Final Report to Modeling, Analysis, Predictions, and Projections Program (MAPP)

Award number: NA11OAR4310094

1. Header

Project Title: Central U.S. Abnormality in Climate Change and Its Response to Global Warming
Recipient Name: Saint Louis University
Investigator(s): Zaitao Pan and Timothy Eichler
Report Period: 9/1/2011- 8/31/2015

2. Results and Accomplishments

Project goals and objectives

The over-arching goal of the project is to identify and understand mechanisms for abnormal cooling, referred to as the "warming hole (WH)", in the central-eastern U.S. during the second half of the 20th century when global warming accelerated. Specific objectives are: 1) to determine to what extent the local and regional feedback processes contribute to the unusual cooling; 2) to assess if these processes can help explain why most CMIP5 were unable to reproduce the cooling trends in their 20th century *historical* simulations; and 3) to generalize the regional feedback processes to other continents where similar abnormal cooling was observed in order to detect common underlying mechanisms that may exist globally.

The award ($218,402) started on September 1, 2011 for three years and then was no-cost extended for a fourth year ending August 31, 2015. The project proposed three tasks achieving three objectives. After four years of effort of two PIs with the help of two graduate students, the project achieved its goal and objectives. During the course of the project, nine peer-reviewed papers associated with the project were published, two master's theses were completed, and numerous conference presentations were delivered. The following highlights the major accomplishments.

2.1. Observed warming hole characteristics

The central U.S. experienced abnormal cooling trend during the 20th century, more prominently in the second half of the century while global warming accelerated. From 1951 to 2000, the south-central U.S. cooling was more extensive, with most areas being cooled by 0.2-0.6 ^{o}C dec^{-1} (Fig. 1). The most extensive and strong cooling occurred in the 1951-1975 when the cooling spread over all the south-eastern states. Notably, there was a strip of over 0.6^{o}C dec^{-1} cooling that occurred in the coastal regions during summer. Interestingly, during 1951-1975 when the Pacific Decadal Oscillation (PDO) index was negative, the southern coastal region experienced sharp cooling, which seems to run against the established negative correlation between PDO and coastal temperature (Wang et al., 2009; Meehl et al., 2012). During the last 25 years (1976-2000), which coincides with the peak global warming period, the cooling was shifted to the central section of the U.S. with cooling up to 0.6 ^{o}C dec^{-1}. Also during the 1976-2000 period, the summer and winter trends are in opposite directions, with sharp warming in winter. An EOF analysis of the 50-year period shows two leading modes corresponding to the coastal (1st) and central (2nd) cooling, explaining more than 50% of the combined variance (Pan et al. 2004, 2009).

It is natural to ask: are there any other WHs similar to the one in the U.S? The answer is that we have identified at least two other similar WHs (although less prominent): one in the south-central China and the other in central South America (Pan, et al., 2009). All the three WHs are located near the center of the continent in the eastern slopes of major mountain ranges. We named them USWH, ChWH (China), and SAWH (S. America), respectively (Pan et al., 2009).

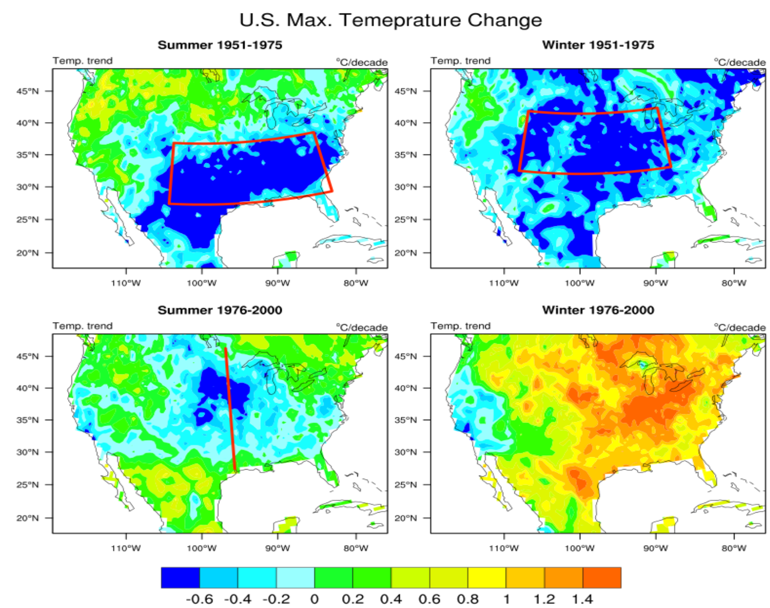

Fig. 1. Observed (CRU) daily maximum surface temperature trend (^{o}C dec^{-1}) over two periods of the 2nd half of the 20th century, showing extensive cooling in 1951-1975 both in winter and summer, but only moderate summer cooling and sharp winter warming in 1976-2000 period. The two red boxes delineate the boundary of the "warming hole (WH)" in the central U.S. (110-85^{o}W, 35-45^{o}N) and southeastern U. S. (105-80^{o}W, 30-40^{o}N), respectively.

