Mechanisms Contributing to the Warming Hole and the Consequent U.S. East–West Differential of Heat Extremes

GERALD A. MEEHL
National Center for Atmospheric Research,* Boulder, Colorado

JULIE M. ARBLASTER
National Center for Atmospheric Research,* Boulder, Colorado, and CAWCR, Bureau of Meteorology, Melbourne, Australia

GRANT BRANSTATOR
National Center for Atmospheric Research,* Boulder, Colorado

(Manuscript received 8 November 2011, in final form 11 April 2012)

ABSTRACT

A linear trend calculated for observed annual mean surface air temperatures over the United States for the second-half of the twentieth century shows a slight cooling over the southeastern part of the country, the so-called warming hole, while temperatures over the rest of the country rose significantly. This east–west gradient of average temperature change has contributed to the observed pattern of changes of record temperatures as given by the ratio of daily record high temperatures to record low temperatures with a comparable east–west gradient. Ensemble averages of twentieth-century climate simulations in the Community Climate System Model, version 3 (CCSM3), show a slight west–east warming gradient but no warming hole. A warming hole appears in only several ensemble members in the Coupled Model Intercomparison Project phase 3 (CMIP3) multimodel dataset and in one ensemble member of simulated twentieth-century climate in CCSM3. In this model the warming hole is produced mostly from internal decadal time-scale variability originating mainly from the equatorial central Pacific associated with the Interdecadal Pacific Oscillation (IPO). Analyses of a long control run of the coupled model, and specified convective heating anomaly experiments in the atmosphere-only version of the model, trace the forcing of the warming hole to positive convective heating anomalies in the central equatorial Pacific Ocean near the date line. Cold-air advection into the southeastern United States in winter, and low-level moisture convergence in that region in summer, contribute most to the warming hole in those seasons. Projections show a disappearance of the warming hole, but ongoing greater surface temperature increases in the western United States compared to the eastern United States.

1. Introduction

Observed trends in annual mean temperature in the second half of the twentieth century show that warming averaged over the western half of the contiguous United States outpaced warming in the eastern half by about a factor of 2 (Fig. 1a). Owing to the relationship between changes in average temperature and changes in record temperatures (e.g., Anderson and Kostinski 2010), the pattern of mean temperature change over the United States (greater warming in the west compared to the east) is similar to the differential changes in the ratio of record highs to record lows (Meehl et al. 2009b; Rowe and Derry 2012). Some areas in the southeastern United States actually show a slight cooling trend of annual-mean surface air temperatures during this time period (Fig. 1a), termed the “warming hole” (Pan et al. 2004; Kunkel et al. 2006). This greater average warming in the west compared to the east is reflected in other observed changes of temperature extremes in the second half of the twentieth

* The National Center for Atmospheric Research is sponsored by the National Science Foundation.
century. For example, there have been proportionately more decreases in observed frost days (defined as daily minimum temperature below freezing) in the west compared to the east (Easterling 2002). Trends in minimum and maximum temperatures (May–June) also show less increase in the east compared to the western United States, or even a decrease (Portmann et al. 2009).

To understand the reason for the differential in warming between the eastern and western United States, this paper explores the factors that could have caused the warming hole in the eastern United States in the second half of the twentieth century. We first identify an ensemble member from a global coupled climate model simulation of twentieth century climate that simulated a warming hole in the second half of the twentieth century in the southeastern United States (Fig. 1c). We then use that member as a case study to examine aspects of the warming hole in the context of decadal time scale climate variability and response to external forcings, mainly increases in greenhouse gases. Previous studies have shown that both tropical Pacific and North Atlantic SSTs can affect climate anomalies over the United States in models and observations (e.g., Robinson et al. 2002; Kunkel et al. 2006; Hoerling et al. 2008; Schubert et al. 2009; Wang et al. 2010; Shin and Sardeshmukh 2011). We will analyze connections of the warming hole to SST patterns in both basins in terms of the processes involved. The dominant role of decadal variability in the tropical Pacific will then be studied for connections to processes that can produce a warming hole. Specified convective heating anomaly experiments will demonstrate the link between SST and precipitation (and associated convective heating) anomalies in the central equatorial Pacific and the warming hole. Finally, the processes that differ with season to produce the warming hole year-round will be described, and the prospects for the future evolution of the warming hole will be addressed. A list of the model simulations considered in this paper is given in Table 1.

