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Changes in severe thunderstorm environment frequency during the 21st century caused by anthropogenically enhanced global radiative forcing

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Severe thunderstorms comprise an extreme class of deep convective clouds and produce high-impact weather such as destructive surface winds, hail, and tornadoes. This study addresses the question of how severe thunderstorm frequency in the United States might change because of enhanced global radiative forcing associated with elevated greenhouse gas concentrations. We use global climate models and a high-resolution regional climate model to examine the larger-scale (or ''environmental'') meteorological conditions that foster severe thunderstorm formation. Across this model suite, we find a net increase during the late 21st century in the number of days in which these severe thunderstorm environmental conditions (NDSEV) occur. Attributed primarily to increases in atmospheric water vapor within the planetary boundary layer, the largest increases in NDSEV are shown during the summer season, in proximity to the Gulf of Mexico and Atlantic coastal regions. For example, this analysis suggests a future increase in NDSEV of 100% or more in locations such as Atlanta, GA, and New York, NY. Any direct application of these results to the frequency of actual storms also must consider the storm initiation.

climate change | United States | convective storm

Severe thunderstorms comprise an extreme class of deep convective clouds and produce high-impact weather, such as destructive surface winds, hail, and/or tornadoes, in addition to dangerous lightning and torrential rainfall. In the United States, these phenomena (less flooding) contributed to an annual average[‖] of 2.1 billion dollars in property and crop losses, 108 fatalities, and 1,463 injuries during 2000–2004. For perspective, consider that tropical cyclones in the United States caused an annual average[**] of 5.5 billion dollars in property and crop losses, 25 fatalities, and 285 injuries over the same period.

In this study, we are concerned with the possibility of changes in severe thunderstorm frequency in response to greenhouse gas (GHG)-induced enhancement of global radiative forcing. Anthropogenic increases in GHG concentrations are expected to raise global mean temperature 2°C to 6°C by the end of this century, with greater warming at high latitudes than at low latitudes (1). Coupled to this warming is an anticipated increase in atmospheric water vapor, which may in turn lead to intensified precipitation and a higher frequency of extreme precipitation events (e.g., refs. 1–4). One may be tempted to immediately extend this projection to severe thunderstorm frequency. However, given the unique set of atmospheric conditions that foster severe storm development, it is not straightforward to assume that the extreme precipitation will necessarily be realized as locally damaging storms. The frequency, and regional variability, with which these unique conditions will exist in association with anthropogenic global warming has not yet been established, thereby motivating this study.

Here we focus on the continental United States, a global hotspot of severe thunderstorm occurrence (5). At present, severe thunderstorms are geographically distributed throughout a region that originates in the southeastern and south-central United States in early spring and then expands westward to the southern plains and northward through the north-central United States by early summer (6). An eastward branch of the distribution extends to the Atlantic coast, yet the maximum in severe thunderstorm occurrence is in the Great Plains. The specific geographical distribution for tornadoes is similar, albeit shifted slightly westward (7).

Individual thunderstorms have length scales of tens of kilometers and time scales of several hours, and consequently they are unresolved in typical climate models. Nevertheless, we can use climate model data by exploiting the fact that the organization of cumulus clouds into severe convective storms is strongly influenced by the larger-scale (or "environmental") distributions of temperature, moisture, and winds.

Two quantitative measures that characterize well the local thunderstorm environments are the convective available potential energy (CAPE; J·kg^{-1}), and the magnitude of the vector difference between the horizontal wind at 6 km above ground level (AGL) ($\vec{V}_6$) and the wind at the lowest model level ($\vec{V}_0$) (S06; m·s^{-1}). CAPE is a parameterized measure of the vertically integrated buoyant energy available to the storm. For an inviscid atmosphere, and given other assumptions, it can be shown that $w_{\max} = \sqrt{2 \times \mathrm{CAPE}}$, where $w_{\max}$ is the theoretical maximum updraft speed (8). Hence, the strong updrafts in storms that occur in environments of large CAPE are more likely to support the growth of large hailstones and otherwise produce large rainfall rates, which can lead to more intense downdrafts and resultant outflow winds.

