EXTENSIVE SUMMER HOT AND COLD SPELLS UNDER CURRENT AND POSSIBLE FUTURE CLIMATIC CONDITIONS: EUROPE AND NORTH AMERICA

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ABSTRACT

The spatial scale of a heat wave is an important determinant of its impacts. Extensive summer hot and cold spells are considered over Europe and North America in observations and coupled model projections. Recent trends towards more frequent and extensive hot spells as well as rarer and less extensive cold outbreaks follow global warming trends, but are regionally modulated on decadal timescales. Coupled model projections reflect these natural and anthropogenic influences with their relative contributions depending on the particular scenarios assumed for global socio-economic development. Europe appears to have gotten an early warning in 2003 of conditions projected for the second half of the 21st century assuming a "business as usual" emissions scenario. North America, on the other hand, in spite of a general summer warming has not seen the extent of summer heat that it can potentially experience even if global emissions of carbon dioxide and sulfate aerosols remain fixed at their current levels. Extensive and persistent heat waves naturally occur in association with widespread drought. The recent warming over North America is unusual in that it occurred without the large-scale encouragement of a dry soil associated with precipitation deficit. Drought has the potential to seriously exacerbate the recent warming over North America to levels more in line with the warmest current model projections. Assuming realistic warming scenarios, a long-term anthropogenic increase (decrease) in the frequency and spatial extent of regional hot (cold) spells is projected to be strong and strongly modulated by decadal-scale variability throughout the 21st century.

Introduction

Outbreaks of anomalous summer heat occur each year somewhere on Earth. Typically associated with persistent blocking anticyclones, summertime heat waves in the midlatitudes have coherent spatial structure that is characterized by lack of rainfall, dry air and soil, and increased fire risk. Disastrous consequences (Macfarlane and Waller 1976, Sheridan and Kalkstein 2004) can result from hot spells that are extreme in their duration and spatial extent. The summer 2003, very likely the hottest in at least 500 years (Lutenbacher et al. 2005), brought periods of sustained temperatures exceeding 35ºC over much of western and central Europe accompanied by an almost complete lack of rainfall (Levinson and Waple 2004) that resulted in wide-ranging environmental degradation including severe impacts on agriculture, river flow, mountain glaciers, energy production and toxicity (e.g. Beniston and Diaz 2004), wildfires in southwestern Europe, and over ten thousand heat-stress-related deaths in France alone (Levinson and Waple 2003, Dhainaut et al. 2004). The "dust bowl" of the 1930's (Schubert et al. 2004), a period of summertime heat and drought affecting large parts of North America sustained over a decade and punctuated by exceptionally intense and extensive heat outbreaks in 1934, 1936 and 1937, saw widespread hardship, farmland abandonment and migration. Even mild hot spells of large spatial extent can cause havoc in the energy sector as demand for air conditioning rises beyond the capacity of power utilities to provide the needed power. Power outages during heat waves can lead to still higher human mortality through exposure. However, with adequate infrastructure in place, the health effects of heat waves can be effectively mitigated if the heat wave is anticipated even in the short term (Palecki et al. 2001, Sheridan and Kalkstein 2004). Economic hardships (Subak et al. 2000) of unanticipated and unmitigated heat waves can result from rising power costs, as well as from decreased crop yield and increased livestock mortality. Environmental consequences of hot spells can range from loss of flora and fauna due directly to heat stress and indirectly by fire to depletion of natural water reservoirs and streamflow through related precipitation deficit and increased evaporation. Sustained hot spells can increase the risk of vector-borne and other infectious diseases (Ballester et al. 2003, Zell 2004). The larger the spatial extent of a heat wave, the more the related hydrologic deficit should be able to exert a positive feedback prolonging the condition.

The spatial scale of a heat wave is an important determinant of its environmental, economic and health impacts. The scale of effort required to mitigate these impacts also depends in large part on the event's spatial extent. Yet, the scale parameter has been largely overlooked in climatological studies of heat waves. Extensive summer cold spells, although not as severe or dangerous in their impacts, can also have important consequences for agriculture and energy demand. They are considered here together with extensive heat waves to provide a fuller picture of variability and trends in summertime temperature extremes over Europe and North America. We shall see that the regional hot and cold spell indices plainly describe the behavior of regional extreme temperature outbreaks in a way complementary to but fundamentally different from examinations of temperature magnitudes on local or global scales. One important and robust feature of regional hot and cold spell occurrence is their strong low-frequency modulation. Global analyses mask regional decadal variability by averaging over it; local analyses tend to obscure it in higher frequencies. Super outbreaks of hot and cold air rarely occur in a temperature sense counter to prevailing decadal and longer-term trends – such outbreaks, after all, largely determine the trends. Recent trends towards more frequent and extensive hot spells as well as rarer and less extensive cold outbreaks can be explained through a combination of natural multi-decadal and anthropogenic influences.

Temperature anomaly magnitude, duration, as well as the spatial extent of a heat wave all contribute to the severity of its impacts. It is difficult to address all three of these characteristics in one study. Recent studies of heat wave occurrence spurred by the record-breaking 2003 European event focused on the magnitude and duration of *local* temperature anomalies (Beniston 2004, Beniston and Diaz 2004, Schar et al. 2004). These studies suggest that the unprecedented temperature anomalies observed at a specific location in connection with the 2003 heat wave are extraordinary with respect to current climate, but emblematic of expected future conditions. Meehl and Tebaldi (2004), moreover, project heat waves to become more intense, more frequent and longer lasting over Europe and North America in general and specifically around Paris and Chicago. All of these studies examined time slices of several decades in observations and climate models to characterize effects of anthropogenic climate change projected for an average summer at the end of the 21st century. In a rather different study, Stott et al. (2004) considered spatially averaged temperatures over the greater Mediterranean region to illustrate that anthropogenic activities have likely increased the current risk of an event such as the 2003 European heat wave more than two-fold in current climate and projected it to increase 100-fold over the next forty years. This transition to enhanced heatwave activity over Europe and North America and its dependence on scenarios for political and social action designed to combat global warming, or not, is a major focus of the present chapter.

Since large regions (e.g. continents) can and do experience simultaneous sub-regional hot and cold outbreaks, broad regional temperature averages are not the most appropriate indices for describing variability of regional heat and cold spells. In this work, we define an index that *explicitly* reflects the spatial scale of hot and cold outbreaks as well as, although implicitly, their magnitude and duration. The spatial extent of North American and European summertime extreme temperature outbreaks is then considered in the context of decadal and interannual observed variability and coupled model projection of anthropogenic climate change. Instead of aggregating observed and modeled data in samples of several decades to represent present and future climates as was done in recent studies (Beniston 2004, Schar et al. 2004, Meehl and Tebaldi 2004), we display time series of hot and cold spell indices at annual resolution computed for each summer on record. In particular, we ask the questions: What is the temporal character of spatially extensive temperature extremes over Europe and North America? To what extent do widespread extremes such as the 2003 European event reflect natural climatic variability? How is natural variability expected to modulate projections of anthropogenic warming? Does the general warmth of recent decades favor extensive hot outbreaks and discourage cold ones? What are the relevant climatological timescales of regional summertime hot and cold spells? Are recent conditions expected to persist, amplify or diminish in future decades? What is the effect of precipitation on regional summer temperatures? How do projections of future heatwave evolution depend on scenarios for future socio-economic development?