2. Case study of the warming hole in a climate model simulation

Ensemble average Coupled Model Intercomparison Project phase 3 (CMIP3) multimodel simulations of twentieth-century climate have shown a somewhat
greater average warming trend in the western United States compared to the east but with no warming hole (Hegerl et al. 2007). In an analysis of changes in frost days in a single model, the National Center for Atmospheric Research (NCAR) Parallel Climate Model, Meehl et al. (2004a) showed the west versus east warming differential in the second half of the twentieth century (projected to continue into the twenty-first century) was associated with a comparable west versus east differential of decreases of frost days (i.e., more decreases in frost days in the west compared to the east as in the observations). That study went on to note that, in the simulations of the future in that model, this west versus east difference was produced primarily by higher sea level pressure (ridging) over the western United States compared to the east as the climate warmed, with consequently warmer temperatures in the west compared to the east. This was due in part to the change in base state of the midlatitude circulation consisting of a zonal wave-5 pattern of upper-tropospheric circulation that produces relatively greater ridging over the western United States (Meehl et al. 2006a; Meehl and Teng 2007). This will be discussed further in section 4.

Thus at least part of the greater warming in the western United States compared to the east over the second half of the twentieth century could be connected to forcing by increases of greenhouse gases (GHGs) [e.g., in the Community Climate System Model, version 3 (CCSM3) by Meehl et al. (2009a)]. A seven-member ensemble average from the CCSM3 [for a description of CCSM3 see Collins et al. (2006)] also shows this west-to-east warming differential (Fig. 1b), but does not show the observed relative cooling trend in the southeastern United States in the second-half of the twentieth century, and also shows warming across the entire Pacific and Atlantic (Fig. 1b). In contrast, as noted previously, the observed warming trend from observations for the second-half of the twentieth century shows a distinct pattern over the oceans with warming in the eastern tropical Pacific, cooling in the northwest and southwest Pacific, warming in the tropical Atlantic, and cooling north of about 30°N in the northern Atlantic (Fig. 1a).

This trend pattern of surface air temperature over the oceans is similar in observed SST datasets (not shown) and is thought to have driven the cooling trend (warming hole) over the southeastern United States (Fig. 1a). This feature is centered in somewhat different locations in the eastern part of the country depending on the period and season being analyzed (e.g., Kunkel et al. 2006), and these details will be discussed later in this paper. The warming hole previously has been attributed to possible altered hydrologic feedback (Pan et al. 2004; Portmann et al. 2009), increased cloudiness (Robinson et al. 2002), or internally generated decadal time-scale variability of either tropical Pacific SSTs, northern Atlantic SSTs, or some combination of both (Robinson et al. 2002; Kunkel et al. 2006; Hoerling et al. 2008; Wang et al. 2009, 2010; Shin and Sardeshmukh 2011).

A single ensemble member was selected from the CCSM3 set of seven twentieth-century simulations analyzed by Meehl et al. (2009b). Daily data were saved from