S06 quantifies the vertical change or "shear" of the environmental horizontal wind vector ($\partial\vec{V}/\partial z$). The internal dynamics of thunderstorms are changed dramatically by large environmental vertical shear, because the shear promotes storm-scale rotation about a vertical axis and also helps sustain a deep updraft in the

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[‖] Based on a compilation of data from the U.S. National Climatic Data Center and the U.S. National Weather Service Office of Climate, Water, and Weather Services (www.nws.noaa.gov/om/hazstats.shtml) from 2000 to 2004, these are 5-year, nonadjusted means that include the fatalities, injuries, and damage inflicted by lightning, tornadoes, severe wind, and hail.

[**] Based on the same U.S. data as above, these are 5-year, nonadjusted means that include the fatalities, injuries, and damage inflicted by tropical cyclones. Note that this averaging period excludes Hurricane Katrina and others during the 2005 season.

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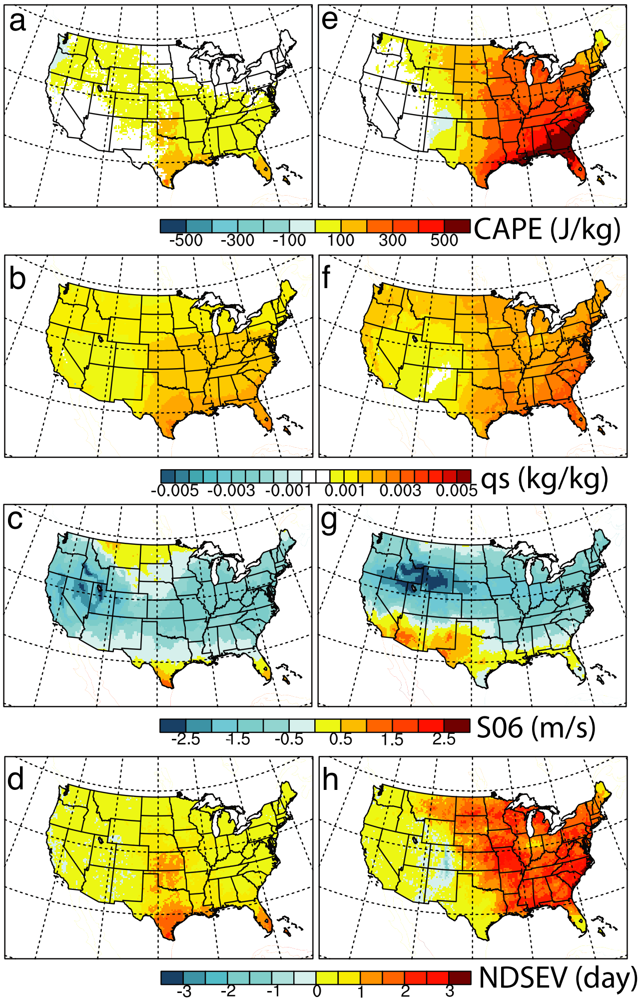

Fig. 1. Difference (A2 − RF) in mean CAPE, vertical wind shear over the surface to 6 km layer (S06), mean surface specific humidity (q_s), and severe thunderstorm environment days (NDSEV) for March–April–May (MAM) (*a*–*d*) and June–July–August (JJA) (*e*–*h*), respectively. The RF integration period is 1962–1989, and the A2 integration period is 2072–2099.

presence of a precipitation-driven downdraft and associated thunderstorm outflow. Both effects enhance storm organization, intensity, and longevity (e.g., refs. 9 and 10). This influence of environmental shear presumes that sufficiently large CAPE also exists to foster thunderstorm formation. Indeed, severe thunderstorms occur most readily when CAPE and vertical wind shear both are large in a local environment (5, 11).

Brooks *et al.* (5) have shown that the product of CAPE and S06 is reasonably effective at discriminating environments of significant severe thunderstorms from those of all other thunderstorms. Herein, the number of days on which CAPE × S06 locally exceeds an empirical threshold based on Brooks *et al.* (5) is denoted by NDSEV. Hence, NDSEV is used as a proxy to the number of days on which thunderstorms could form locally and potentially produce significant surface winds, hail, and/or tornadoes.