2.2. Warming hole mechanism attribution – local/regional

A number of studies have attributed the mechanisms for this abnormal cooling trend to large-scale decadal oscillations such as PDO and Atlantic Multidecadal Oscillation (AMO), while others indicated that regional-scale processes such as the hydrological cycle and land surface interaction may play important roles in the WH. The project proposed and assessed three new regional mechanisms that may contribute to the WH formation and maintenance: (1) east-west climatic warming gradient induced baroclinicity, (2) drying soil's asymmetric effects on daily maximum (Tmax) and minimum (Tmin) temperature trends, and (3) downstream effects of boundary layer (BL) and low-level jet (LLJ) dynamics in the drying southwestern U.S.. We have run WRF simulations over July during 2006-2010 and evaluated the roles of these three regional factors (Pan, 2012).

(1) Baroclinicity: We carried out a numerical experiment mimicking more climatic warming in the Mountain West and the warming gradient effects on the cooling in the central U.S. It shows that 1^{o}C more warming in the West (than central U.S.) would produce a northerly wind of 0.5 m s^{-1}, which in turn cools the central U.S. by about 0.5^{o}C, contributing to the WH (Pan, 2009).

(2) Soil moisture effects on daily temperature range (DTR): DTR has decreased in the 20th century globally and in the U.S., mainly because of a faster warming of Tmin. Typical soil voids vary between 0.36-0.43 for bulk sandy soil and 0.51-0.58 for clay. Whether these voids are

filled with water in wet conditions or with air under dry conditions will have a large effect on soil heat capacity and thus on warming rate. The heat capacity of saturated soil can be 2.5 times that of the dry soil. We want to see to what extent climatic drying in the southwestern U.S. affects local and downstream temperature (Pan, 2012).

The WRF simulations show that drying soil has a net cooling effect on daily mean temperatures (Fig. 2). The simulated simultaneous drying and cooling impact on daily mean temperature seems counter-intuitive. After some analysis, we found that the asymmetric soil heat capacity effect is due to the difference in atmospheric boundary-layer depths. During night, the heat exchange between soil and air is only limited to a shallow stable atmospheric layer, while it spreads through a much deeper layer during the day due to convection. This asymmetric effect implies negative correlations between soil moisture and DTR, which may partly explain some of the observed DTR trend in the 20th century.

(3) Southwest drying and the LLJ effect on the central U.S. cooling: Central U.S. climate is modulated by the Great Plains LLJ that conveys warm-moist air into the region. The Southwest and Great Plains have been drying in recent decades. It has been shown that the surface drying in the Texas region increases LLJ strength through the so-called Blackadar mechanism (Blackadar, 1957). The five-July simulations demonstrate that the drying in the SW indeed results in a deeper local boundary-layer and a stronger nocturnal LLJ. The associated stronger southerly moisture transport downstream to the central U.S. has a cooling effect in the WH region. This regional downstream feedback can reach +/-1-2 ^{o}C, reinforcing/compensating for regional climate change (Fig. 2).

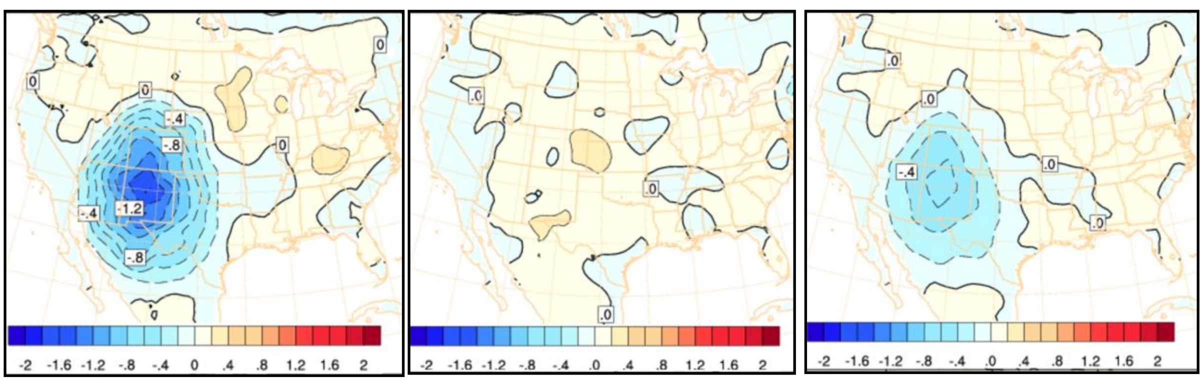

Fig. 2. Surface temperature change (^{o}C) between dry and control cases for July 2008 simulated by WRF model. Left: nighttime; middle: daytime, and right: daily average.