---

**Table 1. Summary of model experiments.**

<table>
<thead>
<tr>
<th>Model experiments</th>
<th>Model configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seven ensemble members for twentieth century all-forcing (anthropogenic and natural) CCSM3 simulations (one of these was analyzed for changes in daily temperature records because daily data were saved, but it did not have a warming hole; another ensemble member produced the warming hole pattern but daily data were not saved for that ensemble member) 500-yr preindustrial control run with CCSM3, external forcings held fixed at 1870 values, model variability is generated internally</td>
<td>Fully coupled CCSM3, atmosphere–ocean–land–sea ice</td>
</tr>
<tr>
<td>CAM3 atmosphere-only: (a) Observed time-evolving SSTs (b) Climatological SSTs with time-evolving atmospheric radiative forcings that include natural (volcanoes, solar) and anthropogenic (GHGs, ozone, sulfate aerosol direct effect) from CCSM3 twentieth-century simulations above (c) Observed time-evolving SSTs from (a), and time-evolving radiative forcing from (b)</td>
<td>CAM3 atmosphere-only 20-yr run with repeating climatological monthly mean SSTs and specified convective heating anomaly centered at equator and date line</td>
</tr>
<tr>
<td>Specified convective heating anomaly experiment</td>
<td>Specified convective heating anomaly experiment</td>
</tr>
</tbody>
</table>

6396 JOURNAL OF CLIMATE VOLUME 25
that ensemble member and not all of the others and shows about a 20% greater warming trend in the west compared to the east for the second-half of the twentieth century and a comparable differential in the ratio of daily record high temperatures to record low minimum temperatures. Yet, there is no indication of the observed cooling trend over the southeastern United States in that model ensemble member.

However, of the seven CCSM3 twentieth-century ensemble members mentioned above and listed in Table 1, one of the members does show a warming hole (Fig. 1c) with a factor of ~3 greater area-averaged warming in the west compared to the east. By applying the standard relationship between mean temperatures and record minimum and maximum temperatures (Anderson and Kostinski 2010), there is a comparable ratio of record high maxima to record low minima with a somewhat greater than observed differential of this ratio of about two to one. A comparison of the observed time series of area-averaged surface temperatures over the southeastern United States (area average over 24°–40°N, 70°–90°W) and this single ensemble member that simulates the warming hole shows in both an increase of temperatures until the early 1950s, then a decline for the next couple of decades, followed by an increase again (Fig. 1d). There is not an exact match in the temporal evolution of temperatures between this ensemble member and observations in Fig. 1d since the unforced internally generated decadal variability is not quite the same. However, both feature temperatures in the late twentieth century over that area of the country that do not quite return to the midcentury values, thus producing the eastern U.S. cooling trend shown in Figs. 1a,c for 1950–99. It is also worth noting that the warming hole reverts to a positive temperature trend in the future in that figure, as will be discussed later. Examination of the other five CCSM3 twentieth-century ensemble members shows that each evolves somewhat differently as would be expected from each having its own realizations of internally generated decadal time scale variability.

That the warming hole is evident in one ensemble member of the CCSM3 twentieth-century simulations is not unique to this model. Kunkel et al. (2006) surveyed the CMIP3 multimodel ensemble and showed that a few ensemble members from several models simulated a warming hole comparable to the observed and connected those warming holes to SST variability in the Pacific and Atlantic Oceans, as noted earlier. This suggests that the warming hole is not completely a product of external forcing (assuming that first-order aspects of anthropogenic and natural forcings are represented in the multimodel ensemble), but likely has a contribution from internally generated decadal-time scale variability. Warming holes with a timing similar to the observations have not been detected in many simulations and only rarely in others. If warming holes are indeed internally generated, it would require a fortuitous matching up of essentially stochastic low frequency variability over the same regions at the same time to produce a simulated warming hole comparable to the observed one. In fact, comparing the observed surface air temperature trends in Fig. 1a with the trends in the single CCSM3 ensemble member in Fig. 1c, there are some striking similarities. Both show warming trends in the tropical Pacific and northeast Pacific off the west coast of North America and cooling north of Hawaii and in the North Atlantic north of ~30°N. Kunkel et al. (2006) show that, in their definition of the warming hole, it is connected to opposite-sign SST variations (very close to surface air temperature changes) in the tropical eastern Pacific and North Atlantic (warm in the tropical Pacific, cool in the North Atlantic off the U.S. East Coast and north of ~40°N). This result has been noted in model simulations that have isolated the relative contributions of Pacific and Atlantic SSTs, cited previously, to precipitation and temperature anomalies over the central United States.

