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Supplementary Materials for

Projected increase in lightning strikes in the United States due to global warming

David M. Romps,* Jacob T. Seeley, David Vollaro, John Molinari

*Corresponding author. E-mail: romps@berkeley.edu

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Supplementary Materials

DAVID M. ROMPS[1] AND JACOB T. SEELEY

Department of Earth and Planetary Science, University of California, Berkeley and the Earth Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, California

DAVID VOLLARO AND JOHN MOLINARI

Department of Atmospheric and Environmental Sciences, University at Albany State University of New York, Albany, New York

1 Methods for 2011 observations

To assess the "CAPE times precipitation" proxy for lightning, three different data sources are needed: high-vertical-resolution radiosonde data (to accurately calculate CAPE), hourly precipitation data (to provide a precipitation rate contemporaneous with the radiosonde releases), and the location and timing of lightning flashes throughout the contiguous U.S. With the three such data sets that were available for this analysis, they overlapped only during the year 2011. Those three data sets are as follows:

- CAPE is calculated directly from the radiosonde data archived by the Stratosphere-troposphere Processes And their Role in Climate (SPARC) project, which is part of the World Climate Research Programme (WCRP). For 2011, the SPARC project has the High Vertical Resolution Radiosonde Data (HVRRD), which stores the thermodynamic profiles at 1-second intervals for radiosonde releases at 0 and 12 Greenwich Mean Time (GMT) from 68 weather stations in the CONUS. For each radiosonde release, CAPE and the level of neutral buoyancy (LNB) is calculated for the adiabatic ascent of an air parcel taken from a height of 50 meters above the surface. As the parcel is lifted to different pressures, its temperature, vapor mass fraction, and condensate loading are obtained using a root solver and an expression for equivalent potential temperature that accounts for the latent heat of fusion and the parcel's varying heat capacity [1]. The maps of CAPE and LNB are interpolated over the CONUS at a 0.5-degree resolution using a bicubic interpolation, and any negative values of CAPE or LNB that result from this procedure are set to zero. The upper-left panel of Fig. 1 shows the mean distribution of CAPE during 2011. The time series shown in Fig. 2 of the CONUS-mean CAPE at 0 and 12 GMT is obtained by spatially averaging these maps.

- Precipitation rates are obtained from hourly, gridded maps of precipitation that are

[1] *Corresponding author address:* David M. Romps, Department of Earth and Planetary Science, 377 McCone Hall, University of California, Berkeley, CA 94720. *E-mail:* romps@berkeley.edu

archived by the National Weather Service (NWS) River Forecast Centers (RFCs), which are part of the National Oceanic and Atmospheric Administration (NOAA). These maps represent a best estimate of the precipitation rate over the CONUS, using a combination of radar and rain-gauge data [2]. The data set contains a map of accumulated precipitation over the CONUS for each hour in 2011 at a resolution of 0.02-0.04 degrees. These hourly maps are then averaged down to a coarser grid of 0.5 degrees in both latitude and longitude, and then maps of mean precipitation rate at 0 and 12 GMT are generated by averaging the four maps centered on each time (e.g., the map at 12 GMT is the mean precipitation rate during 10 GMT to 14 GMT). The mean precipitation rate for 2011 is shown in the upper-right panel of Fig. 1. In this year, no gridded data is available for the western United States, so this region is excluded from the CONUS mean of precipitation. Since the vast majority of precipitation, high CAPE reports, and cloud-to-ground (CG) lightning flashes are to the east of the Rockies, the effect of this omission should be negligible. The time series shown in Fig. 2 of the CONUS-mean precipitation rate at 0 and 12 GMT is obtained by spatially averaging each four-hour map.

- Lightning flashes are obtained from the National Lightning Detection Network (NLDN; [3, 4]), which is a ground-based collection of sensors that detect CG lightning flashes throughout the CONUS. For each flash, the data provide the time (to the nearest second) and location (to the nearest thousandth of a degree in longitude and latitude). Over the CONUS, the detection efficiency of cloud-to-ground flashes is in the range of 90–95% [5]. The data have been filtered down to only cloud-to-ground flashes by removing all positive flashes with a peak current below 15 kA, which validation campaigns have found to be a good discriminator [5]. At 0 and 12 GMT throughout the year 2011, the flashes that occur within a four-hour window centered on the respective time (e.g., for 12 GMT, all the flashes occurring between 10 and 14 GMT) are binned onto a 0.5-degree grid. The lower-right panel of Fig. 1 shows the density of lightning flashes for the year 2011 obtained by averaging these maps. A similar result is obtained by averaging the CG flash rate during the same times (i.e., 22-02 GMT and 10-14 GMT) over the years 2004 to 2008. Since these times sample the minimum and maximum of the diurnal cycle in lightning flash rate over the CONUS (see Fig. 2 of [6]), the lower-right panel of Fig. 1 also broadly resembles the distribution of flashes in the full diurnal and annual mean (Fig. 1 of [6]). The time series shown in Fig. 2 of the CONUS-mean CG flash rate at 0 and 12 GMT is obtained by spatially averaging each four-hour map.

2 Methods for future climate simulations

To calculate the fractional changes in CAPE and precipitation that may accompany 21st century global warming over the contiguous United States, we use GCM data from Phase 5 of the Coupled Model Intercomparison Project (CMIP5), which archives climate model output from a wide range of institutions running a common set of standardized experiments [7]. The years 1996–2005 of the CMIP5 "historical" experiment are used to represent the current climate, while the years 2079–2088 of the "RCP8.5" experiment are used to represent the late-21st century climate.

Calculating CAPE for the weather in a GCM requires access to snapshots of the simulated atmospheric state; daily averages of the thermodynamic quantities that determine convective instability are wholly insufficient for resolving the diurnal cycle of CAPE and deep convection in the United States. At the time of writing, the CMIP5 archive contains the necessary sub-daily 3D snapshots of temperature and humidity for the eleven GCMs listed in Table 1. Since SPARC radiosondes are released at 0 and 12 GMT, we calculate CAPE for the ensemble of GCMs at these two times for each day of the historical and late-21st century time periods. Precipitation data are available in CMIP5 at daily-mean frequency, so we interpolate these data to twelve-hourly resolution.

Maps of annual- and ensemble-mean CAPE and precipitation for the years 1996–2005 are shown in the left column of Fig. S1. The climatologies bear a strong resemblance to the spatial pattern of CAPE and precipitation observed by the SPARC radiosonde network and NWS River Forecast Centers (RFCs) for the year 2011 (Fig. 1), which builds confidence that these climate models are useful tools for predicting changes in CAPE and precipitation in the 21st century. The right column of Fig. S1 shows the ensemble-mean changes in CAPE and precipitation, calculated as the annual mean for the historical period subtracted from the annual mean for the late-21st century RCP8.5 period. The stippling in the right column's plots indicates the statistical significance of inferred trends: if the ensemble mean change at that gridpoint exceeds one (two) standard deviations of the ensemble noise at that gridpoint, a black (gray) dot is displayed.

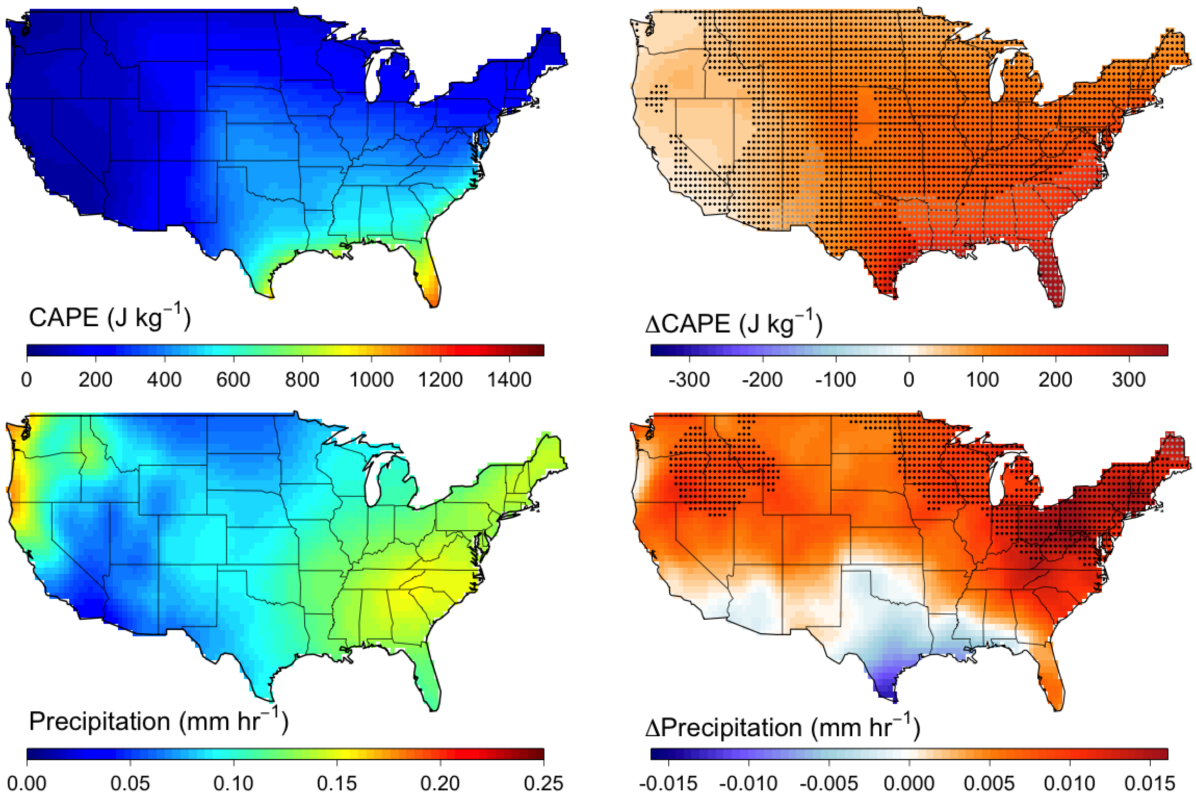

Figure S1: (left column) Maps of annual-mean CAPE and precipitation over the CONUS during the period 1996–2005, from the ensemble of eleven CMIP5 GCMs listed in Table 1. (right column) Late-21st century changes in CAPE and precipitation from this GCM ensemble. Changes are calculated as the difference between the mean for the period 2079–2088 of the RCP8.5 experiment and the mean for the period 1996–2005 of the historical experiment. The robustness of modeled changes is indicated with stippling—black (gray) dots indicate the ensemble mean response exceeds one (two) standard deviations of the ensemble noise. All GCM data are interpolated onto a common 0.5-degree horizontal grid.

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