2.3. Warming hole mechanism attribution - global

(1). PDO modulation of warming hole in central U.S. To quantify the abnormal cooling due to the increase in precipitation locally, we found that nearly half (44%) of WH cooling can be explained by precipitation increase within the WH region (Fig. 3). The remaining cooling must be attributed to other factors such as cold air advection. What causes rainfall to increase then? Studies have suggested that PDO and AMO may partly be responsible for this cooling/wetting. Figure 4 indicates that the WH is negatively correlated to the SST in the northeastern Pacific and positively to the SST over the northern Atlantic (top panel).

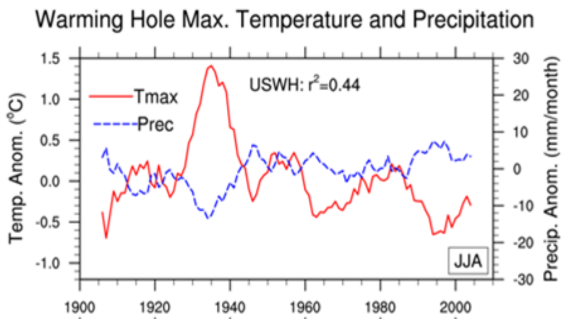

Fig. 3. Temporal correlations between maximum surface temperature and precipitation within the central U.S. WH (100-85°W, 35-45°N).

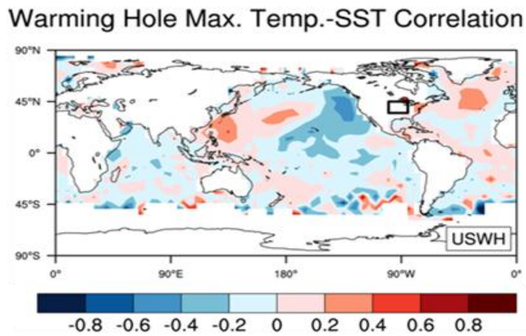

Fig. 4. The temporal correlation between WH temperatures and sea surface temperature (SST) during the second half of the 20th century. The black rectangles represent the three WH regions.

A number of reports showed that a positive PDO, coupled with a negative AMO, is conducive to the development of the WH (Wang et al., 2009; Meehl et al., 2012). These results were largely based on comparing two opposite phases of the PDO: the positive PDO from 1978-1998 and the negative PDO from 1999-current. This project extended the analyses backward to include an additional pair of opposing PDO phases. Figure 5 shows surface air temperature trends during two positive PDO periods (1915-1944 and 1978-1998) and two negative PDO durations (1945-1977 and 1999-2012). Warming trends were observed in both the positive and negative periods; similarly cooling trends were also found in one positive period and one negative period. Thus, PDO phase and U.S. WH may not be as highly correlated as reported in some recent work (Wang et al., 2009). One of the challenges for linking PDO to the WH is that the WH is stronger during summer when the PDO signal is weakest. However, a recent study by Meehl et al. (2012) pointed out the possibility of summer tropical SST effects on central and southeastern U.S. temperature through the Matsuno-Gill mechanism. Thus, our results cast some uncertainty on the PDO mechanism.

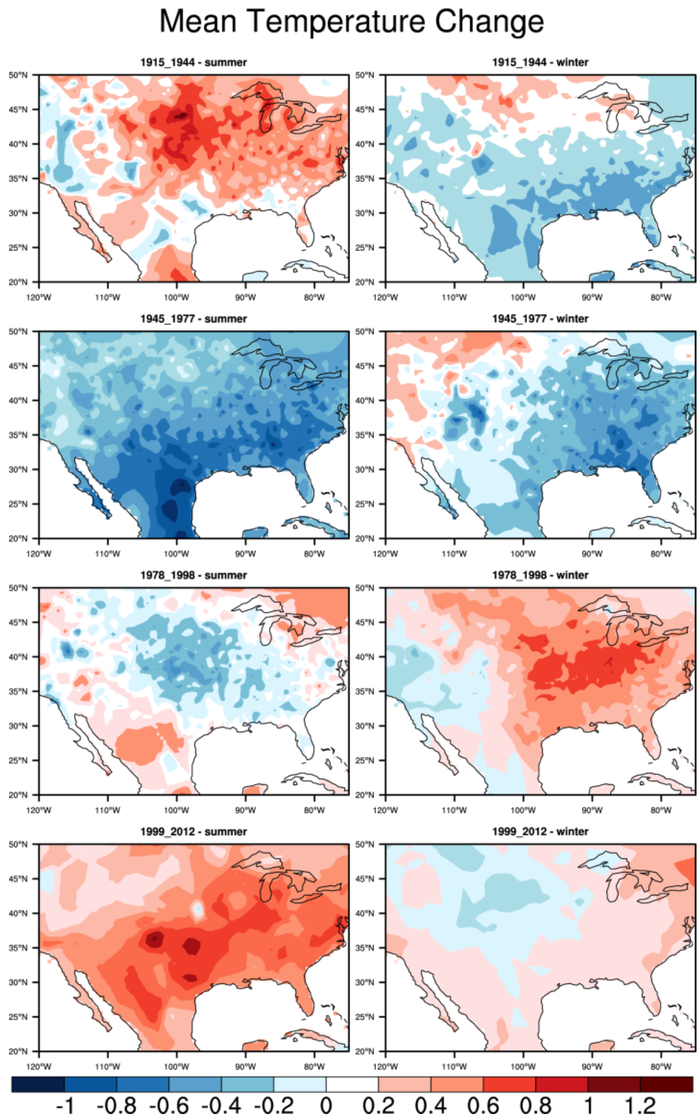

Fig. 5. Linear trend (^{o}C dec^{-1}) in surface air temperature during four periods of alternative PDO phases for summer (left) and winter (winter). The four periods are 1915-1944(+), 1945-1977(-), 1978-1998(+), and 1999-2012(-) from top to bottom panels respectively.