The most notable decadal time-scale feature of temperature variation over the second-half of the twentieth century was the so-called mid-1970s climate shift when SSTs in the tropical Pacific transitioned from negative to positive on the decadal time scale (Trenberth and Hurrell 1994). The mid-1970s shift has subsequently been attributed to a combination of forcing from increasing GHGs and internally generated variability associated with the Interdecadal Pacific Oscillation (IPO) (Meehl et al. 2009a). Since trends calculated over the second-half of the twentieth century would feature the mid-1970s climate shift prominently, it is not surprising that the observed surface air temperature trends (that, as noted above, are very close to the underlying SST trends) in Fig. 1a show a pattern in the Pacific that resembles the positive phase of the IPO. However, Meehl et al. (2009a) implicated greenhouse gas forcing changes in the mid-1970s as making some contribution to the climate shift, so this source of variability could also play a role in the warming hole phenomenon. Since sulfate aerosol concentrations are greater in the eastern compared to the western United States, it is possible that there could be a contribution to the warming hole from the response to those aerosols. However, a model simulation forced only by changes in the direct effect of sulfate aerosols, there is almost uniform cooling across the country (Meehl et al. 2004b). Thus, this source of forcing does not appear to provide the kind of east — west spatial differentiation suggested by the warming hole. There may be aerosol forcings not
accounted for in the model that could have contributed to the warming hole (e.g., Weber et al. 2007; Leibensperger et al. 2012). But the fact that some ensemble members from some models produce the warming hole, while other ensemble members using the same forcings from those same models do not, implicates internally generated decadal time scale variability as at least a significant player in producing the warming hole.

To examine further the effects of SST forcing versus radiative forcing on simulating the warming hole, we analyze five-member Atmospheric Model Intercomparison Project (AMIP)-type experiments with the CAM3 atmospheric component of CCSM3 (Deser and Phillips 2009). The first set includes only the time-evolving SST forcing (Fig. 2c), while the second set has only the time-evolving radiative forcing with climatological SSTs (Fig. 2d). The radiative forcings are the full set from the CCSM3 twentieth century simulations and include time-evolving natural (volcanoes, solar) and anthropogenic forcings (GHGs, ozone, sulfate aerosol direct effect) and forcings from the A1B scenario from 2000 to 2008 as described by Meehl et al. (2006b). These are compared to the SST-plus-radiative forcing experiment (Fig. 2b) and to observations (Fig. 2a). The results show that the warming hole can be generated in the runs that include both SST and radiative forcing (Fig. 2b), but only the SST forcing can produce the warming hole as observed (Fig. 2c), while the radiative forcing by itself simulates warming over the entire United States with no warming hole (Fig. 2d). This confirms earlier results from studies noted above [e.g., Deser and Phillips (2009), who did not show results for surface temperature, and the analysis was for a somewhat shorter time period].

The remaining question is what is producing the decadal time-scale variations of the SSTs that appear to have forced the warming hole, and what parts of the regional patterns of SST trends are most directly connected to the warming hole? The candidate for an internally generated phenomenon in the tropical Pacific, proposed by Meehl et al. (2009a) for the mid-1970s climate shift, is the IPO. Defined as the first empirical orthogonal function (EOF) of low-pass filtered (13 yr)
Pacific Ocean SSTs in a long control run with no changes in external forcings, the surface temperature signature of the IPO in that 500-yr control run from CCSM3 is characterized by warmer temperatures in the tropical Pacific and a warming hole over the eastern part of the United States (Fig. 3a). This is calculated by first computing the IPO from the EOF of detrended low-pass filtered SSTs and then correlating the resulting principal component (PC) time series with surface air temperatures globally.

