Please briefly (16000 chars or less) summarize your most recent results to date:

I. High-Resolution Climate Modeling

1.0 Validation of temperature and precipitation extremes

(Diffenbaugh 2009; Walker and Diffenbaugh, 2009; Ashfaq et al., 2010a; Ashfaq et al., 2010b; Diffenbaugh and Ashfaq, 2010; Trapp et al. 2010; Diffenbaugh et al. 2011; Diffenbaugh and Scherer 2011; Giorgi et al. 2011)

We have extended our work evaluating climate model simulations of temperature and precipitation extremes. We find that some of the global climate model (CCSM3) biases in the simulation of temperature and precipitation over the US are attributable to errors in the simulation of the global SST pattern, and that correction of these biases influences the simulated response to increasing greenhouse gas concentrations. We also find that a high-resolution climate model (RegCM3) is able to capture the pattern of mean, variability, and extremes of temperature and precipitation over the US, as well as the observed intensification of the hydrologic cycle. However, we find that although RegCM3 is able to capture the spatial pattern seen in observations, biases do exist in the magnitude of simulated extremes.

To address these biases, we have employed an approach that uses quantile mapping to correct biases in the times-series of RegCM3-simulated precipitation and temperature. We find that this approach substantial improves the agreement between the simulated extremes and those derived from observational data. Our also results show that biases in the RegCM3 fields not only affect the magnitude of hydro-meteorological variables in the baseline hydrological simulation, but they also affect the response of hydrological variables to projected future anthropogenic increases in greenhouse forcing. Further, we find that changes in the intensity and occurrence of severe wet and hot events are critical in determining the sign of hydrologic change. These results have important implications for the assessment of potential future hydrologic changes, as well as for developing approaches for quantitative impacts assessment.

2.0 Time of emergence of severe heat stress in the United States

(Diffenbaugh and Ashfaq 2010; Diffenbaugh et al. 2011; Diffenbaugh and Scherer 2011)

Our work on decadal and regional scale climate change has thus far been anchored by a new high-resolution climate model experiment. We employ RegCM3, a hydrostatic, sigma coordinate, primitive equation nested climate model. RegCM has been extensively applied across the globe, and captures the pattern and magnitude of long-term climate in the United States. In our experiment, the RegCM3 grid follows that Diffenbaugh et al. 2005, covering the full continental United States at 25-km horizontal resolution, with 18 levels in the vertical. We have extended our transient experiment to include five ensemble members that simulate the period from 1950 to 2099 in the A1B emissions scenario. Each RegCM3 ensemble member uses the same parameterization options, meaning that all five of the members are “physically consistent,” with only the large-scale input varying between the members.

Large-scale boundary conditions are provided to RegCM3 by the NCAR Community Climate System Model (CCSM3), a fully coupled atmosphere-ocean general circulation model (GCM). We use five of the CCSM3 simulations archived as part of the CMIP3 intercomparison and included in the IPCC AR4 (c, e, bES, fES, gES). Because the necessary sub-daily, 3-dimensional atmospheric variables were not saved by NCAR for the multi-member ensemble, we re-run CAM3 (the atmospheric component of CCSM3) using the original CCSM3-generated sea surface temperatures (SSTs) as a prescribed boundary condition for the global atmosphere. These CAM simulations are configured with the same resolution as in the original CCSM3 simulations (T85 spectral truncation with 26 levels in the vertical). They are run from 1948 to 2039, leaving a total of 3 years discarded for CAM equilibration prior to the analysis period.

We have extended our work on the emergence of heat stress in the coming decades to understand the role of coupling between temperature, precipitation and soil moisture. The intensification of severe heat wave occurrence in our RegCM3 ensemble is associated with warm-season drying over much of the U.S. By the 2030-2039 period, a summer anticyclonic circulation anomaly develops aloft (500 mb) over most of the continental United States. Associated with this anticyclonic anomaly are decreases (2030-2039 minus 1980-1999) in precipitation (exceeding -1.5 mm/day), total soil moisture (exceeding -200 mm), and evapotranspiration (exceeding -1.4 mm/day). Many areas of peak intensification of severe heat wave occurrence also exhibit substantial reductions in soil moisture, particularly in the eastern United States. Surface drying associated with anticyclonic circulation anomalies is thought to have amplified severe heat waves such as the 2003 event in Europe, and has been identified as a key regulator of changes in climate variability in response to elevated greenhouse forcing. Our results suggest that near-term increases in greenhouse forcing could create a protracted surface moisture feedback that helps the most severe heat waves of the historical period to become commonplace (more than 5 occurrences per decade) throughout much of the United States.