(2). Anthropogenic vs. natural forcing on the warming hole. Aside from the *historical* experiment where all natural and anthropogenic forcing were included, the CMIP5 experiment suite also includes single-forcing experiments such as greenhouse gases, aerosol, and land use change forcing alone. Compared to the *historical* experiment, fewer models carried out these attribution experiments with fewer ensemble members. We evaluated 6 models with a single member: CCSM4, GFDL-ESM2M, GISS-E2-H, GISS-E2-R, MRI-CGCM3, and NorESM1-M.

Natural forcing alone has a cooling effect in the central and northern U.S. in summer on the century scale. In the 2nd half of the 20th century, the northern tier of the U.S. cooled considerably (not shown). Conversely, greenhouse gases (GHGs) forcing only would make the central U.S. warmer, particularly during the latter half of the century in summer (Fig. 6a, b). This suggests that GHGs would counteract the WH phenomenon, rather than causing or enhancing it. The forcing difference between the *historical* and *historical*Nat should reflect largely land use evolution and anthropogenic aerosol forcing. Interestingly, the difference showed a clear WH feature, especially in summer (Fig. 6c, d). On the century scale, a large area of 0-0.05 °C dec^{-1} cooling over the southeastern-central U.S. resembles the observed WH well.

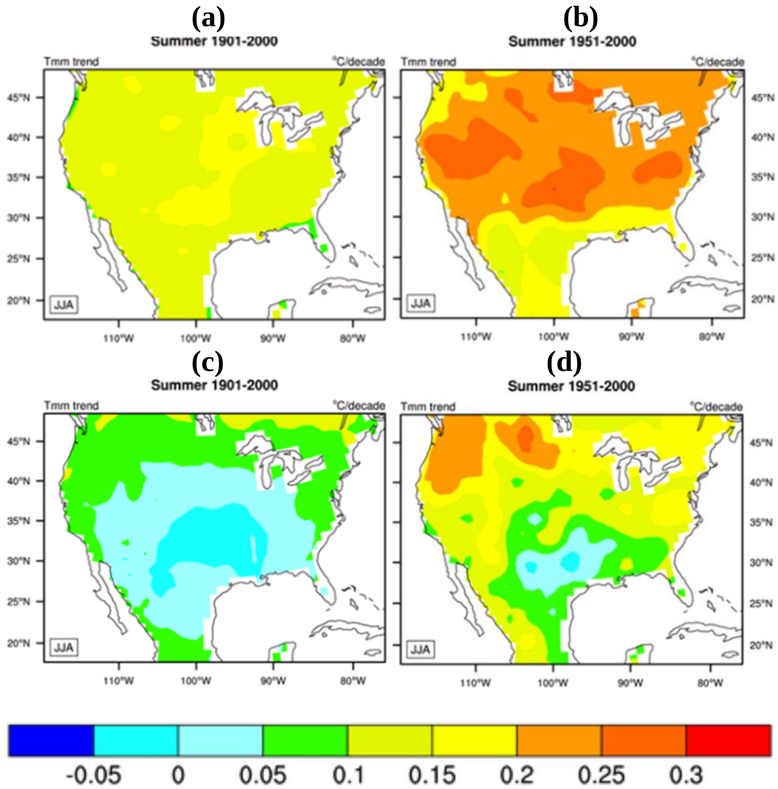

Fig. 6. Six-model ensemble mean of linear trends (°C dec^{-1}) of mean surface air temperature simulated in the *historicaGHG* experiment (a, b), and the difference between *historical* and *historicalNat* (c, d) experiments. Left: during 1901-2000 and right: 1951-2000. (Pan et al., 2013a).