In the observations (Fig. 2a) there are negative surface air temperature trends that extend into the western subtropical Atlantic and high-latitude North Atlantic associated with the southeastern U.S. warming hole. The model IPO surface air temperatures match these negative subtropical features but with warming north of about 40°N (Fig. 3a). This suggests that the most consistent surface temperature signal for this model is coming from the tropical Pacific since the IPO signal matches all but the high-latitude North Pacific trend from observations.

To further investigate the relative importance of the tropical Pacific and North Atlantic SSTs in generating the warming hole in the model, we look at the relationships in the 500-yr preindustrial control simulation analyzed in Fig. 3a. We compute 451 overlapping 50-yr surface air temperature trends from the 500-yr CCSM3 control run. By calculating pattern correlation values over the continental United States between each of these temperature trend patterns and the warming-hole-like events; stippling indicates areas where the ensemble mean divided by the ensemble deviation is greater than 1; (c) for a convective heating anomaly at equator, date line (green circle), surface air temperature anomalies for the DJF season, red are positive values, blue are negative; and (d) as in (c) but for 850-hPa streamfunction (m² s⁻¹).
then picking the 42 cases for which the correlations are greater than +0.5, we produce a composite linear trend pattern of surface air temperature associated with warming-hole-like events generated by internal processes (Fig. 3b). The strongest and most significant (stippling indicates areas where the ensemble mean divided by the ensemble deviation is greater than 1) connection for a warming hole trend over the southeastern United States is to a warm tropical Pacific, cool northwest Pacific and southeast Pacific, and warm North Atlantic. There is no connection to opposite-sign SST anomalies in the North Atlantic in this model. This suggests that, in this model at least, a warming hole over the southeastern part of the United States can be produced in association with warmer than normal tropical Pacific SSTs on the decadal time scale.

To elucidate the mechanism for this connection, an additional experiment is considered in which the CAM3 atmospheric component of CCSM3 is stimulated with a specified heating anomaly centered at the equator and the date line. This is near the region where the tropical SST anomalies associated with the warming hole in the southeastern United States are most statistically significant in the composite of internally generated warming hole events (Fig. 3b). There is also a statistically significant correlation between the warm SSTs there and positive local precipitation anomalies (e.g., the correlation is about +0.55 in this location in the CCSM3 control run). Such positive precipitation anomalies correspond to anomalous tropospheric heating that theory suggests will excite a train of Rossby waves that is generally most pronounced in the winter hemisphere (Webster 1982). The CAM3, with repeating climatological SSTs, is run for 20 years with a specified heating anomaly with maximum value of 5°C day$^{-1}$. The heat source is 1500 km in diameter centered on the equator. In the vertical it has the profile $\sin(\pi \sigma)$, where $\sigma$ is local pressure divided by surface pressure.

We consider northern winter temperature anomalies for the specified heating runs because this is when the teleconnection to the equatorial central Pacific is strongest (e.g., Meehl et al. 2006a), as suggested by theory. Figure 3c shows negative surface air temperature anomalies of about $-2^\circ$C over the eastern United States, with positive surface air temperature anomalies in the western United States of about +1°C, and even larger positive anomalies across Alaska and northern Canada. This pattern is comparable to the observed warming hole in Fig. 1a, and the one in the single model ensemble member in Fig. 1c. Of course, one does not expect a correspondence in surface air temperature over the oceans between these experiments, with specified SSTs, and the coupled experiments.

The mechanism that connects the convective heating anomaly in the central equatorial Pacific is the anomalous Rossby wave response in the atmosphere (e.g., Hoskins and Karoly 1981)—with a barotropic tropospheric trough in the North Pacific, a broad ridge over North America, and another trough in the northern Atlantic (Fig. 3d). These results demonstrate that a warming hole can be generated from convective heating anomalies and the anomalous Rossby wave response in the atmosphere associated with positive precipitation and SST anomalies in the central equatorial Pacific connected to the internally generated IPO (Fig. 3a).