Regional Hot and Cold Spell Indices

We define local heat wave conditions as exhibiting temperatures in the upper 10% of the local climatology over a base period (1950-1999). To focus on the spatial extent of hot outbreaks, we construct the regional hot spell index (HSI) by counting the frequency with which each summer (JJA: June through August) appears as one of the warmest 10% of summers on the available record at individual locations (stations or grid cells) covering the region of interest. This amounts to detecting average summer temperature warmer than the 90th percentile of the local 1950-1999 JJA temperature for all locations over recorded or modeled summers describing a region's climate evolution. The cold spell index (CSI) is constructed similarly for the coldest 10% of summers. Because HSI and CSI (H&CSI) are computed relative to the local input data, these indices are insensitive to local systematic biases and extremely robust with respect to the nature of the input data used as long as the data coverage reasonably represents the region of interest.

The locally warmest (coldest) summer, by design, does not have a heavier weighting than the second, third, etc. warmest (coldest) summers on a specific record. The indices are, therefore, very robust with respect to outliers as well as to the spatial detail of heat wave patterns, which may be noisy and/or model specific. But, the hot and cold spell indices are designed to be highly sensitive to the *spatial scale* of the individual summer's hot and cold air outbreaks. The H&CSI are powerful detectors of temporal variability in spatially extensive extreme temperature outbreaks that are long-lived enough to strongly mark local average JJA temperature. A fundamental difference between H&CSI and standard regional indices constructed by spatially averaging seasonal temperature anomalies can be appreciated by the fact that the H&CSI perform as intended even when different parts of the region experience opposite temperature extremes.

Of course, H&CSI are sensitive to the spatial scale of the region of interest and to the percentile of the local temperature climatology chosen to define hot and cold extremes. Both regions considered here are large enough to experience significant hot and cold outbreaks in their different sub-regions in a specific summer, but also compact enough to allow most of their area to be covered by unusually extensive hot or cold extremes. The temporal structure of H&CSI becomes spikier for smaller regions as well as for more extreme temperature thresholds; more saturated for much larger regions and less extreme percentile thresholds. However the main conclusions of this study do not change with the choice of, say, a 75% or 98% threshold for HSI. We apply a 90% JJA temperature threshold as a reasonable compromise between spikiness and saturation.

The new and improved Climatic Research Unit (CRU) observational 5° X 5° gridded surface air temperature, CRUTEM2v (i.e. two-meter air temperature, Ta2m), was used to define past heatwave activity. This monthly global land surface temperature record covers the years 1851-2004 and includes variance adjustment due to changing station density within each grid box (Jones et al. 1997). More information on the CRUTEM2v data set, hereafter referred to as CRU2, can be found in Jones and Moberg (2003). To avoid values derived from sparse station records, we used these data from 1900 on.

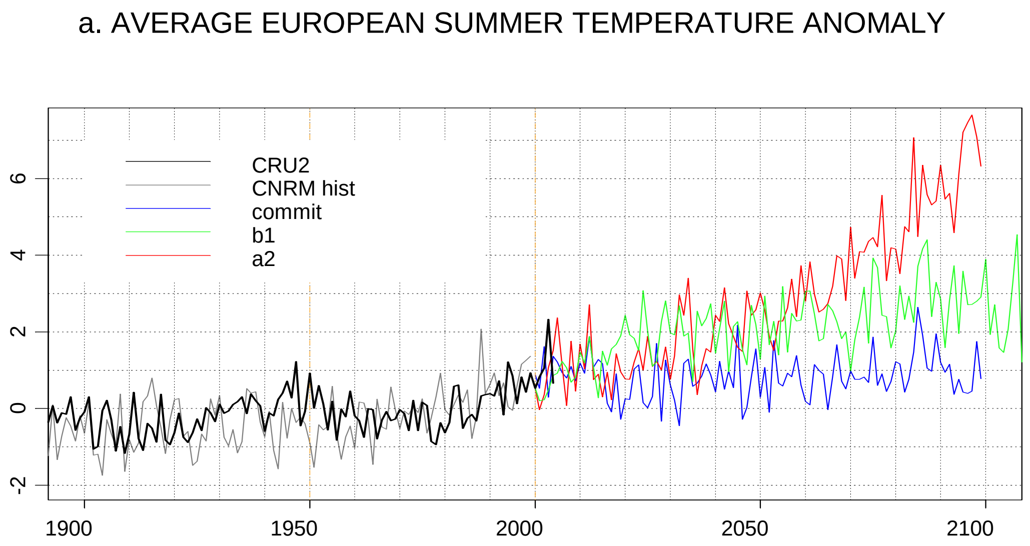
Surface air temperatures from four coupled global dynamical climate models (CGCMs) out of the twenty-two available in the IPCC4 data base (http://www-pcmdi.llnl.gov/ipcc) were analyzed. Because our indices are computed relative to regional climatologies, they downplay individual model biases. And since most models show generally similar features of H&CSI index behavior relative to their own climatologies, we show results based on one model that is reasonably close to the average of model projections. The CGCM (Douville et al. 2002) is a fully coupled land-ocean-ice-atmosphere dynamical spectral model developed and run at the Centre National de Recherches Météorologiques (CNRM) of Météo-France at the spatial resolution of approximately 2.8º. Four integrations of the CGCM have been analyzed. The "historical" run (1860-1999) was forced with observed greenhouse gas and sulfate aerosols concentrations. The "commit" run (2000-2099) is based on concentrations of these gases fixed at the year 2000 level. The SRES-B1 and A2 projections evolve according to different scenarios for socio-economic development (Arnell et al. 2004). The B1 is a conservative warming scenario that assumes enlightened action by governments to reduce anthropogenic emissions and population growth, while the A1 is essentially "business as usual".

When truly global observational data is required, we use two-meter air temperatures from the NCEP/NCAR reanalysis (Kistler et al. 2001) available from 1948 to the present. Although known biases exist in these data (Simmons et al. 2004), they are the most globally complete and physically consistent data available and are adequate for the purposes of this investigation. Reanalysis has a cold bias in surface air temperature owing to the fact that only upper air temperature observations are assimilated meaning that land use effects are not incorporated. Also, before the late 1970s, the bias is stronger because fewer observations were available for assimilation. Nonetheless, Reanalysed H&CSI are well correlated with those derived from CRU2.