In order to test the robustness of the RegCM3-simulated changes, we are able to compare the relationships between changes in summer soil moisture, temperature and precipitation between our RegCM3 ensemble and the CMIP3 GCM ensemble. We find that for the 2030-2039 period, all five RegCM3 members exhibit a negative correlation between changes in summer total soil moisture and changes in summer temperature, and a positive correlation between changes in summer total soil moisture and changes in summer precipitation (Fig. 5). (The ensemble mean correlation is -0.35 for change in temperature and 0.37 for change in precipitation.) We also find that all five RegCM3 members exhibit a decrease in summer total soil moisture across the domain for the 2030-2039 period (relative to the 1980-1999 period). (The ensemble mean fractional change in total soil moisture is -0.02.) For the GCM ensemble, we find that 89% of the realizations show a negative (positive) correlation between changes in summer soil moisture and changes in summer temperature (precipitation). (The ensemble mean correlation is -0.28 for change in temperature and 0.30 for change in precipitation.) We also find that 78% of the GCM realizations show a decrease in summer total soil moisture across the domain for the 2030-2039 period. (The ensemble mean fractional change in total soil moisture is -0.03.)

Based on these findings, we are also working to understand the dynamics that shapes the variations in the pattern of projected decadal and regional climate change between the ensemble members. Integrating the potential for climate change impacts into policy and planning decisions requires quantification of the emergence of sub-regional climate changes that could occur in response to transient changes in global radiative forcing. However, this transient response is likely to be strongly influenced by the internal variability of the climate system, particularly in the relatively narrow range of forcing expected over the near-term decades. Indeed, although some regions show robust climate change in response to expected near-term increases in global radiative forcing, internal climate system variability exerts a stronger and more persistent influence on regional scales than at the global scale, dominating the near-term spread in global climate model projections over many regions.

We focus on the time of emergence of summer temperature change beyond the variability that currently exists in different areas of the continental U.S. The time of emergence of climate change beyond the baseline variability is an indicator of the statistical robustness of the projected change. In addition, systems experiencing change that substantially and permanently exceeds the baseline variability will need to adapt to a new climate that exhibits little overlap with the present temperature range. Systems experiencing earlier permanent emergence face a more rapid transition to this new climate, while systems experiencing later emergence face a more gradual transition. Therefore, in addition to being a measure of statistical robustness, the time of emergence is also an important measure of the pace with which projected global warming is likely to move the climate of a given area outside of the envelope of baseline variations to which systems are currently accustomed. Given the importance of a range of timescales of climate variability, we explore the time of emergence of climate change beyond both the annual- and decadal-scale baseline variability.

Decadal-scale warming that permanently exceeds the baseline decadal-scale variability emerges prior to 2020 over most areas of the continental U.S. (including prior to 2010 over the western U.S.), and prior to 2040 over all areas of the continental U.S. The earliest emergence of summer warming that permanently exceeds the baseline annual-scale variability occurs over the southwestern U.S. and northern Mexico, including widespread emergence prior to 2040. Permanent annual-scale warming also emerges over parts of the Pacific Northwest prior to 2040, and over most of the western U.S. prior to 2050. Permanent annual-scale warming likewise emerges over much of the northeastern U.S. between 2030 and 2060, and over much of the northcentral U.S. between 2040 and 2080. However, summer warming that permanently exceeds the annual-scale baseline variability does not emerge prior to the end of the 21st century over much of the southcentral and southeastern U.S., a pattern that is similar to the pattern of summer cooling and muted warming that has been observed over those regions in recent decades.

Although the time of emergence of summer warming is latest over the central and southeastern U.S., the absolute magnitude of summer warming is also largest over those regions, and smallest over the western and northeastern U.S. The differences in the patterns of time of emergence of warming and absolute magnitude of warming result in part from the spatial variations in the baseline annual-scale variability, with the warming that occurs over the central and southeastern U.S. representing a much smaller fraction of the baseline variability than the warming that occurs over the western and northeastern U.S.

The increases in summer temperature over the central U.S. are associated with decreases in summer precipitation, including decreases of up to 0.75 mm/day in the 2020-2039 period. The area of maximum precipitation decrease expands and intensifies as greenhouse forcing increases in the 21st century, including decreases of at least 0.5 mm/day over much of the central U.S. in the 2040-2049 period, and decreases of at least 1.0 mm/day over much of the central and eastern U.S. in the 2080-2098 period. These decreases in precipitation over the central U.S. represent between 20% and 60% of the baseline mean precipitation, and 1.5 standard deviations of the annual-scale baseline precipitation variability.