Results

We consider seasonal mean values of CAPE, S06, and NDSEV, determined over the periods 1962–1989 (RF) and 2072–2099 (A2) using simulations of United States regional climate performed by Diffenbaugh *et al.* (2) (Fig. 1). The A2 CAPE is higher than the RF CAPE almost everywhere in the United States, with the largest changes (A2 − RF) in proximity to the Gulf of Mexico and Atlantic coastal regions. As demonstrated graphically in Fig. 1, the CAPE increases can be attributed primarily to increases in atmospheric water vapor within the planetary boundary layer (12), which is a consequence primarily of increased vapor transport (e.g., refs. 13 and 14). During the seasons of March–April–May (MAM) and June–July–August (JJA), respectively, this attribution is supported by high linear correlations (0.75 and 0.96, respectively) between difference (A2 − RF) surface-specific humidity (q_s) and difference (A2 − RF) CAPE.

The increases in q_s, and hence CAPE, are expected from basic considerations of the Clausius–Clapeyron equation, which embodies the direct dependence of water vapor on temperature and thus the low-level humidification given low-level warming (13, 14). Similarly, the overall decreases in vertical wind shear shown in Fig. 1 are anticipated by virtue of the thermal wind relation,

$$\frac{\partial \vec{V}}{\partial z} \cong \frac{g}{fT}\hat{k} \times \nabla T, \qquad [1]$$

where f is the Coriolis parameter and g is the gravitational acceleration, owing to projected weakening of the horizontal (nominally, equator to pole) gradient of temperature (∇T). The open question up to this point has been which of these responses would dominate: Recall that the observations (5, 11) indicate that severe thunderstorms occur most readily when CAPE and vertical wind shear both are large in a local environment. Hence, one possible outcome from the increased CAPE and decreased shear expected under anthropogenic climate change is the predominance of less organized thunderstorms, still capable of extreme rainfall but generally nonsevere.

However, over most of the United States, the relative increases in A2 CAPE more than compensate for the relative decreases in A2 shear, leading to relative increases in A2 NDSEV and hence in the frequency of severe thunderstorm environments. For example, during MAM, a modern period of high severe thunderstorm occurrence, the positive differences in CAPE and hence NDSEV are largest over a "tornado-alley"-like region extending northward from Texas (Fig. 1). During JJA, positive differences in NDSEV cover the eastern one-half of the United States and are similarly well associated with the positive CAPE difference.

Changes in severe convective weather could have particular impact in areas of high population. To better assess this possibility, we have calculated the mean annual cycles of NDSEV at model grid points nearest to Atlanta, GA (ATL), New York, NY (NYC), Chicago, IL (CHI), Dallas, TX (DFW), Phoenix, AZ (PHX), and Los Angeles, CA (LAX) (Fig. 2). Characteristic of the southeast United States over the A2 period, ATL exhibits a substantially amplified cycle, with a doubling of the RF NDSEV during most of the spring and summer months. A similar amplification is found in NYC, albeit confined to summer. We find more limited increases outside of the Gulf of Mexico and Atlantic coastal regions, where increases in boundary layer moisture and hence CAPE are comparatively higher (Fig. 1). The NDSEV cycle at CHI differs only slightly in A2 relative to RF, except for the noteworthy, several-day increase during the month of June. At DFW, the mean annual NDSEV cycle in A2 is enhanced by ≈60% during the month of May, with more modest increases during the remaining warm season. At PHX and in other parts of the southwest United States, the relatively weak annual cycle is amplified during the months of August–September–October, which reflects the regional increase in specific humidity during this time (data not shown) and is suggestive of a higher frequency of severe thunderstorm environments during the Arizona monsoon (15). Finally, despite the substantial fractional increases in NDSEV, the weak annual