The main agent by which the remotely stimulated circulation anomalies influence annual mean surface air temperature over the southeastern United States is low-level temperature flux convergence as seen in Fig. 4a for the CCSM3 warming hole member and Fig. 4b for the specified convective heating anomaly experiment. That is, cold-air advection from the northeast, as indicated by the vector arrows for low-level wind anomalies at 850 hPa in Fig. 4, contributes to surface temperature flux divergence (negative values in Fig. 4 over the eastern United States). Area averages of surface temperature flux divergence in the area 24°–40°N, 70°–90°W (see outline box in Fig. 1c) are $-2.44 \times 10^{-5}$ K s$^{-1}$ (50 yr)$^{-1}$ for the warming hole CCSM3 member, and $-1.67 \times 10^{-5}$ K s$^{-1}$ for the specified convective heating anomaly experiment (note different units reflecting different averaging). This pattern is associated with the anomalous ridge–trough pattern over the United States connected to convective heating anomalies in the Pacific. This type of teleconnection pattern is strongest in winter, so the annual mean is influenced mostly from that season. But to understand the nature of the warming hole, processes in the warm season must also be considered.

### 3. Seasonal results

Observations in Fig. 5 show that some manifestation of the warming hole is in evidence year round though, as noted earlier, its strength and position vary with season. The greatest cooling trends over this time period occur in the southeastern United States in December–February (DJF) (Fig. 5a) while in June–August (JJA) (Fig. 5b) negative temperature trend values spread from that area into the Great Plains. As mentioned earlier, presumably the strongest forcing through the anomalous Rossby wave response from SST and convective heating anomalies in the tropical Pacific would be in the cold season. Previous studies that showed the connection of the warming hole to tropical Pacific SSTs noted a similar seasonal connection (Robinson et al. 2002; Kunkel et al. 2006; Wang et al. 2009; Shin and Sardeshmukh 2011).
But, the warming hole is also present in the warm season, raising the question of whether there are different processes producing the warming hole that are a function of season.

In the specified convective heating anomaly experiment, there is evidence of cooling over the eastern United States in DJF, with the cooling centered more over the Great Plains in JJA (Fig. 6). The 850-hPa streamfunction anomalies in the convective heating anomaly experiment show that the strongest anomalous planetary wave response occurs in DJF (Fig. 7a, same as Fig. 3d), but in JJA the pattern is mostly a tropical
quadrupole. This JJA quadrupole with negative anomalies north of the equator and west of the date line and positive anomalies north of the equator and east of the date line, and opposite signed anomalies south of the equator, is reminiscent of the combined Rossby wave–Kelvin wave response to equatorial heating found in the Gill (1980) equatorial beta-plane model. In association with this pattern in winter there should be advection of cooler air into the eastern United States and in summer there should be convergence of moisture on the north side of the anomalous high over southern North America. Indeed, anomalies of the 850-hPa temperature flux convergence, in Fig. 8, for the specified convective heating anomaly experiment show, in winter, surface temperature flux divergence (from advection of cool air) as a major contributor to the warming hole. In summer, the small positive values of low-level temperature convergence over the central United States should contribute to warming, but there is cooling in Fig. 6b. Something else is going on in summer to contribute to cooling of surface air temperatures. In fact, the pattern of anomalous temperature flux convergence in Fig. 8 coincides with simultaneous convergence of moisture in summer over the central United States (not shown) that likely overcomes the impact of the temperature convergence and contributes to increased precipitation and cooling.

Figure 9 shows that this positive low-level moisture convergence contributes to increased precipitation over most areas of the central United States in summer with concomitant increases of soil moisture, surface evaporation, and increased cloudiness (not shown), which all contribute to cooler surface temperatures in summer. Such a connection between observed increases of precipitation and decreased surface air temperature has been noted for the May–June season by Portmann et al. (2009). Thus, the specified convective heating anomaly experiment suggests that the contribution from positive tropical Pacific SST anomalies to positive convective heating anomalies produces a different set of responses over the United States in cold and warm seasons. In winter the anomalous Rossby wave response produces a ridge–trough pattern that results in cold-air advection from the northeast, surface temperature divergence, and cooler surface air temperatures. In summer there is more of a Gill-type response with
low-level moisture convergence over the central United States, increased precipitation and cloudiness, greater soil moisture and evaporation, and cooler surface air temperatures.