In order to test the robustness of the pattern of summer warming emergence to variations in model formulation, we compare the baseline variability, 21st century warming, and time of emergence of warming seen in our high-resolution ensemble with those seen the CMIP3 multi-AOGCM ensemble (Figure 8). Over the southwestern U.S., all of the RegCM3 and CAM3 realizations show permanent emergence of warming beyond the decadal-scale baseline variability during the first decade of the 21st century. Thirty-seven of the 52 CMIP3 realizations likewise show emergence prior to 2010, while the remaining 15 CMIP3 realizations all show emergence prior to 2030. Over the central U.S., all of the RegCM3 realizations exhibit permanent emergence beyond the decadal-scale baseline variability prior to 2010, while the CAM3 realizations exhibit emergence ranging from 2010 to 2070. Thirty-two of the 52 CMIP3 realizations show permanent emergence beyond the decadal-scale baseline variability prior to 2010, and 48 show permanent emergence prior to 2030.

We also seek to quantify the time of emergence of seasonal temperatures that permanently exceed the hottest season of the late 20th century. This quantification is of both scientific and public interest. Climate policy decisions are currently focused in two primary domains: (1) “mitigation”, – or avoidance – of increases in GHG concentrations, and (2) “adaptation” to climatic changes that do occur or are expected to occur. Given that extreme heat already causes a broad array of severe impacts on natural and human systems, quantifying how quickly a novel heat regime could emerge in different areas of the globe is important both for determining the “safe” target for mitigation policy and for generating successful climate change adaptation plans, particularly if the emergence is more abrupt than the horizon for effective action in either the mitigation or adaptation domain.

We analyze simulated surface air temperature from the CMIP3 global climate model archive. We analyze a total of 52 realizations of the 24 models that contributed both 20th century and A1B simulations. We focus on 3 metrics of severe heat emergence: (1) the percentage of seasons warmer than the late 20th century maximum; (2) the "time of emergence" of ensemble exceedence of the late 20th century maximum; and (3) the timing of the last occurrence of a season cooler than the late 20th century maximum. These are probabilistic metrics, and we calculate them across the realizations in the CMIP3 ensemble.

We find that the most immediate increase in extreme seasonal heat occurs in the tropics, with up to 70% of seasons in the early 21st century period (2010-2039) exceeding the late 20th century maximum (for both JJA and DJF). This tropical intensification continues with higher GHG concentrations, including greater than 90% of seasons exceeding the baseline maximum over most of tropical Africa, tropical South America, and Southeast Asia in the late 21st century (2070-2098). In the extra-tropics, exceedence is generally greater during the summer than the winter, including greater than 90% over much of extra-tropical Africa, southern Eurasia, and western North America in the late 21st century. The ensemble signal of extreme seasonal heat occurrence emerges above one standard deviation of the ensemble spread in the decade of the 2030s over the tropical oceans in JJA and DJF, in the decade of the 2040s over areas of tropical Africa and western South America in JJA and DJF, and in the decade of the 2040s over areas of northern Africa and southern Eurasia in JJA.

In addition to the time of emergence of a robust signal across the ensemble, we also identify the last season in each model realization that is cooler than that realization's late 20th century maximum. This last occurrence signifies the date of permanent 21st century exceedence of the baseline maximum in each realization, and the ensemble distribution of dates can be quantified at each grid point from the dates in the individual realizations. The earliest date of permanent exceedence across the ensemble occurs during the first decade of the 21st century over much of the tropics in both seasons, as well as areas of North America, northern Africa, and Eurasia in JJA. The median date of permanent exceedence occurs by the end of the 2020s over the tropical oceans and parts of tropical Africa, and by the end of the 2050s over most of the tropics and large areas of northern Africa and southern Eurasia. The 25th percentile permanent exceedence emerges prior to 2060 over large areas of extra-tropical North America, South America, Africa and Eurasia, while the 75th percentile is confined primarily to the tropics prior to 2060.

We can use the observed emergence of extreme seasonal heat over the late 20th century and early 21st century to assess the ability of the CMIP3 ensemble to simulate future emergence. Observed temperatures show that the globe and 7 of the 8 regions have experienced statistically significant increases in occurrence of maximum warm-season temperature over the past four decades (relative to a mid 20th century baseline). The CMIP3 ensemble mean underestimates the observed global emergence for both JJA and DJF, while the ensemble-mean emergence is very similar to that seen in warm-season observations over Central Africa, Southern Africa, Northern South America, India, China and the Mediterranean. Alternatively, the simulated intensification is too strong over Southeast Asia in JJA and DJF, and over North America in JJA.