Near-global gridded station precipitation data (GHCN V2) were obtained from the National Climatic Data Center (NCDC) and consist of observations from 1900 to the present on a 5X5 degree grid (http://www.ncdc.noaa.gov/oa/climate/research/ghcn/ghcngrid_prcp.html#Overview). All gridded data were weighted by cosine of latitude, although it does not significantly affect any of the computed indices.

Over North America, where extensive original and homogenized station temperature and precipitation records are available, results derived from the gridded products (i.e., CRU2, GHCN V2, and Reanalysis), were further validated with an extensive station data set derived from US (NCDC 2003, Easterling 2002, Groisman et al. 2004), Mexican (Miranda 2003) and Canadian (Vincent and Gullett 1999) networks over North America. In the interest of brevity, we do not show results based on these extensive station records here, but note that the gridded products give essentially the same results. The interesting regional detail that emerges from the station analyses will be presented in future publications.

Europe


a. AVERAGE EUROPEAN SUMMER TEMPERATURE ANOMALY

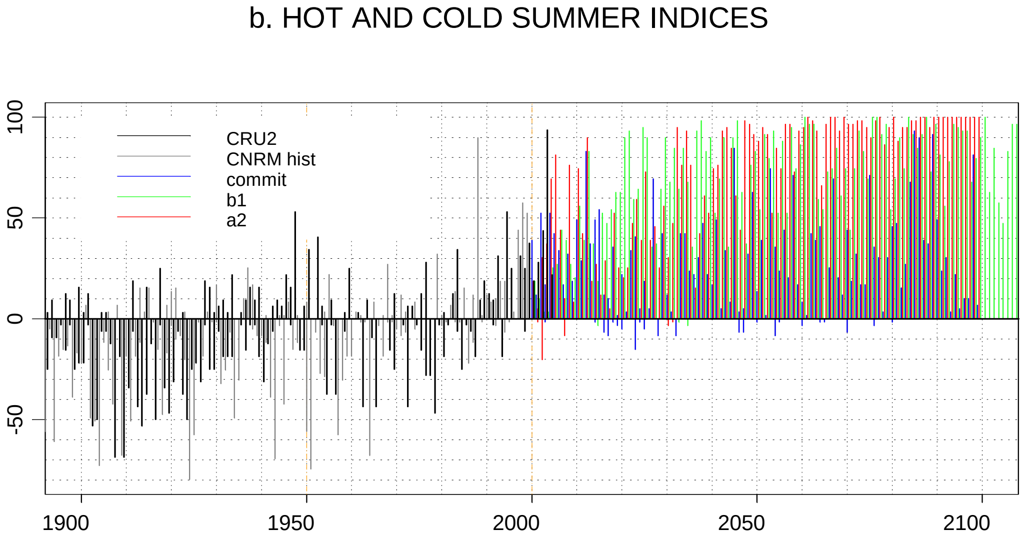


Figure 1. (top): European average temperature anomaly relative to the base period 1950 – 1999 from CRU2 observations and the CGCM historical and future scenarios. **(bottom)**: H&CSI displayed as percentage of European grid points with summer temperatures above the 90th or below the 10th percentiles of their local summer 1950 – 1999 climatology. HSI (CSI) is displayed in positive (negative) values. By definition, during the base period, the mean values are 10% of the area covered experiencing unusually hot or cold summers. HSI and CSI falling outside of the 10% thresholds represent unusually hot and/or cold conditions over larger-than-expected total area of Europe. Values falling inside these bounds represent unusually average conditions.

Defining Europe by its midlatitude west-central area as the region situated between 10ºW and 25ºE, 37º and 57ºN, we first compute the average temperature anomaly from observations and the coupled model relative to their respective 1950-1999 climatologies (Figure 1a). In contrast to regionally averaged temperatures, which reflect a mixture of magnitude and spatial extent of all seasonal temperature anomalies with coexisting warm and cold anomalies canceling each other, the hot and cold spell indices (H&CSI, Figure 1b) reflect primarily the spatial extent of seasonal warm and cold temperature extremes. Of course, strong coherent anomalies that cover most of the region (i.e. summer 2003) are reflected in both average temperature and in H&CSI. Regional average temperature, needless to say, is closely correlated with the average of HSI and CSI, the latter being denoted by negative values as a matter of convention in display. We provide the average temperature anomaly as a reference that shows general temperature tendencies of an entire region, but the H&CSI provides more detail and will therefore be discussed in greater detail.

The general character of H&CSI viewed simultaneously follows along with average temperature, but the H&CSI time series are marked with more pronounced multi-decadal and interannual variability. Aside for several localized heat waves that covered less than a quarter of the area, Europe was predominantly cold until the early 1940s with the largest cold extremes, affecting almost 70% of the region, occurring in 1907 and 1909. A general warming ensued and, after a few warmer summers, 1947 experienced a heat wave that covered more than half of Europe. After that, extremes of both signs became more common. However, Europe continued to experience mostly cold summers in the 1950s, 60s and 70s. The summer of 1976, when approximately 30% of the area experienced hot spell conditions, stands out as the largest heat wave since 1952, while the concurrent cold spell of similar spatial extent seems unremarkable for that period. The 1976 heat wave affected North-Western Europe (Figure 2b). It was centered on Great Britain (Green 1978), where it was the hottest summer on record until 2003 and the cause of much adversity (Subak et al. 2000). However, summer 1976 was actually uncommonly cold over Eastern Europe and most of the rest of the northern midlatitudes (Figure 2b). The hot and cold spell indices reflect this fact (Figures 1b, 2a), while the average summer temperature anomaly over the region is close to zero (Figure 1a). The case of 1976 accentuates the fact that sub-regions of a continent or of an entire hemisphere can experience temperature extremes opposite in sign to the prevailing large-scale conditions. It also emphasizes the relative nature of extremes and their impacts viewed in terms of human adaptation to decadal trends. Since the early 1980s, a heat event like that of 1976 was no longer exceptional[1], with seven hot spells surpassing 1976, as well as generally higher mean temperatures. The heat wave of 1994 with over 50% of Europe experiencing heat wave conditions (Figure 2a,c) was the largest event since 1947. The 2003 event[2] was significantly more severe still, both in terms of temperature anomaly magnitude and spatial extent (Figures 1 and 2a, d). What's more, no significant cold outbreaks were experienced since 1993. Viewed in the context of the last century, the heat wave of 2003 is unprecedented. However, it exemplifies the warming trend observed over the last several decades in average summer temperatures as well as in the magnitude and scale of European heat waves (Figures 1 and 2). This is part of the warming trend that is manifested globally on the snapshots of Figure 2 (b, c and d), a trend consistent with model projections of anthropogenic warming for Europe and the globe. Even without 2003, European HSI observed during the last decade is the longest and warmest such period on record, a period wholly consistent with the model estimation of warming for anthropogenic forcing fixed at year 2000 levels (the commit run, Figure 1a and b).