Now we turn to the CCSM3 twentieth-century simulation for which it is hypothesized that the warming hole in that ensemble member is internally generated in connection with positive SST anomalies in the tropical Pacific that resemble the positive phase of the IPO. We intend to use the results from the specified convective heating anomaly experiment described above to help interpret the CCSM3 results in terms of the processes that may be at work in both.

As in the observations in Fig. 5, there is a warming hole year-round in CCSM3 in the eastern United States, strongest in winter and weakest in summer (Fig. 10), though the observed warming hole in summer in Fig. 5b is a bit farther west than the warming hole in CCSM3 in Fig. 10b. Also, as in the specified convective heating anomaly experiment, 850-hPa height anomalies (not shown, but similar to Fig. 7) produce a pattern of 850-hPa temperature flux divergence in winter (Fig. 11a) with values averaged over the area 24°–40°N, 70°–90°W of \(-1.05 \times 10^{-4} \text{ K s}^{-1} (50 \text{ yr})^{-1}\), and weak area-averaged temperature convergence in summer over that area of \(+0.06 \times 10^{-4} \text{ K s}^{-1} (50 \text{ yr})^{-1}\) (Fig. 11b). The latter should contribute to warming, but there is surface cooling in summer in Fig. 6b. As in the specified convective heating anomaly experiment, there is positive low-level moisture convergence in summer over the southeastern United States (Fig. 12) with an area-averaged value of \(+0.85 \times 10^{-10} \text{ s}^{-1} (50 \text{ yr})^{-1}\). This should contribute to increases of summertime precipitation and, indeed, that is the case, as shown in Fig. 13a, with positive precipitation anomalies over the southeastern United States amounting to \(-15\%\), along with increases \([O (10\%–20\%)]\) of soil moisture (Fig. 13b), and low cloud (Fig. 13c). Enhanced soil moisture increases evaporation and surface cooling, and more low clouds reduce incoming solar radiation. Both then combine to produce the summertime warming hole.

### 4. Possible future changes

In Fig. 1d the CCSM3 ensemble member with the warming hole shows a resumption of warming over the southeastern United States as the model simulation moves into the twenty-first century. That ensemble member shows slightly greater overall warming in the western compared to the eastern United States through the 21st century (Fig. 14, top panels), with mostly positive west minus east differences later in the century (Fig. 14 bottom panel). In fact, all other ensemble members also show greater future warming on average in the western United States compared to the east (Fig. 15, top panels) with a greater tendency for positive values of area-averaged west minus east temperatures (Fig. 15, bottom). This is associated with a consistent wave-5 response to increasing CO₂ (Meehl and Teng 2007), that has a regional wave-3 signature over North America (Teng and Branstator 2012). Such
a response pattern to increasing CO₂ indicates that the ratio of record highs to record lows will likely remain somewhat greater in the western compared to the eastern United States throughout the twenty-first century but with internally generated fluctuations in amplitude from decade to decade.

5. Conclusions

A prominent feature of U. S. climate trends over the second-half of the twentieth century was stronger warming in the west than in the east. The most dramatic aspect of this east–west gradient was a complete lack of warming over parts of the eastern United States, the so-called “warming hole.” The east–west gradient produced greater increases of the ratio of daily record high temperatures to record low temperatures in the west compared to the east in about the same proportion as the average warming (about two to one). Climate model simulations tend to also produce somewhat greater warming in the western United States compared to the east, associated with a warmer tropical Pacific mainly in response to increasing GHGs. The contrast between west and east coincides with, and is likely caused by, ridging over the western United States that in many climate change simulations is associated with a wave-5 pattern of upper-troposphere circulation that circles the Northern Hemisphere. However the warming in multi-ensemble member averages in the west due to external forcing is only about 20% greater than the warming in the east, and there is no warming hole. To understand the observed east–west proportion of the changes of record temperatures, climate model experiments are analyzed to gain insight into what has produced the warming hole.