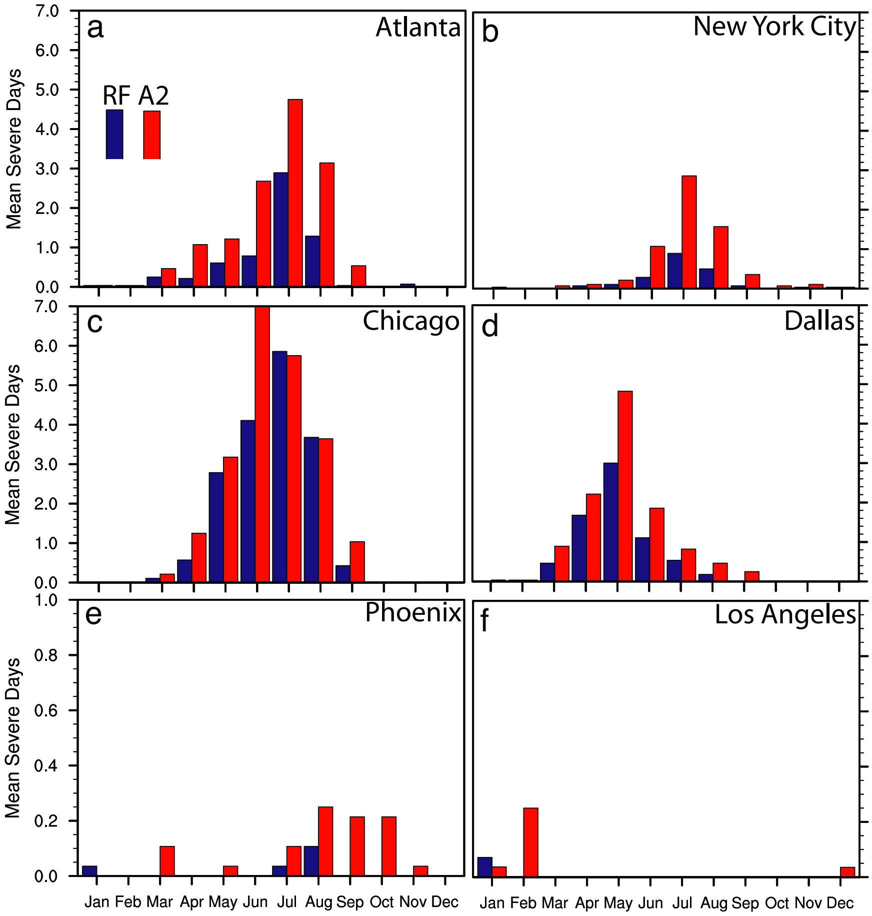

Fig. 2. Mean annual cycle of NDSEV over the RF and A2 periods, evaluated at model grid points nearest Atlanta, GA (ATL) (*a*), New York, NY (NYC) (*b*), Chicago, IL (CHI) (*c*), Dallas, TX (DFW) (*d*), Phoenix, AZ (PHX) (*e*), and Los Angeles, CA (LAX) (*f*). Note that the ordinate has a different scale in *e* and *f*.

cycle at LAX implies that the severe storm risk remains low even during the A2 period.

The results presented thus far are derived from a single-model realization. To begin to address the obvious question of result robustness and generality, we offer a comparison between the Abdus Salam Institute for Theoretical Physics Regional Climate Model version 3 (RegCM3) integrations and integrations of three general circulation models (GCMs). The members of this "ensemble of opportunity"[††] were chosen based on the availability of subdaily, 3D atmospheric data. Nonetheless, they allow us to consider how NDSEV might be affected by model resolution, integration period, and GHG scenario.

Each of these GCMs depicts NDSEV difference fields that agree broadly with RegCM3 during at least one of the most relevant seasons. For example, during MAM, National Center for Atmospheric Research (NCAR) Community Climate System Model version 3 (CCSM3) and the Max Planck Institute (MPI) European Centre Hamburg Model version 5 (ECHAM5) produce a positive NDSEV difference that extends northward from Texas (Fig. 3), as similarly produced by RegCM3 (Fig. 1). During JJA, the ECHAM5 and Geophysical Fluid Dynamics Laboratory Coupled Model, version 2.1 (GFDL CM2.1) integrations show strong positive changes in NDSEV in the southern and eastern United States (Fig. 3); this response is positive yet weaker in the CCSM3 integration. As in the RegCM3 integrations, these future increases in NDSEV are driven by future increases in CAPE (data not shown). Future decreases in CAPE, and hence in NDSEV, during JJA are particularly noticeably in each of these GCM integrations throughout parts of the southern Great Plains. This documented response (16, 17) is likely a model artifact, associated with the misrepresentation of the land surface–atmospheric interactions; the result is a warm, dry model bias.

Further evidence of this bias is found through a comparison between the RegCM3 RF integration and the North American Regional Reanalysis (NARR) data set (18). In addition, this comparison reveals low values of RegCM3 CAPE and NDSEV in the southeast United States caused by a wet model bias recently described by Diffenbaugh *et al*. (17). Otherwise, the NARR data indicate a much higher frequency of modern NDSEV (Fig. 4), indicating that the future NDSEV could be correspondingly underestimated.