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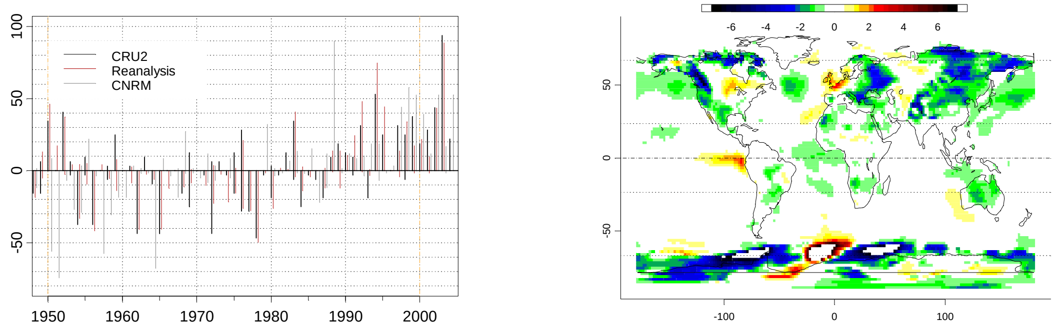
[1] Except, of course, from a distinctly British viewpoint.

[2] The 2003 summer heat wave consisted of two outbreaks, one in June and a second in August. Most of the adverse impacts occurred during the second outbreak when hot anomalies rose above the seasonal temperature maximum in August. For convenience, we refer to the sum effect of these two outbreaks as reflected in JJA average temperature as the summer 2003 heat wave.

Examples of European Hot Summers and Global Conditions

a. EUROPEAN H&CSI **b. HSI EXTREME SUMMER 1976**



c. HSI EXTREME SUMMER 1994 **d. HSI EXTREME SUMMER 2003**

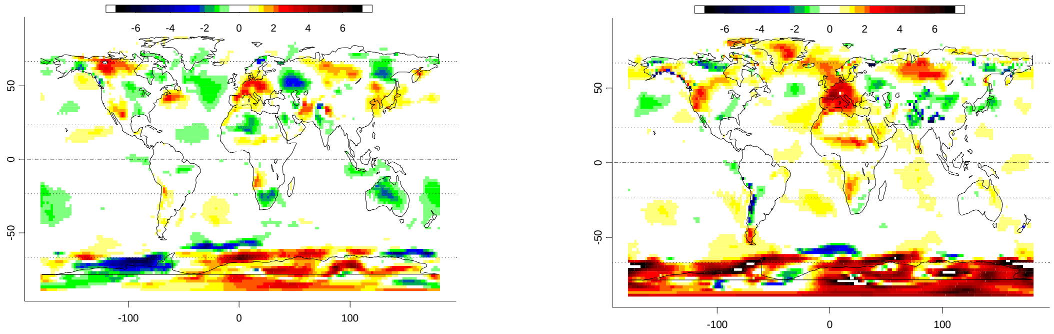


Figure 2. (a) H&CSI from CRU2 (black), NCEP/NCAR Reanalysis (brown) and CGCM (grey) for the common period 1950-2003. **(b)** Reanalysed temperature anomalies for summer 1976, **(c)** 1994, and **(d)** 2003.

The coupled model cannot reproduce the observed decadal variability (i.e. the warm late 1940s and early 50s, the cool late 70s) – it is not supposed to – but it is able to reproduce the observed warming trend quite well, as do most other coupled models, suggesting an anthropogenic cause to the warming observed since the late 1970s. This being a regional manifestation of a global trend, it is difficult to say to what extent natural decadal variability played a part. The historical model run contains one event of this magnitude (model year 1988). The CGCM with forcing fixed at year-2000 levels produced three more events of this general magnitude during the 21st century. Encouraged by natural decadal variability these events all occur in the model during the same decade, the 2080s. Natural decadal variability masks the difference between the two more realistic scenarios (SRES-A2 and B1) in the first half of the 21st century when a 2003-level average temperature becomes common in both model scenarios. Clear differences in scenarios of anthropogenic forcing become apparent in the second half of the century. Since the 2050's, 2003-level heat is exceeded in the milder B1 warming scenario in most summers and always in the A2[3].

Estimating the probabilities of specific events in various time periods and climate change scenarios for Europe involves several problematic assumptions. We prefer to let the reader

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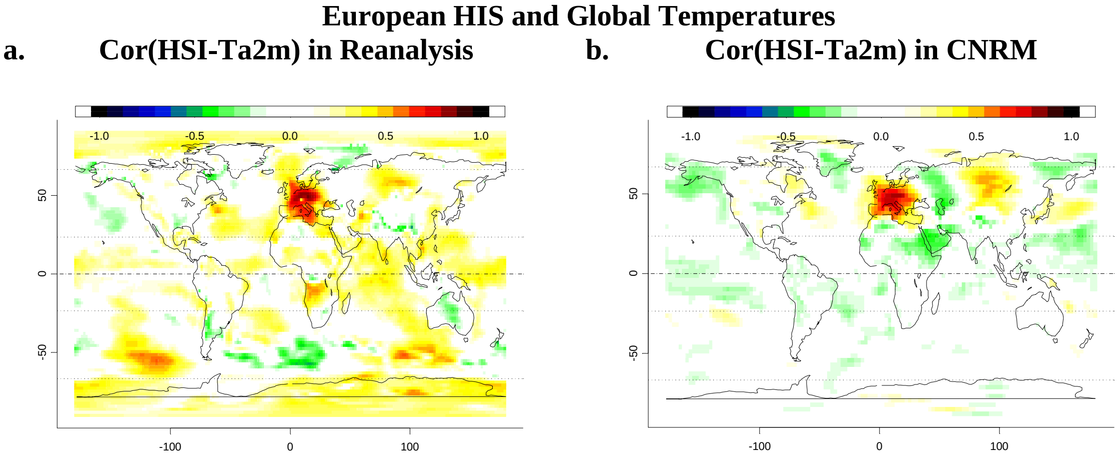
[3] In the next half century, according to model results, although regional manifestations of global warming should become more evident, it may be impossible to regionally assess the effects of global policies implemented to mitigate it.

qualitatively gauge the danger of extremely hot summers in the future by visually examining Figures 1 and 2.