2.4. CMIP5 model simulated warming hole in *historical* and *amip* experiments

(1). *Historical* run. We analyzed the CMIP5 suite's 27 models, totaling 175 ensemble members in *historical*, RCP4.5, *historical*GHG, and *historical*Nat experiments. The models are ACCESS1-0, bcc-csm1-1, CanESM2(5), CCSM4(5), CNRM-CM5, CSIRO-Mk3-6-0(10), FGOALS-S2.0, GFDL-CM3, GFDL-ESM2G, GFDL-ESM2M, GISS-E2-H(16), GISS-E2-R(15), HadCM3, HadGEM2-AO, HadGEM2-CC, HadGEM2-ES, inmcm4, IPSL-CM5A-LR, IPSL-CM5A-MR, IPSL-CM5b-LR, MIROC5(3), MIROC-ESM, MIROC-ESM-CHEM, MPI-ESM-LR(3), MPI-ESM-P, MRI-CGCM3, and NorESM1-ME. The numbers in the parentheses are the number of ensemble members in the *historical* experiment. To quantify the model skill in reproducing the WH phenomenon, Fig. 7 shows the trends of 25 models' first ensemble member (r1i1p1) in summer and winter for Tmax and Tmin averaged over the WH region (110-85^{o}W, 35-45^{o}N). On the century scale in summer (top left panel), the observed cooling only occurred in Tmax (rightmost red bar denoted "O" on the X-axis). Eight out of 25 models simulated negative trends ranging from -0.005 to -0.06^{o}C dec^{-1} in summer. The remaining models simulated warming trends from 0.001-0.20^{o}C dec^{-1}. The all-model mean is +0.06^{o}C dec^{-1}.

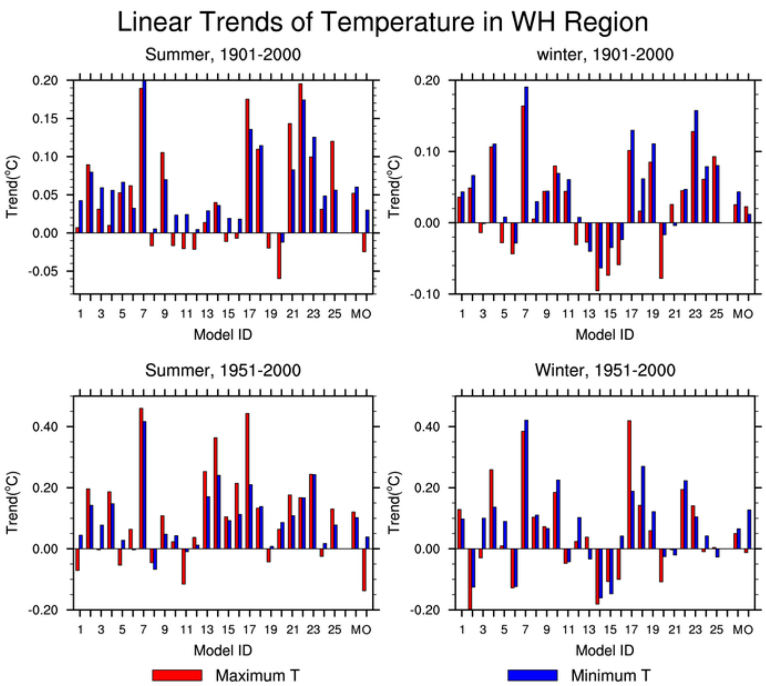

Fig. 7. Trends of Tmax and Tmin over the southeast WH region (105-80^{o}W, 30-40^{o}N) in summer and winter during 1901-2000 and 1951-2000 periods. The X-axis is model ID. The right most two dual-bars represent all model mean (M) and observation (O), respectively. Only the first ensemble of each model is used (Pan et al., 2013a).

The observed winter temperatures in the WH region warmed during the century by 0.01-0.02^{o}C dec^{-1} (top right panel). The model means simulated slightly stronger warming (0.03-0.04^{o}C dec^{-1}) although a number of models simulated larger positive and negative trends. On the 50-year scale (bottom panels), the observed cooling on Tmax reached -0.17 ^{o}C dec^{-1} in summer. The majority of models simulated warming on both Tmax and Tmin with an all-model mean of +0.13^{o}C dec^{-1} (donated "M" on X-axis). Only 6 models produced negative trends of Tmax (bottom left). In winter, 8 models simulated sizeable negative trends of temperatures.

In summary, i) only 19 out of 100 all-forcing *historical* ensemble members simulated a negative temperature trend (cooling) over the southeast U.S. with 99 members under-predicting the cooling rate in the region; (ii) the lack of cooling in the models is likely due to the poor performance in simulating the spatial pattern of the cooling rather than the temporal variation, as indicated by a larger temporal correlation coefficient than spatial one between the observation and simulations (Pan et al., 2013a; Kumar et al., 2013 for detail).

Although a majority of the CMIP5 models showed low skills in simulation of the WH temperature during the 2nd half of the 20th century, some model members did capture a WH-like feature in the vicinity of the region. Figure 8 contrasts model skills between the top and bottom quartiles of the 100 members based on bias. As expected, the best-trend members collectively simulated a well-defined cooling region in the south-central U.S., matching the observed WH quite well (left). The worst 25 members simulated a clear warming in the region (right). While the sharp disparity in bias performance between the two quartile is somewhat expected, it does demonstrate that a portion of members can indeed reproduce the WH phenomenon, which allows for the opportunity to further diagnose what caused the two quartiles to differ.