Discussion and Conclusions

The objective of this study was to investigate possible changes in the frequency of severe thunderstorm environments in the United States, in response to anthropogenic increases in GHG concentration. Global climate model output and high-resolution regional climate model output were used to compute fields of CAPE and vertical wind shear. These two parameters characterize the meteorological conditions that foster severe thunderstorm formation.

CAPE increases throughout the United States under the A2 emissions scenario, relative to a modern reference period. This

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[††] Santer B (2005) *The IPCC Historical Forcing Runs: PCMDI Analyses of an Ensemble of Opportunity*, 10th Annual CCSM Workshop, June 21–23, 2005, Breckenridge, CO.

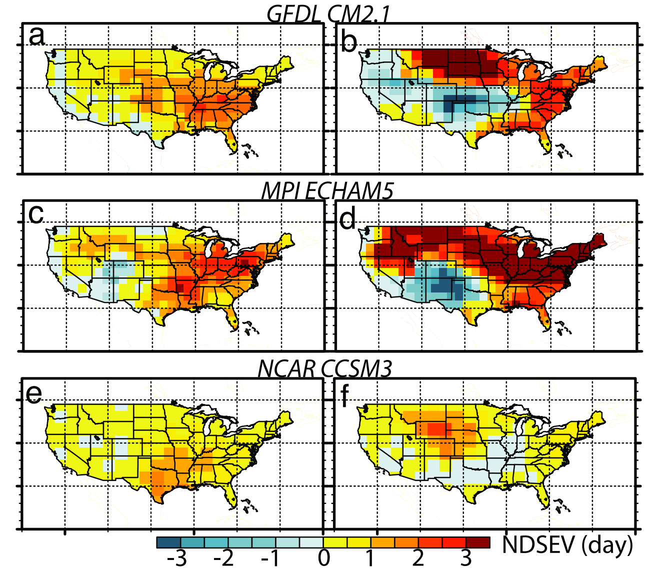

Fig. 3. Difference in NDSEV for the MAM the JJA seasons, respectively, from the following GCM integrations: (*a* and *b*) GFDL CM2.1, A2 (2042–2069) − 20th century (1972–1999); (*c* and *d*) MPI ECHAM5, A1B (2070–2089) − 20th century (1960–1979); and (*e* and *f*) NCAR CCSM3, A1B (2078–2098) − 20th century (1978–1998).

change is consistent with theoretical predictions, as is the decrease of shear. Because severe thunderstorms have been thought to occur most readily when CAPE and vertical wind shear both are large in a local environment, a possible outcome from increased CAPE and decreased shear is the predominance of less organized, generally nonsevere thunderstorms. However, when jointly evaluated, the increase in CAPE more than compensates for the decrease in shear such that the environment would still be considered favorable for severe convection. The result is a net increase in NDSEV, the number of days on which meteorological conditions would support the formation of severe thunderstorms.

It is emphasized that the extent of this change varies regionally and seasonally. In particular, the largest future increases in CAPE and therefore NDSEV occur during JJA, throughout the densely populated regions of the southern and eastern United States; analogous regional variations also are shown in calculations of CAPE and NDSEV made by using the results of GCM experiments. Identified model biases obscure the details of the projected number of severe days, with regional reanalysis data suggesting significant model underestimates. Nonetheless, in terms of percentage changes in NDSEV in the late 21st century relative to present, our analysis suggests the possibility of an increase of up to 100% or more in locations such as Atlanta, GA, and New York, NY.

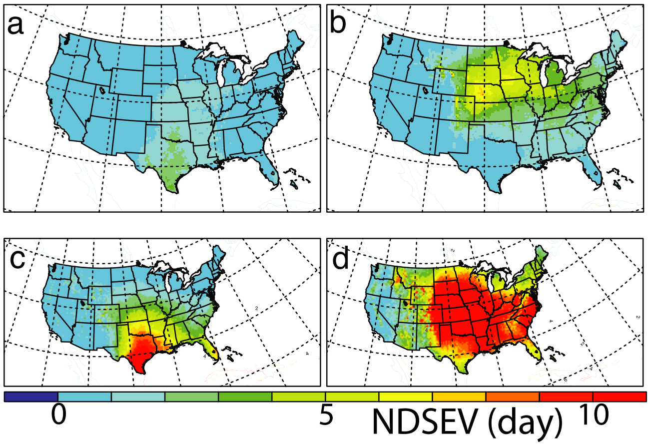

Fig. 4. Mean NDSEV for the MAM and JJA seasons, respectively, from analysis of output from the RF integration over the period 1980–1989 (*a* and *b*) and analysis of the North American Regional Reanalysis (NARR) data over the same period (*c* and *d*).