European HIS and Global Temperatures

a. Cor(HSI-Ta2m) in Reanalysis

b. Cor(HSI-Ta2m) in CNRM

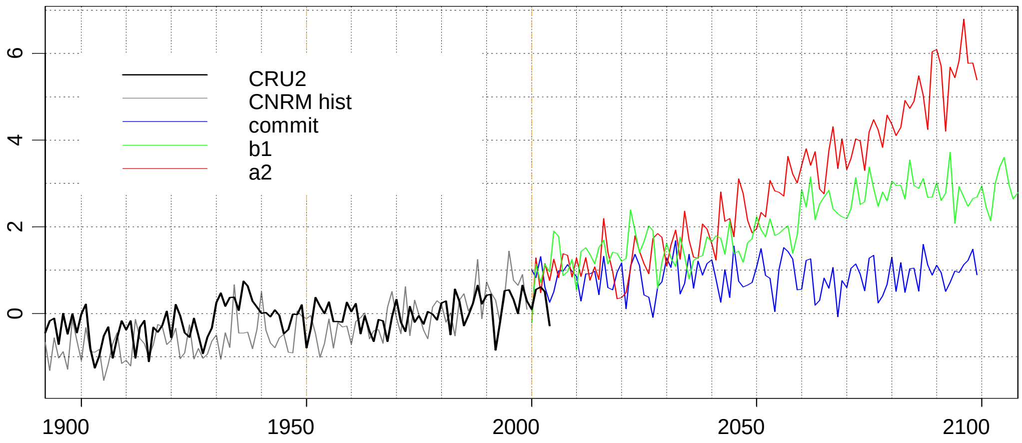
Figure 3. Correlation coefficient between Western European HSI and local JJA Ta2m over the globe in (a) Reanalysis 1948 – 2003, and (b) the CGCM commit run 2000 – 2099.

To place European heat waves into a global temperature context as well as to validate the CGCM, we correlate the HSI with summer surface air temperatures over the globe derived from the Reanalysis and compare these patterns to those derived from the CGCM's commit (i.e. stationary) run (Figure 3). Western European heat waves are seasonally correlated with a Eurasian-scale summer temperature wave structure characterized by in-phase behavior over Western Europe and north-central Siberia and out-of-phase behavior over part of European Russia and the Russian Far East. This is evident on Figure 2, but to see it clearly in Ta2m correlations with HSI, we should remove the observed warming trend from HSI and Ta2m. Figure 3a shows the correlations with the trend present. This has the effect of better illustrating European heat wave activity in the context of a warming planet (notice the mostly positive correlations with boreal summer temperatures around the globe) at the expense of masking especially the out of phase portions of the Eurasian temperature wave train associated with European heat waves. The wave train correlation structure becomes obvious when the long-term trend is removed from observations (result not shown) and it is well borne out in the commit model run (Figure 3b), which is stationary by design. In both model and observations, there is a strong interannual propensity for Far Eastern Europe to be cold during heat wave summers in West-Central Europe. Both recent extreme European heat wave summers of 1994 and 2003 were cold in far-eastern Europe (e.g. anomalous snowfall occurred in Moscow in June 2003; Levinson and Waple 2004) and warm over north-central Siberia, thus exhibiting Eurasian summer temperature wave train conditions typical of large European heat waves (Figure 2c,d).

Midlatitude North America

We limit the study area to the latitudinal band between the Tropic of Cancer and the 53rd parallel, north of which latitude population and station density becomes sparse; a fact manifested in CRU2 as well as GHCN V2 data gaps over Canada. North American average temperature and H&CSI derived from observations and the CGCM are displayed in Figure 4.

a. AVERAGE NORTH AMERICAN SUMMER TEMPERATURE ANOMALY



b. HOT AND COLD SUMMER INDICES

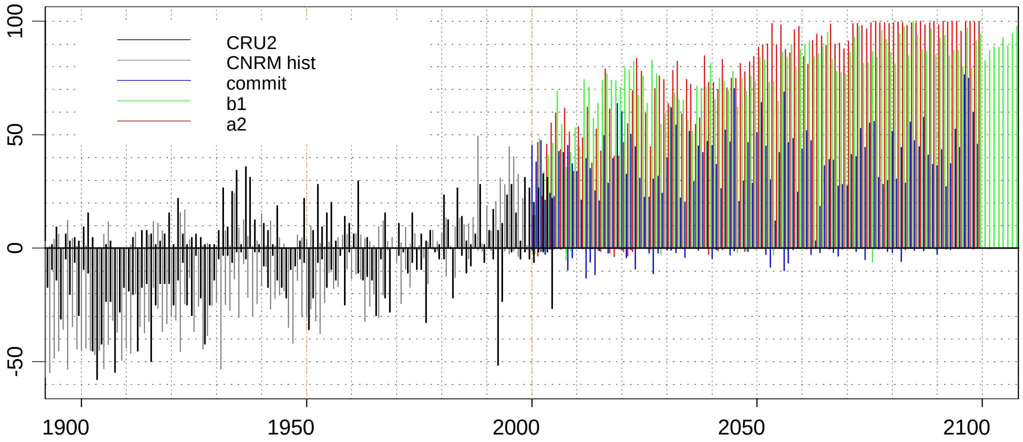


Figure 4. Same as figure 1, but for North America; **(top)**: North American average temperature anomaly relative to the base period 1950 – 1999 from CRU2 observations and the CGCM historical and future scenarios. **(bottom)**: H&CSI displayed as percentage of North American grid points with summer temperatures above the 90th or below the 10th percentiles of their local summer 1950 – 1999 climatology. HSI (CSI) is displayed in positive (negative) values. By definition, the mean values are 10% of the area covered experiencing unusually hot or cold summers. HSI and CSI falling outside of the 10% thresholds represent unusually hot and/or cold conditions over larger-than-expected total area of North America. Values falling inside these bounds represent unusually average conditions.

The first three decades of the 20th century were the coldest on record with summers of 1903, 1907 and 1915 experiencing widespread cold anomalies affecting at least ½ of North America, a scale not reached again until 1992: the largest summer temperature extreme of the second half of the century. We note that these, as well as smaller-scale recent cold outbreaks (e.g. 1976, 1982, 1993, 2004) were associated with locally wet summers (result not shown). On the other hand, the 1930s appear to have experienced the warmest and most consistently warm conditions on record, at least until very recently, 7 of 11 (1930-1940) summers were more extensively warm (none cool) than expected, and all 11 warmer than average (see Figure 6a for the spatial pattern). The summers of

1934, 1936 and 1937 experienced by far the most severely extensive hot spells of the century (> 30% of North America under hot spell conditions). These summers were also exceptionally dry (result not shown for the individual summers; see Figure 6b for the 11-yr average precipitation anomaly). No summers during the 1930s saw cold outbreaks that even remotely approached their expected spatial extent of 10%.

The 1940s were generally and mildly cool. The 1950s were unusually variable, but the warm summertime temperature anomalies associated with the 1950s drought[4], although large, were not as spatially extensive, temporally persistent, or exclusive as in the 1930s; they were balanced out by comparably large cold anomalies, a fact reflected in near-zero average temperature anomalies. The 1960s and 1970s saw less variability with predominantly cool conditions. North America became more variable in the 1980s and 1990s while warming into the opening of the 21st century. In the midst of general warmth, a cold spell covered 50% of midlatitude North America in 1992, the first time such widespread coldness was observed since 1907. The extremely cold summer of 1992 was followed by the mostly cool 1993, both perhaps related to the Mount-Pinatubo volcanic eruption[5] (Robock 2000). But even in the cool summer 1993 (CSI = 23%), the expected area was hot (HSI = 11%) and the decade that followed (1994-2003) was akin to the 1930s with nine out of ten summers exceeding the mean extent of heat and three summers (1998, 2002 and 2003) with hot spell conditions covering more than 30% of the continent for the first time since the 1930s. The last observed summer (2004) was both anomalously warm (HSI = 22%) and cold (CSI = 27%). The recent Midwestern heat waves of 1995 and 1999 each resulted in HSI values of under 30%.

