ing these messages. Extending the record of climate variability back through time reveals changes, often sudden and sometimes persistent on decadal to century timescales that lie outside the range of instrumental records. The concepts of future sustainability, water supply and food security may be dangerously short sighted if they fail to accommodate the evidence from the longer term record. This is especially the case in relation to changes in the magnitude and frequency of extreme events (e.g. Knox, 2000) and to shifts in hydrological regime (e.g. Hodell *et al.*, 1995; Messerli *et al.*, 2000). The growing consensus however, is that future climate change will reflect not only natural variability but anthropogenic forcing as well. It is interesting to compare even the most modest predictions of greenhouse warming with natural variability recorded in the recent past. Even though the last six centuries appear to have recorded both the coldest and warmest decades to have occurred in the late Holocene (e.g. Bradley, 2000), the amplitude of variation in Northern Hemisphere mean annual temperature between these extremes is less than the lowest projected temperature increases for the next century.

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Improving Estimates of Drought Variability and Extremes from Centuries-Long Tree-Ring Chronologies: A PAGES/CLIVAR Example

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The impact of severe drought on agriculture, water supply, and the overall environment is an increasing global concern as the demand for water outstrips supplies in many areas of the world. Reliable long-range forecasting methods need to be developed to allow agricultural and water resource planners and administrators to reduce the impact of future droughts. In addition, longer climate records are needed for improving regional drought risk assessments, especially those dealing with the rare, extreme events. For both purposes, the instrumental climate database is likely to be inadequate, even in the well monitored U.S. It is very difficult to know if the instrumental records are long enough to include the full range of drought variability likely to happen in any given region in the future. This issue was specifically addressed in a recent workshop convened by NOAA and NASA: "Assessing the Full Range of Central North America Droughts and Associated Landcover Change", Boulder, Colorado, June 2–4, 1999. One conclusion drawn from this workshop was that instrumental climate data over the U.S. are inadequate for capturing the "full range" of drought. Consequently, there is an urgent need to develop long records of past drought from a variety of proxy records. Among those available, precisely dated annual tree-ring chronologies from centuries-old trees growing on drought-stress sites are ideally suited for this pupose.

A recent paper by Woodhouse and Overpeck (1998) has likewise highlighted the limitations of instrumental climate data by examining the paleoclimate record of drought in the western U.S. They find evidence of past "megadroughts" of unusual severity and duration in the paleoclimatic record, ones that appear to have exceeded even the Midwestern "Dustbowl" drought of the 1930s. The analysis of Woodhouse and Overpeck (1998) illustrates the tremendous value of paleoclimate data in studying past drought. However, it also shows the current limitations of the available proxy records. Among the data they use is the 154 grid point network of well-calibrated and verified summer drought reconstructions from annual tree-ring chronologies produced by Cook *et al.* (1999) for the coterminous U.S. This network, based on the Palmer Drought Severity Index (PDSI; Palmer, 1965), provides a highly detailed record of drought and wetness over the U.S. in both space and time. Unfortunately, these reconstructions only extend back to 1700 at the present time. Yet, Woodhouse and Overpeck (1998) clearly show in a sparser collection of much longer individual drought reconstructions that some notable megadroughts occurred in the western US, mostly prior to AD 1600. Therefore, there is a great need to produce a substantially longer, high-density network of drought reconstructions for the U.S. that extends 600–800 years back into the past. Such a network would provide the means to carefully map the occurrence of drought during these megadrought periods. In so doing, it may be possible to analyze the spatial patterns and evolutive trajectories of these megadroughts and infer their causes.

To illustrate the importance of extending the drought reconstructions further back in time, we have applied optimal interpolation (OI; Kaplan *et al.*, 2000) to the U.S. PDSI reconstruction grid (Cook *et al.*, 1999) after it had been augmented with a number of much longer tree-ring estimates in certain parts of the network. This has enabled us to use OI to extend the PDSI reconstructions over the entire U.S. from 1200 to 1994. Figure 1 shows the first varimax rotated EOF of reconstructed PDSI and its scores using the extended OI PDSI data. This factor emphasizes the southwestern US and is probably the highest quality region produced by the OI analysis. The OI scores have a correlation of 0.77 with instrumental PDSI from the Southwest on an annual basis and 0.86 on a smoothed, inter-decadal basis over the period 1895–1994. They also have a correlation of 0.93 with the varimax factor scores for the same region based on non-interpolated PDSI reconstructions over the common period 1469–1978.