These results are based largely on one emissions scenario. A range of global emissions pathways is still possible (19), and reduced emissions could in turn reduce the increases in severe thunderstorm environment occurrence projected here. It also is reiterated that we have quantified the frequency of meteorological conditions that are favorable for the generic category of severe thunderstorms. The frequency of actual storms is conditional upon convective clouds initiating in these environments and then realizing the potential for severe thunderstorms implied by the product of CAPE and shear (20). An implicit assumption is that the mechanisms responsible for such initiation will not undergo significant future changes; some such mechanisms involve orography, and others are intimately tied to the large-scale dynamics that also provides the generative setting for the CAPE and shear. A complementary study in progress is examining the implications of these potential limitations by considering the climate statistics of convective storms that are explicitly simulated within an evolving large-scale atmosphere (21).

Methods

We used the simulations of United States regional climate performed by Diffenbaugh *et al.* (2) with the RegCM3 (22). With horizontal grid-point spacings of 25 km, these high-resolution climate simulations can account for much of the known regional variability in thunderstorm environmental conditions and accordingly should be better suited for this type of study than are typical GCM simulations.

The subdaily, 3D atmospheric data produced by RegCM3 were analyzed over two integration periods, 1962–1989 (RF) and 2072–2099 (A2). The National Aeronautics and Space Administration (NASA) Finite Volume General Circulation Model (FV-GCM) (23) provided the atmospheric boundary conditions for both of these RegCM3 integrations. During the RF period, the imposed, time-varying atmospheric CO_2 followed that given by Schlesinger and Malyshev (24), whereas during the A2 period, the imposed CO_2 followed the Special Report on Emissions Scenarios A2 scenario (19). Sea surface temperatures (SSTs) for the RF FV-GCM and RegCM3 simulations were taken from the observational data set of Rayner *et al.* (25). SSTs for the FV-GCM and RegCM3 A2 simulations were calculated in response to the elevated GHG concentrations, as described in Coppola and Giorgi (26).

The two quantitative measures of CAPE and S06 were computed at each model grid point, for each day during the RF and A2 periods, using the RegCM3 output at 00 UTC. For the domain of consideration, this 6-hourly output time represents the typical time of maximum CAPE. This finding was confirmed with CAPE computations using the 18 UTC output.

A third parameter (NDSEV) then was introduced to quantify the number of days on which potentially significant surface winds, hail, and/or tornadoes could occur locally (in the vicinity of a model grid point) if thunderstorms develop. NDSEV was incremented at a model grid point when, on a given day:

$$\mathrm{S06} \times \mathrm{CAPE} \geq 10{,}000. \tag{2}$$

The threshold was derived from the Brooks *et al.* (5) "best discriminator" between environments of significant severe thunderstorms and those of all other thunderstorms. In practice, Eq. **2** was applied only after some initial criteria are satisfied: CAPE $\geq$ 100 J·kg^{-1}, $|\vec{V}_6| \geq |\vec{V}_0|$, and S06 $\geq$ 5 m·s^{-1}.

The preceding calculations also were made using integrations of three GCMs: GFDL CM2.1 (27, 28), MPI ECHAM5 (29–31), and NCAR CCSM3 (32). The members of this limited ensemble were chosen based on the availability of the subdaily, 3D atmospheric data necessary to perform the CAPE, S06, and NDSEV calculations. For GFDL CM2.1, we analyzed the "H2" member of the 20th century (1972–1999) coupled atmosphere–ocean GCM (AOGCM) ensemble simulation and the "W1" member of the A2 (2042–2069) AOGCM ensemble simulation. For MPI ECHAM5, we analyzed one member of the 20th century (1960–1979) and A1B (2070–2089) AOGCM simulations. For NCAR CCSM3, we analyzed "time-slice" integrations created by running the atmospheric component of CCSM3 (at T42 resolution) with SSTs prescribed from the "e" member of the CCSM3 20th century (1978–1998) and A1B (2078–2098) AOGCM ensemble simulations [as described in Diffenbaugh *et al*. (17)].

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