The questions as to what global climate conditions are conducive to intense summer heat outbreaks over North America and whether these conditions are reproduced by the model can be addressed by considering maps of correlation coefficients between HSI and local Ta2m over the globe (Figure 5). In Reanalysis and the CGCM, spatially extensive hot spells over North America tend to organize preferentially around the Midwestern United States and they tend to be associated with cool temperatures in the northeast midlatitude and tropical eastern Pacific, warm temperatures in the subtropical western Pacific, as well as a general tendency toward warm temperatures in the tropical and northwestern Atlantic. Other patterns apparent in Reanalysis are characterized by mostly weak positive correlations in patches around the globe reflecting the general recent global warming. As before in the case of European HSI, these patterns are not reproduced by the model’s “commit” climate run which is stationary by design. What's more, the association between HSI and preferred heat wave location appears to be weakened in Reanalysis (Figure 5a) because the recent warming did not manifest itself in the preferred natural heat wave region of the Midwestern and north-central United States (see below). Other differences may be due in part to the larger noise level in the shorter Reanalysed climatic sample. As an aside, we have also examined multi-decadal changes in global correlation patterns. Modeled correlations computed in consecutive 50-year periods using the model’s historical as well as B1 and A2 runs (figures not shown) plainly resemble the main patterns of Figure 5. They also indicate a consistent change in the characteristic pattern of the HSI amounting to a progressive migration of North American heat outbreaks toward the north of the study region. In summary, the model produces North American hot and cold spells consistent with observed global-scale climate conditions, exemplified here by near-surface temperature patterns.

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[4] The bulk of the 1950s warmth was coincident with drought, which was mostly concentrated in the fall and winter seasons.

[5] Both these summers 1992 and 1993 were also anomalously wet over the regions corresponding to the largest observed cooling: Great Plains in 1992, Northern Plains and Northwestern US in 1993 (result not shown). The summer 1993 was considerably wetter than 1992.

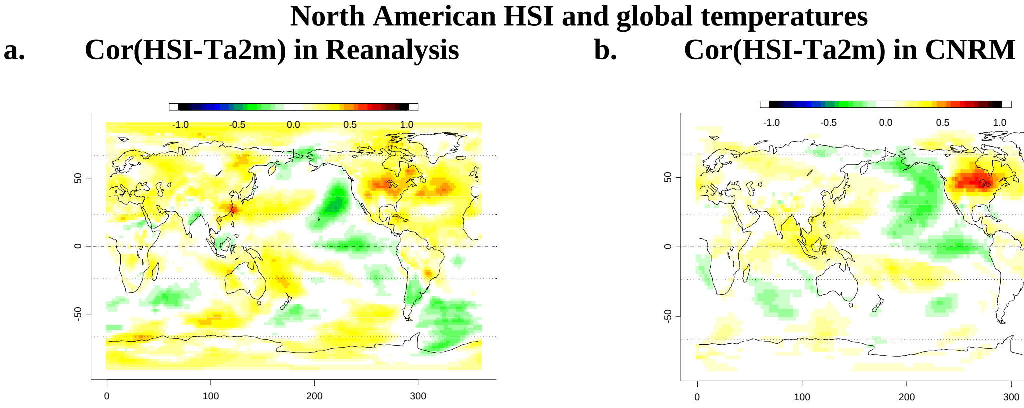

Figure 5. Correlation coefficient between North American HSI and local JJA Ta2m over the globe in (a) Reanalysis 1948 – 2003, and (b) the CGCM commit run 2000 – 2099.

The marine temperature patterns associated with extensive North American summer heat spells are analogous to the anomalous sea surface temperature "forcings" for the 1930s Dust Bowl drought as outlined by Schubert et al. (2004). It is also well known that large-scale summer heat can be caused or exacerbated by atmospheric drought through soil moisture deficit (e.g. Alfaro et al. 2006). This was the case in the hot and dry 1930s when precipitation, especially in summer, was scarce[6] (see Figure 6a,b). However, the most recent period of summer heat observed over North America, although on the scale approaching that of the 1930s, was not associated either with prolonged large-scale drought or with an anomalously cold tropical Pacific.

In fact, the most recent warm period 1994-2004 is very much unlike the 1930s. The central and eastern United States have been mostly wet over this period[7] (Figure 6c,d). Despite this recent wetness, the central and eastern US have not cooled as would be naturally expected. Such expectation is supported by Figure 7a, which shows observed local correlations between summer temperature and precipitation. Meanwhile, much of the recent warming over midlatitude North America has been due to warmer summers all around this central and eastern US wet spot (Figure 6c,d). Recent summer warmth over the mountainous West is probably related to the strong warming observed in the West during winter and spring that resulted in changes in the snow-to-rain ratio (Knowles et al. 2006) as well as the spring's earlier arrival and related changes in surface hydrology (Cayan et al. 2001) drying the soil in summer without appreciable changes in precipitation amounts. This western summer warming (Figure 6c) is reflected in increasing values of the North American HSI.

Strong and extensive Canadian warming apparent on Figure 6c did not affect any of the earlier results because Canadian data, for reasons of data quality given above, was excluded from North American Index calculation. Had Canadian data been included, the recent warming would have appeared larger. This observation is consistent with the model result projecting heat waves to spread progressively towards the north (not shown).

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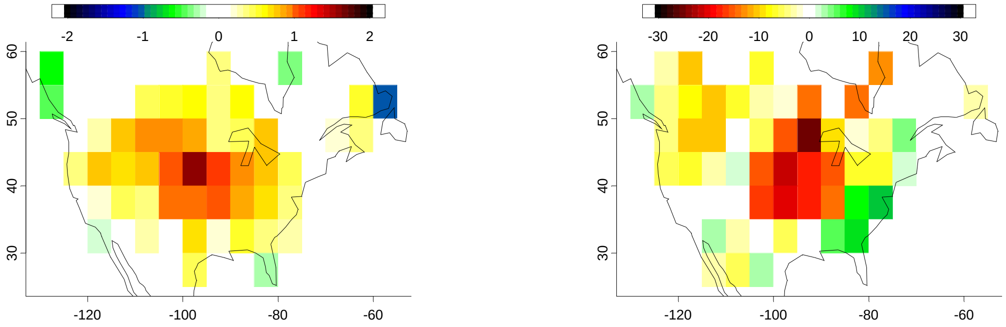
[6] Drought reconstructions show that the 1930s "Dust Bowl" drought was the most severe and widespread such event to strike the United States since 1700 (Cook et al. 1999).