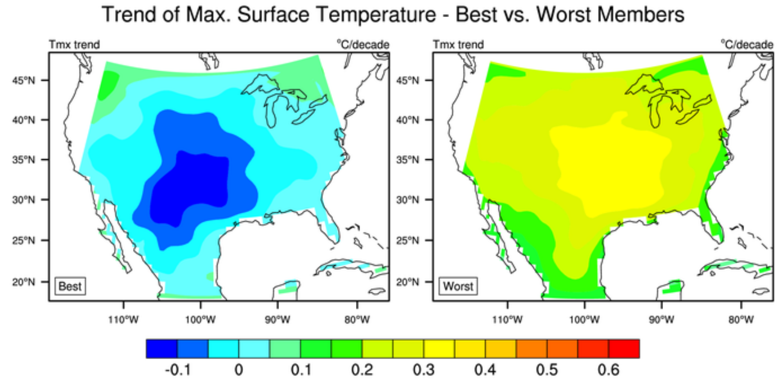

Fig. 8. Linear trends (°C dec^{-1}) of Tmax of best (left) and worst (right) quartile members during 1951-2000 periods sorted by bias.

(2). Comparison between *historical* and *amip* runs. Two general schools of thoughts were proposed to explain abnormal cooling trend observed during late 20th century: large-scale decadal oceanic oscillations such as PDO and AMO and local and regional hydrological processes (Pan et al., 2004) and land surface interactions. What the relative contributions of these two factors are is still a subject of debate. Comparison between CMIP5's ocean-coupled *historical* run and uncoupled *amip* run helps isolate SST forcing on central U.S. climate anomaly as portrayed in the CMIP5 models.

We analyzed available 25 *historical* and 25 *amip* model runs. Figure 9 compares the time series of daily Tmax/Tmin over the central U.S. simulated by the two types of runs (Pan et al., 2015a).

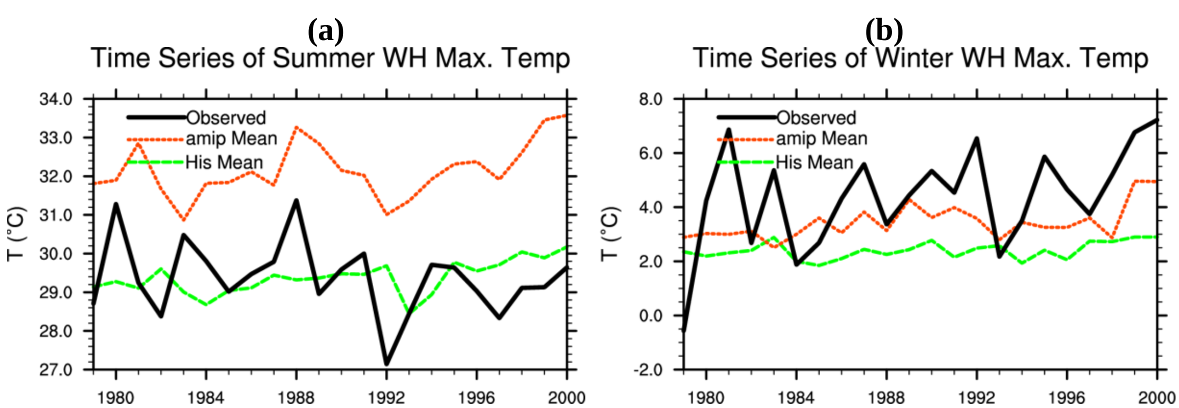

Fig. 9. Comparison of time series of seasonal mean temperature averaged over the U.S. (110-85°W, 35-45°N). (a): summer Tmax ; (b) winter Tmax.

The coupled *historical* run simulated summer Tmax agrees well with the observed in magnitude, but the *amip* run captured the inter-annual variability better (Fig. 9a). For the winter Tmax, both runs give similar results that have a cold bias (Fig. 9b). Figure 10 contrasts the inter-model spread within each run between *historical* and *amip* runs, indicating that, although the near-surface temperature spread over the PDO region (20-70^{o}N, 110-260^{o}E) is noticeably smaller in *amip* run as expected, this narrowness in uncertainly in the *aimp* run did not translate into temperature simulations in the central U.S., as indicated by an almost similar "spreadness" in WH temperature between the two runs. This run spreadness disparity implies that WH temperature is loosely controlled by SST over PDO region in the models (assuming here near-surface temperature does not differ much from SST underneath).