The factor scores clearly illustrate the importance of extending the drought reconstructions as far back in time as possible. Prior to 1600, there is evidence for three megadroughts in the 1280s, 1340s, and 1580s. The 1280s "Great Drought" has been associated with the disappearance of the Anasazi indian culture in the Southwest (Douglass 1929); and the 1580s drought is coincidental (perhaps linked) with the drought associated with the disappearance of the colonists on Roanoke Island (Stahle *et al.* 1998). Woodhouse and Overpeck (1998) also document the occurrence of the 1280s and 1580s droughts in the western US, but do not describe the 1340s event indicated here. Besides having three of the worst droughts of the past 800 years, the AD 1200–1600 interval is also characterized by enhanced inter-decadal variability that is associated with more prolonged episodes of drought and wetness. This is clearly illustrated in the following table, which lists the five driest 5, 10, and 20-year periods in this southwestern US drought record.

	5-Year Period		10-Year Period		20-Year Period	
Rank	Dates	Mean	Dates	Mean	Dates	Mean
1	1581–1585	–1.717	1576–1585	–1.442	1573–1592	–1.008
2	1666–1670	–1.584	1338–1347	–1.237	1336–1355	–0.730
3	1338–1342	–1.479	1664–1673	–1.010	1273–1292	–0.709
4	1399–1403	–1.343	1728–1737	–0.987	1945–1964	–0.629
5	1421–1425	–1.289	1280–1289	–0.910	1445–1464	–0.609

Table 1. *List of the five driest 5, 10, and 20-year periods in the PDSI factor scores shown in Fig. 1. The units are in standard normal deviates. Note the prevalence of megadroughts in the AD 1200–1600 period that would be totally missed if the PDSI reconstructions only extend back to, say, 1600.*

Note that for both the 5-year and 20-year intervals, 4 of the 5 driest periods were in the AD 1200–1600 epoch. Also, the late–16th century drought examined by Stahle *et al.* (2000) appears to be *the* megadrought of the past 800 years in the southwestern US. Thus, it is clear that PDSI reconstructions covering only the past 300–400 years are not sufficient to capture the full range of drought/wetness variability across the coterminous US. In fact, the recent few centuries could be interpreted as being conspicuously *deficient* of megadroughts, due perhaps to climate associated with the "Little Ice Age" (see Bradley, this issue). Why this is so is a mystery that needs to be solved and modeled. Any return to the modes of climate variability characteristic of the pre–16th century period in the US Southwest would be diasterous. If we truly want precisely dated, annual estimates of past drought for improving our understanding of drought variability and extremes, and for testing hypothesized forcings of drought and wetness (e.g. Cole and Cook, 1998; Cook *et al.*, 1997), the only recourse is to use centuries-long tree-ring chronologies and novel statistical estimation procedures to reconstruct the past.

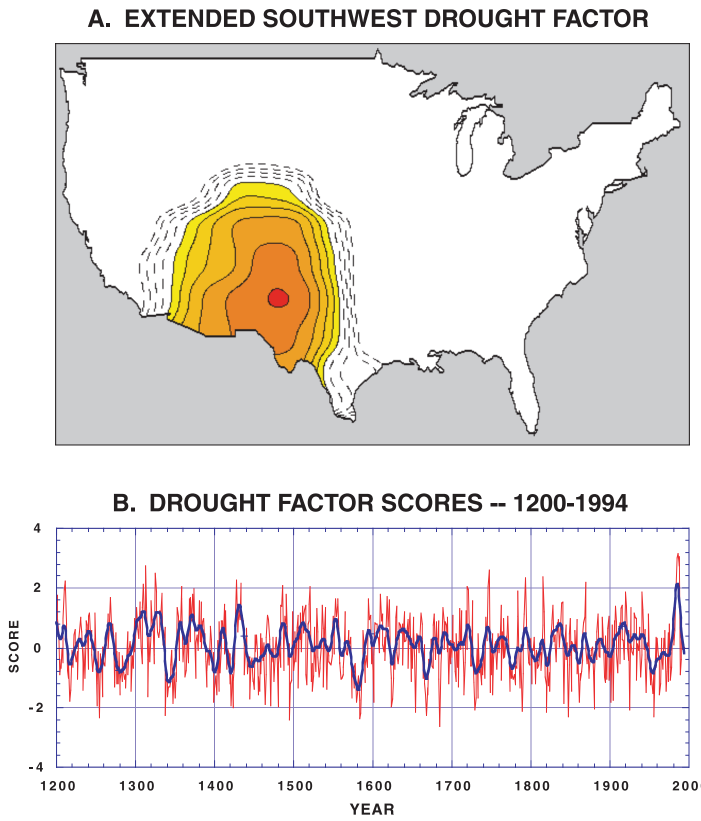

Figure 1:

(A) The first varimax rotated Empirical Orthogonal Function (EOF) of a Palmer Drought Severity Index (PDSI) grid derived from optimally interpolated tree ring chronologies. This factor emphasizes the southwestern US and is probably the highest quality region produced by the analysis.