[7] In fact, the entire country has been generally wet over the last quarter century.

Climate anomalies relative to 1950:1999 base period

a. Temperature anomaly 1930:1940

b. Precipitation anomaly 1930:1940



c. Temperature anomaly 1994:2004

d. Precipitation anomaly 1994:2004

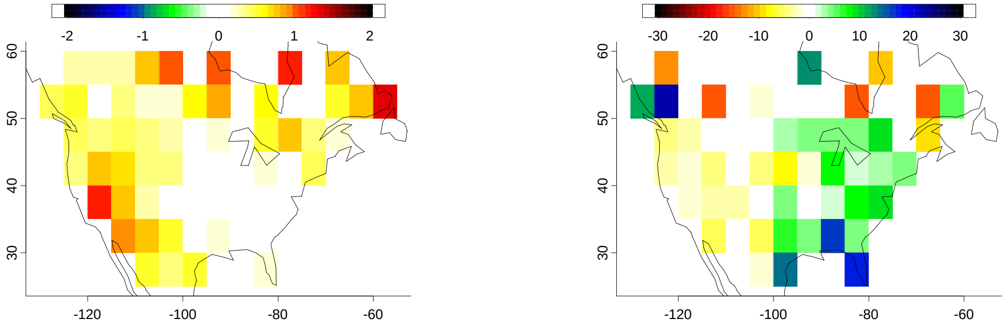


Figure 6. Summer temperature (a,c) and precipitation (b,d) anomalies for two 11-year periods: 1930-1940 (a,b) and the most recent period of record, 1994-2004 (c,d). Canadian precipitation records end in **1998 or 2001** explaining the visible discontinuity along the US-Canada border on panel d.

The role of precipitation

There is a well-known interaction between soil moisture and surface level temperature. On the one hand, anomalous prolonged warmth can desiccate the soil, on the other, the drier the soil, the less energy is required to heat it. Precipitation deficit can, therefore, enhance regional heat wave activity and partially account for multi-decadal timescales in extreme summer heat outbreaks that can temporarily either promote or dampen the effects of global warming. Summer heat and precipitation are, of course, dynamically linked for the anticyclonic circulation that produces heatwaves also precludes precipitation. In regions that typically receive much summer precipitation, it is therefore difficult to isolate the effect of contemporaneous (summer) precipitation on temperature while antecedent precipitation's effect on summer temperature through soil moisture accumulations is typically small and may influence heatwaves primarily in the early summer. In regions where summer precipitation amounts are small, the delayed precipitation/soil moisture effect can be much stronger.

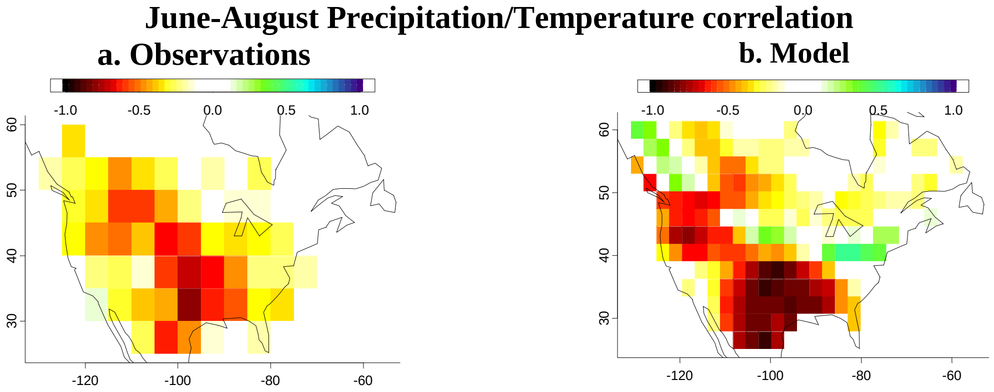


Figure 7. Correlation coefficient between local June-August average temperature and precipitation in observations (a: GHCN V2 and CRU2 evaluated over the period of record, 1900 – 2004, or slightly shorter based on data availability for the individual grids) and in the model (b: the commit run, 100 years).

We have examined the contemporaneous and lagged relationships between local summer temperature and precipitation. Figure 7 shows that the two are strongly anti-correlated over North America[8], particularly along the Front Range of the Rockies and to the southeast over the Great Plains and a great part of the Midwest and the Gulf Coast, the Mexican Plateau and the mountainous northwestern US. We have also regressed precipitation out of local summer temperature and compared resulting regionally averaged temperatures as well as H&CSI with raw values discussed above over both Europe and North America. These results are not shown, but they indicate that precipitation deficit appears to have played a critical role in enhancing the severity of Europe 2003 as well as the Dust Bowl and other observed extremes. However, the bulk of the recent observed warming trend over Europe is not associated with drying[9]. Moreover, the area that traditionally experiences large-scale heat waves, the Midwest and Great Plains region of the United States (Figure 5a), has remained normal, i.e. not particularly hot (Figure 6c). In this area and to the south and west of it, summer temperature is strongly anti-correlated with precipitation (Figure 7a). It is important to emphasize that this has been true historically on interannual as well as longer timescales, but lately, the local anti-correlation on decadal timescales has disappeared. Although the central/eastern US has been unusually wet in recent decades, no significant long-term cooling has occurred there. Rather normal conditions have prevailed in this region recently. Unless the laws of thermodynamics have ceased to operate lately, we are left to assume that there has been a concurrent warming which has offset the cooling expected in the central and eastern US in response to increased wetness. Giving further support to this inference, the rest of North America has most certainly warmed. If this background warming persists or continues as we can expect from model results (see Figure 4 as well as from results of numerous other modeling studies), we can reasonably expect that the end of the current wet spell should be accompanied by stronger and more extensive summer warmth.

As for the model, the regions of largest projected midlatitude continental summer warming in both A2 and B1 scenarios are those with projected regional decreases in precipitation (result not shown). This is not surprising. The model is certainly able to reproduce the spatial signature of

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[8] Europe presents a similar picture, but the anti-correlation is somewhat weaker than over North America.

[9] Rather, it appears to be associated with the enhanced greenhouse effect of water vapor (Philipona et al. 2005).

the local summertime precipitation/temperature relationship, albeit with somewhat stronger than observed coupling (Figure 7b).