Our analyses of observational data and the current generation of global climate models carry a number of important implications. First, imminent, permanent emergence of unprecedented heat in the tropical regions is likely to result in substantial human impact, particularly given previous humanitarian crises associated with severe heat, and the synergies between environmental and development challenges. Second, the fact that areas of the United States, Europe and China also show permanent emergence by the mid-21st century highlights the fact that nations with developed and emerging economies are also likely to face unprecedented climate stresses even with the relatively moderate warming expected over the next half-century. The fact that global climate models are able to capture the observed intensification of extreme heat globally and over many regions strengthens confidence in the model projections. However, where model biases do exist, they predominantly serve to decrease occurrence of unprecedented heat. Further, actual GHG emissions over the early 21st century have exceeded those projected in the SRES scenario used here, suggesting that our results could provide a conservative projection of the timing of permanent emergence of an unprecedented heat regime.

3.0 Quantifying the effects of temperature extremes on energy demand and carbon dioxide emissions

In collaboration with Dr. Kevin Gurney (Arizona State University), we are beginning to use the knowledge gained about the variability and sensitivity of extreme temperature to understand relationships between extreme temperature events and energy demand and associated carbon dioxide emissions. The relationship between CO_2 emissions (non-electric residential from Vulcan) and the HDD is constructed from examination of past variations in time. Hence, the past HDD variations come from RegCM daily mean temperature from 1995 to 2005. The relationship between the CO2 emissions and HDD is remarkably good (R2 > 0.7 over most of the country) and hence, HDD is shown to be a good (albeit simple) predictor of non-electric residential emissions at Vulcan scale (10 km). In fact, over the portion of the country where there is any significant winter, R2 exceeds 0.9.

We have completed a preliminary analysis of HDD-driven non-electric carbon emissions for the near-term 21st-century period (using the high-resolution RegCM3 ensemble experiment). HDD-driven non-electric carbon emissions are a convolution of three things (1. where the warming is pronounced 2. how "sensitive" people have shown themselves to be to HDD variations and 3. To what extent they heat with electricity). In our preliminary analyses, much of the resulting decline in carbon emissions is driven by warming. However, the intermountain West - though there are some large HDD decline values - does not show up as dramatically in carbon decline because of the mix of energy sources.

Work is continuing in both the heating and cooling domains, as well in both the residential and non-residential domains.

Please briefly (7000 chars or less) describe papers and other products delivered:

Diffenbaugh, N.S. M. Ashfaq, and M. Scherer, Transient regional climate change: analysis of the summer climate response in a high-resolution, century-scale, ensemble experiment over the continental United States, *Journal of Geophysical Research – Atmospheres*, 116, D24111, doi:10.1029/2011JD016458, 2011.

Here we report results from a high-resolution, century-scale, ensemble simulation of climate in the U.S. We find that 21st century summer warming permanently emerges beyond the baseline annual-scale variability prior to 2030 over areas of the southwestern U.S., but not prior to the end of the 21st century over much of the southcentral and southeastern U.S. The magnitude of warming is greatest over the central U.S., due to stronger coupling of changes in surface air temperature, precipitation, moisture and energy fluxes, and atmospheric circulation. However, as a fraction of the baseline variability, the transient warming over the central U.S. is smaller than the warming over the southwestern or northeastern U.S., delaying the emergence of the warming signal over the central U.S.

Diffenbaugh, N.S. and M. Scherer, Observational and model evidence for global emergence of unprecedented heat in the 20th and 21st centuries, *Climatic Change*, 10.1007/s10584-011-0112-y, 2011.

Our analyses of global climate model experiments and observational data reveal that many areas of the globe are likely to permanently move into such a climate space over the next four decades. In contrast to the common perception that high-latitude areas face the most accelerated response to global warming, our results demonstrate that in fact tropical areas exhibit the most immediate and robust emergence of unprecedented heat, with many tropical areas exhibiting a 50% likelihood of permanently moving into a novel seasonal heat regime in the next two decades. We also find that global climate models are able to capture the observed intensification of seasonal hot conditions, increasing confidence in the projection of imminent, permanent emergence of unprecedented heat.

Giorgi, F., E. Coppola, E.S. Im, N.S. Diffenbaugh, X. Gao and Y. Shi, Higher hydroclimatic intensity with global warming, *Journal of Climate*, 24(20), 5309-5324, 2011.

We introduce a new measure of hydroclimatic intensity (HY-INT), which integrates metrics of precipitation intensity and dry spell length. Our analysis identifies increasing hydroclimatic intensity as a robust integrated response to both observed and projected global warming, implying increasing risks for systems that are sensitive to wet and dry extremes and providing a potential target for detection and attribution of hydroclimatic changes.