(B) The scores for this EOF for the period 1200–1994. This timeseries has a correlation of 0.77 with instrumental PDSI from the Southwest on an annual basis and 0.86 on a smoothed, inter-decadal basis over the period 1895–1994.

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Conceptual Framework for Changes of Rainfall and Extremes of the Hydrological Cycle with Climate Change

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A physically based conceptual framework is put forward that explains why an increase in heavy precipitation events should be a primary manifestation of the climate change that accompanies increases in greenhouse gases in the atmosphere. The same arguments apply generally for all kinds of climate change. This paper summarizes Trenberth (1998, 1999) and a full set of references is given in those works.

The term "global warming" is often taken to refer to global increases in temperature accompanying the increases in greenhouse gases in the atmosphere. In fact it should refer to the additional global heating (sometimes referred to as radiative forcing, e.g., by the IPCC (1996)) arising from the increased concentrations of greenhouse gases, such as carbon dioxide, in the atmosphere. Increases in greenhouse gases in the atmosphere produce global warming through an increase in downwelling infrared radiation, and thus not only increase surface temperatures but also enhance the hydrological cycle, as much of the heating at the surface goes into evaporating surface moisture. This occurs in all climate models regardless of feedbacks, although the magnitude varies substantially.

Temperature increases signify that the water-holding capacity of the atmosphere increases and, together with enhanced evaporation, the actual atmospheric moisture should increase, as is observed to be happening in many places. Of course, enhanced evaporation depends upon the availability of sufficient surface moisture and over land, this depends on the existing climate. However, it follows that naturally-occurring droughts are likely to be exacerbated by enhanced potential evapotranspiration. Further, globally there must be an increase in precipitation to balance the enhanced evaporation but the processes by which precipitation is altered locally are not well understood.

Precipitating systems of all kinds feed mostly on the moisture already in the atmosphere at the time the system develops, and precipitation occurs through convergence of available moisture on the scale of the system. Hence, the atmospheric moisture content directly affects rainfall and snowfall rates, but not so clearly the precipitation frequency and thus total precipitation, at least locally. Thus, it is argued that global warming leads to increased moisture content of the atmosphere which in turn favours stronger rainfall events, as is observed to be happening in many parts of the world, thus increasing risk of flooding. It is further argued that one reason why increases in rainfall should be spotty is because of mismatches in the rates of rainfall versus evaporation.

The arguments on how climate change can influence moisture content of the atmosphere, and its sources and sinks are assembled in the schematic in Fig.1. The sequence given is simplified by omitting some of the feedbacks that can interfere. For example, an increase in atmospheric moisture may lead to increased relative humidity and increased clouds, which could cut down on solar radiation (enhance short-wave cloud forcing) and reduce the energy available at the surface for evaporation. Those feedbacks are included in the climate models and alter the magnitude of the surface heat available for evaporation in different models but not its sign. Figure 1 provides the rationale for why rainfall rates and frequencies as well as accumulations are important in understanding what is going on with precipitation locally. The accumulations depend greatly on the frequency, size and duration of individual storms, as well as the rate and these depend on static stability and other factors as well. In particular, the need to vertically transport heat absorbed at the surface is a factor in convection and baroclinic instability both of which act to stabilize the atmosphere. Increased greenhouse gases also stabilize the atmosphere. Those are additional considerations in interpreting model responses to increased greenhouse gas simulations.

However, because of constraints in the surface energy budget, there are also implications for the frequency and/or efficiency of precipitation. The global increase in evaporation is determined by the increase in surface heating and this controls the global increase in precipitation. But precipitation rates are apt to increase more rapidly, implying that the frequency of precipitation must decrease, raising the possibility of fewer but more intense events.

It has been argued that increased moisture content of the atmosphere favours stronger rainfall and snowfall events, thus increasing risk of flooding. Although there is a pattern of heavier rainfalls observed in many parts of the world where the analysis has been done, flooding records are confounded by changes in land use, construction of culverts, dams and so forth designed to control flooding, and increasing settlement of flood plains which changes vulnerability to flooding.

The above arguments suggest that there is not such a clear expectation on how local total precipitation amounts should change, except as an overall global average. With higher average temperatures in winter expected, more precipitation is likely to fall in the form of rain rather than snow, which will increase both soil moisture and run off, as noted by the IPCC (1996) and found in many models. In addition, faster snow melt in spring is likely to aggravate springtime flooding. In other places, dipole-like structures of precipitation change should occur in places where storm tracks shift meridionally. Beyond this, it is suggested that examining moisture content, rainfall rates and frequency of precipitation and how they change with climate change may be more important and fruitful than just examining precipitation amounts in understanding what is happening in model projections. To be compatible with life times of significant rain