreme (> 50.8mm) 1-day precipitation events	+	(1,1)/(1,2)	< 0.001/ < 0.001
% of U.S. with much below normal day-to-day temperature differences	+	(1,1)/(2,1)	0.14/0.12

TABLE 3. Same as Table 1 for this century, except for indices. Hypotheses tested: Trends of extremes are not stationary; Trends in the greenhouse response are not stationary and are positive.

INDICES	Sign of Trend	Model Order ARMA (p,q)	P-value of trend
U.S. Climate Extremes Index	+	(1,1)/(1,0)	0.21/0.10
U.S. Greenhouse Response Index (Weighted)	+	(1,2)/(1,1)	0.08/0.05
U.S. Greenhouse Response Index (Unweighted)	+	(1,1)/(0,1)	0.04/0.01