We build on previous studies that showed some individual model ensemble members in climate change experiments produced a warming hole. A case study of an individual ensemble member in a CCSM3 twentieth-century experiment that produces a warming hole comparable to observations, in addition to an analysis of a multicentury control run with that model, shows a dominant role of tropical Pacific SST decadal variability associated with the IPO in the generation of the warming hole. A positive phase of the IPO (warmer tropical Pacific SSTs) is connected with the warming hole over the eastern United States.

An atmosphere-only experiment with a specified heating anomaly indicates that positive local precipitation and heating anomalies produced by SST anomalies near the equator and date line can generate a warming hole over the eastern United States, not
unlike what was observed and also like that in the CCSM3 single ensemble member. This occurs via an anomalous atmospheric planetary scale wave response to the specified convective heating anomaly.

However, there is an interesting seasonal signature to the warming hole with different processes for cold and warm seasons, all connected to positive SST and convective heating anomalies in the tropical Pacific. In

Fig. 12. (a) As in Fig. 11a but for moisture convergence \( [s^{-1}(50 \text{ yr})^{-1}] \); (b) for JJA.

Fig. 13. As in Fig. 10b but (a) for precipitation \( [\%(50 \text{ yr})^{-1}] \), (b) for soil moisture \( [\text{kg m}^{-2}(50 \text{ yr})^{-1}] \), and (c) for low cloud \( [\%(50 \text{ yr})^{-1}] \).
winter the midlatitude wave response is primarily by Rossby waves that result in a ridge–trough pattern over the United States with cold-air advection from the northeast and low-level divergence of temperature fluxes being the main factors that produce cooling in the eastern United States. However, in summer the same positive SST and convective heating anomalies produce a Gill-like combined Rossby–Kelvin wave response with low-level moisture convergence over the southern United States that contributes to greater precipitation and cloudiness, increased soil moisture and surface evaporation, and consequent cooler temperatures.

This does not rule out a role for North Atlantic SSTs in producing a warming hole since, as noted earlier, previous studies have demonstrated a contribution to North American climate from SSTs in that region. Additionally, the single CCSM3 ensemble member that simulated a warming hole had negative SST trends in the North Atlantic similar to the observations (comparing Figs. 1a,c). However, the analysis of the model control run trends indicates that the IPO in the Pacific is a dominant contributor to the warming hole, at least in this model.

Additionally, since the warming hole is mainly a product of internally generated decadal time-scale variability, as the Interdecadal Pacific Oscillation transitions back to negative polarity, the warming hole should be replaced by a more rapid rate of warming. For example, in the CCSM3 ensemble member that produces the warming hole, the future evolution of southeastern U.S. temperatures in Fig. 1d [following the midrange Special Report on Emissions Scenarios (SRES) A1B scenario] shows little trend from about 2000 to 2020, then a warming jump of nearly 1°C from roughly 2020 to 2025, then nearly no trend again from 2025 to 2045. However, long-term forced trends from other ensemble members indicate a preponderance of periods of relatively greater warming over the western United States compared to the east. Other factors such as differences in terrain height (the higher elevation mountainous west could warm more than the lower elevation terrain of the east) or land use contrast between west and east could also play a role. However, the model results show that
the greenhouse-gas-forced temperature trend is due in part to a wave-5 circulation response of the midlatitude circulation that favors a ridge over the western United States and a trough over the east.

Acknowledgments. Portions of this study were supported by the Office of Science, Biological and Environmental Research, U.S. Department of Energy, Cooperative Agreement DE-FC02-97ER62402 and Grant DE-SC0005355, NOAA’s Climate Prediction Program for the Americas Award NA09OAR4310187, and the National Science Foundation. We thank Andy Mai for his assistance with accessing the convective heating experiments.

REFERENCES