SUMMARY AND CONCLUSIONS

Examination of hot and cold summer indices over continental-scale regions suggests that practically every summer is extreme in some temperature sense somewhere (Figures 1b and 4b). The European HSI shows the 2003 event to be the largest since the beginning of record. According to our definition, more than 90% of western and central Europe experienced hot spell conditions in 2003. At many European locations, 2003 was the hottest summer on record, probably the hottest in over 500 years (Luterbacher et al. 2004), with average summer temperature anomalies reaching 5ºC (Figure 2d). This intensely and extensively hot summer was consistent with the multi-decadal warming trend towards more frequent and extensive European heat waves apparent since the late 1970s (Figure 1b). Coupled model projections show a combination of natural and anthropogenic influences with their relative magnitude being a function of the particular scenario assumed for global socio-economic development, i.e. resolute action or inaction on the part of nations. For now, Europe appears to have gotten an early warning in 2003 of conditions projected for the second half of the 21st century assuming inaction. This conclusion is consistent with other recent studies (Beniston 2004, Beniston and Diaz 2004, Schar et al. 2004, Meehl and Tebaldi 2004, Stott et al. 2004). Drought certainly enhanced the severity of the 2003 event (Levinson and Waple 2004). Apart from this, drought does not appear to have had a hand in the recently observed warming trend. Fresh observational evidence suggests that much of recent warming over Europe, at least around the Alps, has been caused by the enhanced greenhouse effect due to the water vapor feedback (Philipona et al. 2005), the most important and variable greenhouse gas. For now, Europe is warming at least as much and as fast as predicted by the climate model.

North America, while also warming, has not yet felt the feasible level of heat projected for the current stage of anthropogenic climate change. Interestingly, the current warm period, although at least in spatial extent on par with the 1930s Dust Bowl, does not involve the same region of North America, is not associated with severe drought and is, therefore, very much unlike the similar-scale 1930s warming. The recent summertime warming over North America has occurred notably in the mountainous west, where it is consistent with observed hydrological changes initiated by warming trends in the winter and spring. Specifically, the western summertime warming occurred alongside with a strong observed trend towards warmer winter and spring and earlier snowmelt (Cayan et al. 2001) as well as decreasing snow/rainfall ratios (Knowles et al. 2006). The hydrological changes initiated by these trends in winter and spring result in drying of the soil into the summertime and can partially explain the western summertime warming. It is possible that European-Alpine-type water vapor feedback processes (e.g. Philipona et al. 2005) may also explain a part of this western summertime warming. Supporting such a possibility, as well as giving further verification of a large-scale environmental change, is the fact that North American warming also has a broad Canadian footprint (Figure 6c). However, Canadian data were excluded from index calculations here.

The only portion of North America that has not warmed lately is the central and eastern US, a preferred area for heat wave occurrence, an area where summer temperature and precipitation are strongly anti-correlated, i.e. an area with high drought-related heatwave potential. The anomalous recent wetness over this region would be normally associated with cool summers, but the region has experienced average temperatures recently. These observations point to global warming as a likely cause for the *lack* of cooling over the central and eastern US over the last couple of decades. In other words, natural decadal variability associated with precipitation appears to be at work taking the edge off the anthropogenic warming over the central and eastern United States. This means that the next large-scale Great Plains summer drought will likely be associated with warming exceeding that of the 1930s both in magnitude and spatial extent. By the same token, a mega drought of the 1930s' intensity and spatial extent does not appear to be any longer required to produce heat wave activity on the scale of the Dust Bowl. A more pedestrian drought will do.

The CGCM driven with anthropogenic forcing reproduces well the warming observed over Europe and North America. It also reproduces well the coupling of summertime temperature and precipitation. Model results interpreted in light of the observations, suggests that, even at anthropogenic output fixed at current levels, we can expect much larger heat waves than have been observed up to now in North America as soon as natural decadal variability (e.g. precipitation) turns to conspire with, or at least stops to counteract, the anthropogenic signal. The model also provides variants of likely further evolution of summer heat. The A2 and B1 warming scenarios are indistinguishable from each other in the next several decades mostly due to the fact that each model run is strongly modulated by its own natural decadal variability. However, by the middle of the century, the two scenarios clearly diverge with the B1 stabilizing at a temperature anomaly of about 3ºC and an HSI between 75 and 98%, while the A2 saturates at 100% by about 2070 with temperatures continuing to rise.

Our results agree with recent studies in general, and complement them by providing a time-evolving view of regional heat wave activity in individual summers that naturally emphasizes higher frequency variability on top of the anthropogenic trend. Moreover, our explicit focus on the heat wave's spatial extent emphasizes the European 2003 heat wave type, as well as 1934 and 1936, the Dust Bowl's defining years, over the much smaller-scale heat waves such as the more recent Midwestern heat waves of 1995 and 1999. Our results further identify the central, midwestern and eastern United States as the area most at risk of a "surprise" intensification of summer heatwave activity. This is an area traditionally prone to heat waves, but that has been cooled off recently by unusually wet conditions, which cannot be expected to persist much longer.

Over North America, a spatially extensive heat wave of the magnitude of Europe 2003 has not occurred in observed history, however, the probability of such an event may be significant and increasing. The observed current level of warming agrees with the cooler decades projected by the model run with anthropogenic forcing fixed at current levels. However, even with this fixed forcing, 22% of the projected heat waves cover over half of North America, a level heretofore not reached in observations. Realistically, this level and spatial extent of summer heat, were it to occur in the near future and in its preferred location, will be coupled with drought. It is clear that if such extensively hot and dry summers were to occur in reality, especially if unanticipated, would produce adverse consequences for North America. Observational and model results both suggest, furthermore, that such extremes exhibit natural cycles and tend to congregate in decadal sequences of warm summers.

Public perception of climate variability and change is strongly influenced by seasonal extremes. For example, the summers of 1976–1978 experienced extremely cold conditions over widespread northern mid-latitude regions even when considered in the context of the 1960's and 1970's, two consistently cold decades. It is not surprising, therefore, that twenty plus years ago, the actual concern was global cooling (Kukla et al. 1977), although no plausible mechanisms for such cooling were identified. Time scales are easily confused, however, and, at least in non-scientific literature, this strong decadal variation was at the time widely taken for the beginning of an ice age (Ponte 1976). Conversely, the last two decades of the 20th century experienced a mean warming trend globally and over the midlatitude northern hemisphere unprecedented in recent centuries (Mann et al. 1998, Moberg et al. 2005), a trend that continues strongly up to the present (Hansen et al. 2006, Jones and Palutikof 2006). This recent warming was punctuated by increasing frequencies of large-scale regional hot summer outbreaks and a decrease in the frequencies of cold summers. Plausible mechanisms for such a trend do exist and are exemplified by the IPCC socio-economic and emissions scenarios (Arnell et al. 2004). In spite of projected further warming, it appears that differences between "business as usual" and "enlightened management" scenarios may not be detectable for several decades. Of course, although the probability of regional-scale cold outbreaks is expected to diminish over the next century, they are still possible and will occur with a generally decreasing frequency and spatial extent, but certainly frequently enough to spur outbreaks of regional skepticism regarding the nature and causes of climatic change for several decades to come.

ACKNOWLEDGMENTES

The original ideas and research presented here initiated during Gershunov's visit to CNRM in the summer of 2004. This visit was supported by Météo-France through the visiting scholar program. We thank Sophie Tyteca and Mary Tyree for help with data acquisition and processing.

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