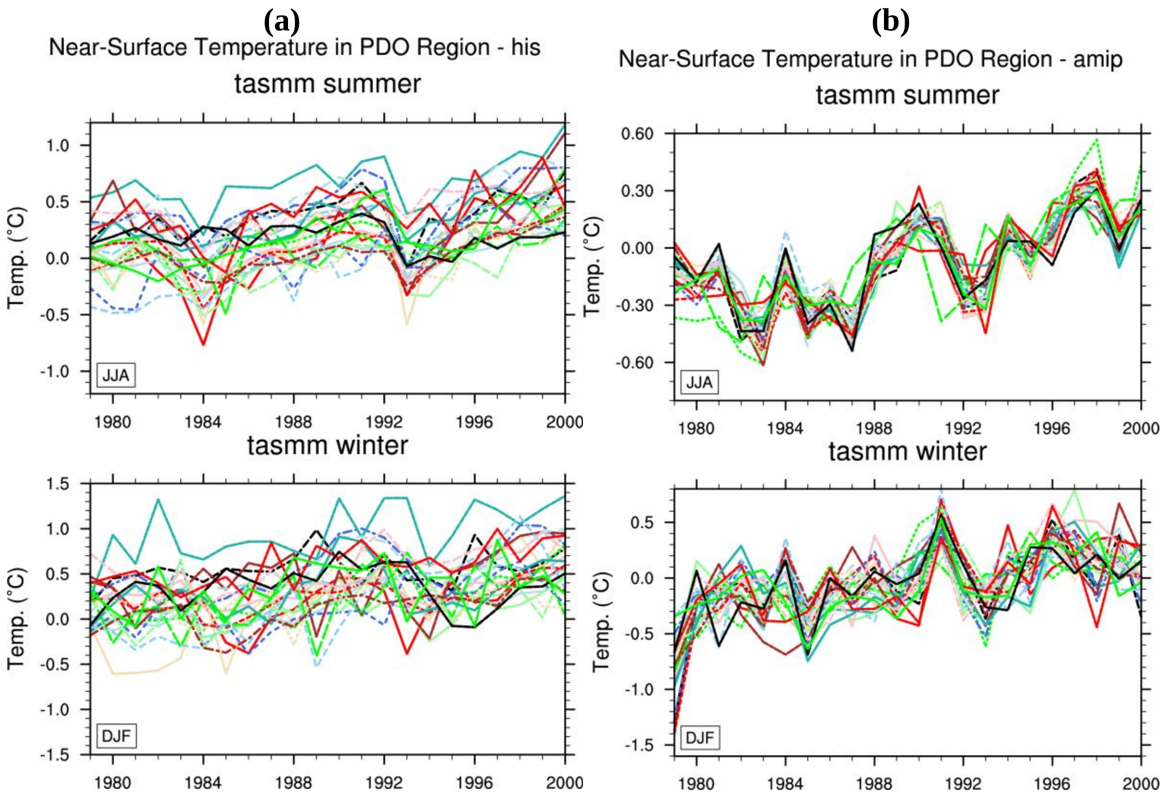

Fig. 10. Time series of mean temperature anomaly (Tm) averaged over the northern Pacific region simulated by 25 individual models. (a): *historical* and (b): *amip*.

In the observations, WH temperature was negatively (positively) correlated with PDO index in summer (winter) during 1979-2000 period (Tab. 1), with winter association being stronger (r=0.54) than summer (r=-0.42). In the models, however, both runs produced moderate positive correlations (about 0.42 for summer) in temperatures between PDO region and WH region. The *r* values between the two runs are almost identical. This suggests that SST in the models played little roles in affecting the central U.S. temperature, unlike in observations where PDO mode has a strong modulating effect on the central U.S. climate.

Table 1. Temporal correlations (r) between temperatures over the central U.S. WH region (35-45^{o}N, 85-110^{o}W) and PDO region (20-70^{o}N, 110-260^{o}E) in the models.

	Correlation		
	Obs.	*historical*	*amip*
Sumner,Tmax	-0.52	0.40	0.43
Summer, Tmin	-0.31	0.51	0.50
Winter, Tmax	0.55	0.22	0.24
Winter,Tmin	0.53	0.24	0.20

2.5. Other studies related to central U.S. climate

(1). Daily precipitation extremes over central U.S. simulated in CMIP5 models (Pan et al., 2015b). On local-regional scales, temperature and precipitation are well correlated, as seen in Fig. 3. The central U.S. is one of a few regions globally that experienced wetting, while most regions of the world have experienced drying under global warming environment. The wetting especially contrasts the decadal droughts in the western U.S. The precipitation increase mostly occurred in terms of heavy rainfall during warm season. The model consensus showed steadily declining frequencies for the lightest precipitation category and increasing occurrence for intermediate categories (2.5-50 mm per day). For the heaviest category, the model simulated sudden drop in frequency in late 1960 from 85% of peak frequency year to about 50% and stayed that low for remaining years. Under the RCP8.5 scenario, the lightest precipitation in the central U.S. decreases in frequency persistently and more significantly after about 2025 and so does the heaviest category, while the intermediate ones become more frequent throughout the first half of the 21st century. This implies that both light and heavy precipitation would become less frequent, whereas the intermediate precipitation would become more frequent in coming decades. Hence, the so-called “rich-gets-richer” regime for future precipitation change may not apply to the central U.S.

2). NARCCAP regional simulations (Thompson, 2015). So far we have analyzed only global model simulations at coarse resolution that often is blamed for poor model performance. The high-resolution North American Regional Climate Change Assessment Program (NARCCAP) provides a unique set of regional climate simulations. We analyzed model skills in simulating current climate and future changes of four pairs of GCM-RCM combinations, focusing on record breaking temperatures and extreme climate indices (Thompson, 2015). It is found that all the four pairs reproduced similar trends of record-temperature days, showing an increase (decrease) in high (low) record temperature frequencies. These regional models simulated statistics of record-breaking temperatures resembles the observations quite well (not shown).

3). Contrasting storm activity during 1988 drought and 1993 flood in the central U.S. (Eichler and Pan, 2015). These two years are representative of central U.S. extreme climate. Our results demonstrate that the 1988 drought featured a poleward-displaced cyclone track with a reduced role for cyclone-induced precipitation, especially in the spring of 1988. In contrast, the 1993 flood featured a strong 200 hPa subtropical jet stream over the Baja to the Gulf of Mexico in the spring of 1993 and a stronger than normal jet stream across the upper-Midwest in the summer of 1993. The former was associated with a cyclone track across Mexico eastward to the Gulf of Mexico and northeast into Missouri accompanied by enhanced precipitation in the Midwest. The latter was associated with two cyclone tracks: one in the southwestern U.S. and the other across Canada linked to the right-entrance and left-exit regions respectively of the strong 200 hPa jet stream across the upper-Midwest. Enhanced 850 hPa inflow from the Caribbean westward to the Gulf of Mexico and northeast to the Midwest with high precipitable water values occurred in conjunction with the right entrance portion of the jet (Eichler and Pan, 2015).

3. Highlights of Accomplishments

Listed below are the major achievements and scientific findings of this project.

- Published extensively in peer-reviewed journals and scientific conferences.
    - Published 9 peer-reviewed journal papers and numerous conference abstracts.
    - Supported two master's students, each finishing a thesis.
    - PIs actively participated in MAPP CMIP5 Task Force activities and contribute two individual papers and participated in three overview papers in the Special Collection organized by the Task Force.
- Found seasonal and diurnal contrasting cooling patterns in the central-eastern U.S. warming hole region.
    - Tmin trend follows the global one more closely than Tmax, reflecting the local/regional contribution to the latter (cooling).
    - The abnormal cooling during 1951-1975 seems related to remote forcing, whereas the cooling in the central U.S. during the warming peak (1976-2000) is likely more related to regional forcing.
- Identified and tested three regional mechanisms that may contribute to the warming hole.
    - Warming gradient along the eastern slope of the Rockies favoring northerly cold air advection as the mountainous region warms faster.
    - Drying soil affects DTR asymmetrically
    - The drying SW affects downstream central U.S. climate through the boundary-layer and low-level jet dynamics.
- Found similarities between the U.S. warming hole and the other two other warming holes in the central-south China and central South America. The common underlying features among these three warming holes (plus the U.S. Warming hole) are
    - on the eastern slope of major mountain ranges where the warming gradient exists,
    - at the low-level jet terminals where warm-moist air converges, and
    - in the intense agricultural regions where the deep crop roots can extract soil moisture.
- Both CMIP5 *historical* and *amip* experiments have difficulty in reproducing the abnormal cooling (warming hole)
    - Only 19 out of 100 CMIP5's all-forcing *historical* ensemble members simulated a negative temperature trend (cooling) over the southeast U.S. with 99 members under-predicting the cooling rate in the region.
    - Even if SST forcing in *amip* runs are "perfectly" represented in the models, their skills in simulating the WH temperature in the central U.S. shows little improvement over the *historical* run where SST is calculated.

    - The GHG forcing has a warming effect in the central U.S., implying that the WH is not due to the GHG forcing.
    - The difference between the all-forcing and natural-forcing-only runs showed a well-defined cooling region resembling the WH location, implying that land surface change and anthropogenic aerosols may contribute to the WH.
- Determined that the U.S. WH will more likely become weaker in coming decades.
    - CMIP5's GHG forcing alone tends to warm more over the central portion of the continental U.S.
    - The intensity of the WH seems to be strongly modulated by PDO and to a lesser degree, AMO
    - The CMIP5's future simulations (RCP experiments) projected diminishing WH. However this does not conclusively indicate the absence of the WH since the *historical* run could not reproduce the observed WH in the past.

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4. Publications

Peer-reviewed Journal papers:

1. Pan, Z., Y. Zhang, X. Liu, and Z. Gao, 2015: Current and future precipitation extremes over Mississippi and Yangtze River Basins as simulated in CMIP5 models, *J. Earth Sci*., (in press).
2. Eichler, T., and Z. Pan, 2015: The Impact of storm tracks on warm-season precipitation in the Midwest: Contrasting the 1988 Drought and 1993 Flood. *Advances in Meteorology*, Article ID 380241.
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1. Pan, Z., 2014: Intra-seasonal rainfall prediction for agricultural applications during growing season, *39th NOAA Climate Diagnostics and Prediction Workshop***,** St. Louis, OM, Oct. 20-23, 2014.
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