Diffenbaugh, N.S. and M. Ashfaq, Intensification of hot extremes in the United States, *Geophysical Research Letters*, L15701, doi:10.1029/2010GL043888, 2010.

Using a large suite of climate model experiments, we find that substantial intensification of hot extremes could occur within the next 3 decades, below the 2°C global warming target currently being considered by policy makers. We also find that the intensification of hot extremes is associated with a shift towards more anticyclonic atmospheric circulation during the warm season, along with warm-season drying over much of the U.S. The possibility that intensification of hot extremes could result from relatively small increases in greenhouse gas concentrations suggests that constraining global warming to 2°C may not be sufficient to avoid dangerous climate change.

Ashfaq, M., C.B. Skinner, and N.S. Diffenbaugh, Influence of SST biases on future climate change projections, *Climate Dynamics*, 10.1007/s00382-010-0875-2, 2010.

We use a quantile-based bias correction technique and a multi-member ensemble of the atmospheric simulations to investigate the influence of sea surface temperature (SST) biases on future climate change projections. Bias correction leads to significantly different simulated precipitation and surface temperature changes over many oceanic and terrestrial regions (predominantly in the tropics). Many of these differences are comparable to or larger than the spread of future precipitation changes across the CMIP3 ensemble. These results help to quantify the influence of climate model biases on the simulated climate change, and therefore should inform the effort to further develop approaches for reliable climate change projection.

Ashfaq, M., L.C. Bowling, K.A. Cherkauer, J.S. Pal and N.S. Diffenbaugh, Influence of climate model biases and daily-scale temperature and precipitation events on hydrological impacts assessment - A case study of the United States, *Journal of Geophysical Research-Atmospheres*, doi:10.1029/2009JD012965, 2010.

The biases and coarse spatial resolution of global climate models limit their usefulness in hydrological impacts assessment. We use a high-resolution regional climate model (RegCM3) to drive a hydrological model (VIC) for the full contiguous United States. A quantile-based bias correction technique is applied to the times-series of RegCM3-simulated precipitation and temperature. Our results show that biases in the RegCM3 fields not only affect the magnitude of hydro-meteorological variables in the baseline hydrological simulation, but they also affect the response of hydrological variables to projected future anthropogenic increases in greenhouse forcing. Further, changes in the intensity and occurrence of severe wet and hot events are critical in determining the sign of hydrologic change.

Trapp, R.J., E.D. Robinson, M.E. Baldwin, N.S. Diffenbaugh, and B.R.J. Schwedler, Regional climate of hazardous convective weather through high-resolution dynamical downscaling, *Climate Dynamics*, 10.1007/s00382-010-0826-y, 2010.

We explore the use of high-resolution (4.25 km) dynamical downscaling as a means to simulate the regional climatology and variability of hazardous convective-scale weather. The resultant 10-year sequence of WRF model integrations yields precipitation that, despite its positive bias, has a diurnal cycle consistent with observations, and otherwise has a realistic geographical distribution. Similarly, the occurrence frequency of short-duration, potentially flooding rainfall compares well to analyses of hourly rain gauge data. The results suggest that the proxy occurrences, when coupled with information on the larger-scale atmosphere, could provide guidance on the reliability of trends in the observed occurrences.

Walker, M.D. and N.S. Diffenbaugh, Evaluation of high-resolution simulations of daily-scale temperature and precipitation over the United States, *Climate Dynamics*, 10.1007/s00382-009-0603-y, 2009.

We examine the ability of a high-resolution nested climate model, RegCM3, to capture the statistics of daily-scale temperature and precipitation events over the conterminous United States, using observational and reanalysis data for comparison. Our analyses reveal that RegCM3 captures the pattern of mean, interannual variability, and trend in the tails of the daily temperature and precipitation distributions. The biases in heavy precipitation in the western United States are associated with excessively strong surface and low-level winds. The biases in daily-scale temperature and precipitation in the southcentral United States are at least partially driven by biases in circulation and moisture fields.

Diffenbaugh, N.S., Influence of modern land cover on the climate of the United States, *Climate Dynamics*, 10.1007/s00382-009-0566-z, 2009.

We use a high-resolution nested climate modeling system to test the sensitivity of regional and local climate to the modern non-urban land cover distribution of the continental United States. The dominant climate response is cooling of surface air temperatures, particularly during the warm season. The statistically significant warm-season cooling is driven by changes in both surface moisture balance and surface albedo. The simulated changes in surface moisture and energy fluxes also influence the warm-season atmospheric dynamics, creating greater moisture availability in the lower atmosphere and enhanced uplift aloft.

Please provide any new notes (7000 chars or less) concerning the project: