Climate, Extreme Heat, and Electricity Demand in California

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ABSTRACT

Over the twenty-first century, the frequency of extreme-heat events for major cities in heavily air conditioned California is projected to increase rapidly. Extreme heat is defined here as the temperature threshold for the 90th-percentile excedence probability (T90) of the local warmest summer days under the current climate. Climate projections from three atmosphere–ocean general circulation models, with a range of low to midhigh temperature sensitivity forced by the Special Report on Emission Scenarios higher, middle, and lower emission scenarios, indicate that these increases in temperature extremes and variance are projected to exceed the rate of increase in mean temperature. Overall, projected increases in extreme heat under the higher A1fi emission scenario by 2070–99 tend to be 20%–30% higher than those projected under the lower B1 emission scenario. Increases range from approximately 2 times the present-day number of days for inland California cities (e.g., Sacramento and Fresno), up to 4 times for previously temperate coastal cities (e.g., Los Angeles and San Diego), implying that present-day "heat wave" conditions may dominate summer months—and patterns of electricity demand—in the future. When the projected extreme heat and observed relationships between high temperature and electricity demand for California are mapped onto current availability, maintaining technology and population constant for demand-side calculations, a potential for electricity deficits as high as 17% during T90 peak electricity demand periods is found. Similar increases in extreme-heat days are likely for other southwestern U.S. urban locations, as well as for large cities in developing nations with rapidly increasing electricity demands. In light of the electricity response to recent extreme-heat events, such as the July 2006 heat waves in California, Missouri, and New York, these results suggest that future increases in peak electricity demand will challenge current transmission and supply methods as well as future planned supply capacities when population and income growth are taken into account.

1. Introduction

Since 1980, U.S. electricity demand has increased by more than 75%, with the largest increases in the residential and commercial sectors for space heating and cooling. As the southwestern United States becomes more populated, and as extreme-heat days become more frequent, electricity demand in these areas will continue to rise. The energy infrastructure, the refinery capacity, and the electricity line transmission system in the United States have not adequately kept up with peak demand, and electricity supply shortfalls have resulted. Electricity generation and transmission deregulation have compounded these problems as remote transmission and energy gaming have pushed electricity

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flow up to and beyond the capacity limit, often resulting in electricity supply failure. This has already occurred during extreme summer heat events over the last several years, most notably in the summer of 2003, when a system failure resulted in the largest blackout in U.S. history, leaving as many as 50 million people without power for several days.

In addition to increasing electricity demand, significant increases in the frequency, intensity, and duration of summertime extreme-heat days are also projected to result from climate change (Alley et al. 2007; Hayhoe et al. 2004; Tebaldi et al. 2006; Miller and Hayhoe 2006). The observed correlation between daily mean near-surface air temperature (Ta) and peak electricity demand during heat extremes suggests the potential for significant temperature-driven increases in future electricity demand for air conditioning across a variety of locations (Belzer et al. 1996; Amato et al. 2005; Mendelsohn and Neumann 1999; Rosenthal and Gruenspecht 1995; Henley and Peirson 1998; Cartalis et al. 2001; Valor et al. 2001). Although this would be expected in the heavily air-conditioned South, such increases may also occur in northern cities. For example, Colombo et al. (1999) analyzed the frequency of extreme heat and electricity demand for nine Canadian cities using the current climate and a warmer climate based on a doubling of atmospheric greenhouse gas concentrations. Their study suggested that a 3°C increase in the daily maximum temperature would lead to a 7% increase in the standard deviation of current peak energy demand for these cities during the summer.

California is one of the world's largest economies and is a world leader in energy efficiency and demand-side management practices. Electricity demand per capita statewide has remained essentially flat since the late 1970s, partially as a result of energy efficiency incentives. However, California's aggregate energy demand is growing rapidly, spurred by the rapid expansion of population (over 36 million), especially in the warm Central Valley region, and an overall increase in the use of air conditioners. The upward trend in aggregate peak demand in California is expected to approach or exceed 67 GW in 2016, which is an increase of 1.35% per year since 2000 (CEC 2004). The anticipated population growth underlying these forecasts over the same period is 1.30% (CEC 2005), indicating that demand growth is expected to slightly outpace population growth. These assumptions can be translated into an approximate annual growth of per capita demand of 0.05%. During warm summer days in California, the use of air conditioning and other cooling appliances increases electricity load linearly with higher temperatures (CEC 2004; Bartholomew et al. 2002). In 2004, 30% of California's peak electricity demand was due to residential and commercial air-conditioning use alone (CEC 2004).

Extreme-heat days during recent summers in California have triggered energy alerts with brownouts and blackouts. Electricity transmission lines and related infrastructure, along with the restructured energy market, place limits on current expansion of the flow of electricity supply during peak demand periods and these limits are not expected to be rectified in the near term (CEC 2004). During the recent July 2006 heat wave, the warmest year to date since California weather records began in 1895 (NOAA 2006), California minimum temperatures were 8°–15°F (4.4°–8.3°C) above average. Los Angeles experienced 20 consecutive days at or above 100°F (38°C), and Sacramento experienced 11 consecutive days at or above 110°F (43°C). During this heat wave, there was an all-time single-day record electricity demand of 50.3 GW, and several regions within California were without power from hours to days because of infrastructure failures for a variety of reasons, including the fact that some transformers in northern California were unable to cool properly and caught fire.

One indicator of increased "peakiness" of the electric system is the load factor, which measures the relationship between annual peak demand (GW) and consumption (GW h). If peak demand grows more quickly than the aggregate consumption, then the load factor decreases, highlighting the likelihood of the types of conditions leading to brownouts or even blackouts. CEC (2005) shows that load factors adjusted for weather have decreased in recent years in California—a fact that is primarily blamed on the increased use of air conditioners.

California's electricity supply reliability problems in periods during which demand exceeds the available generating and/or transmitting capacity have already resulted in industries moving out of California to regions with a more dependable supply of electricity. In the future, this issue is likely to continue to plague California, the southwestern United States, and other heavily air conditioned regions in which electricity shortfalls occur.

World demand for energy is approximately equivalent to a continuous power consumption of 13×10^{12} W (i.e., 13 TW). With aggressive conservation and energy efficiency, an expected global population of 9 billion accompanied by rapid technology growth is projected to more than double energy demand to 30 TW by 2050 and to more than triple it to 46 TW by 2099 (GAO 2005). The same Government Accounting Office report (GAO 2005) concludes that, because of the consumer choices of high consumption, all major fuel sources face environmental, economic, or other constraints or tradeoffs in meeting projected demand. Energy shortfalls are already occurring in the Chinese economy and other emerging economies for which the economic expansion has led to a surge in the adoption of household appliances, including air conditioners. If our economies continue on a high-energy-consumption trajectory into the future, projected temperature increases over the coming century may further strain energy providers, resulting in electricity shortages and negative health and economic impacts. Clear and consistent policy is therefore needed to guide energy markets, suppliers, and consumers in the face of both developing economies and incipient warming caused by human-induced climate change.

Here, we describe the details of our approach to determining historical and projected extreme-heat frequency, intensity, and duration; cooling degree-days; and electricity demand for California. We then follow with a discussion of the results, an evaluation of a potential adaptation strategy, and, last, the conclusions.

2. Approach

To quantify the impacts of extreme-heat days on peak electricity demand, we define extreme-heat days as the warmest June–September (JJAS) days for the historical reference period 1961–90 that exceed the 90% probability of the summertime daily maximum temperatures for a given location, and refer to this quantity as the T90 value for each city. We then calculate the number of projected future JJAS days with maximum temperatures at or above the historical T90 values. T90 values are an important metric used in California energy capacity analyses and are often described as the 1-in-10 JJAS high-temperature days.

In addition to the T90 values, we also calculate standardized JJAS cooling degree-days (CDD) as defined by the National Climatic Data Center (NCDC; Owenby et al. 2006). The standard formula for calculating CDD is CDD = (Ta − Tac) × days, where Ta is the daily-mean near-surface air temperature, Tac is an average daily-mean temperature threshold for human thermal comfort, or "balance temperature," and "days" is the number of days with temperatures that exceed Tac. Tac is commonly set to a value between 65° and 75°F (Glickman 2000; MRCC 2007); here, we use the most common threshold of 65°F (18°C).

The intensity of extreme-heat days is simply the difference between Ta and Tac, but it can be further broken down into daytime (maximum) and nighttime (minimum) temperature intensities by region. Humidity also plays a role in the human thermal comfort threshold; however, California is very dry during the summer, and therefore this is not a significant factor for this region.

In our analysis of projected changes in extreme heat, we implicitly account for technology and population change through atmosphere–ocean general circulation model (AOGCM) simulations forced by the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emission Scenarios (SRES; Nakicenovic et al. 2000). The SRES scenarios include a range of population increases and accompanying technological and societal changes estimated at the national scale. However, in the calculation of California's regional energy demand we hold the state's technology and population constant at today's levels to quantify the range of possible outcomes as a perturbation about the historical demand. This perturbation approach has been used in previous impact assessment studies (e.g. USGCRP 2000) and provides a constrained estimate of potential outcomes that can be extrapolated using a range of projected changes in population and technology applied to demand. In our discussion, we explore the possibility of such extrapolated scenarios, although technological advancement is difficult to project beyond about a 10-yr timeline because of the large uncertainties pertaining to the rate of discovery, evaluation, and social adaptation of new technologies (Jaffe et al. 2003).

Similar to previous assessments of temperature and extreme-heat increases for California (e.g., Hayhoe et al. 2004; Cayan et al. 2006), we use three AOGCMs: the U.S. Department of Energy–National Center for Atmospheric Research Parallel Climate Model (PCM; Washington et al. 2000), the National Oceanic and Atmospheric Administration/Geophysical Fluid Dynamics Laboratory (NOAA/GFDL) Climate Model, version 2.1 (CM2.1; Delworth et al. 2006), and the Met Office (UKMO) Third Hadley Centre Coupled Ocean–Atmosphere GCM (HadCM3; Pope et al. 2000). As illustrated by Fig. 1, use of three AOGCMs captures a significant percent of the range of scientific uncertainty inherent to future projections of temperature increases in response to human emissions. PCM lies at the lower end, and GFDL and HadCM3 fall at the middle to higher end of the full IPCC best estimate range of 1.8°–4.0°C by the end of the twenty-first century for a doubling of atmospheric carbon dioxide (CO_2) concentrations (Alley et al. 2007).

As also illustrated in Fig. 1, socioeconomic uncertainty is addressed through use of AOGCM simulations driven by a range of potential future emissions from human activities. Here, the three AOGCMs are forced by the IPCC SRES higher (A1fi; fossil intensive, with rapid technological and economic growth), midhigh

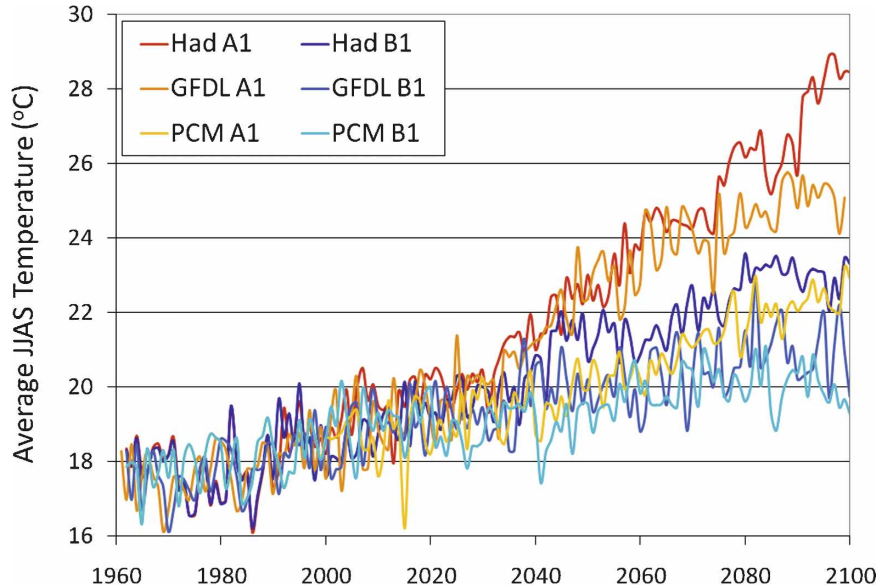

FIG. 1. Projected average summer (JJAS) temperature increases for California under the SRES higher (A1fi), midhigh (A2), and lower (B1) emissions scenarios, as simulated by the HadCM3, GFDL CM2.1, and PCM models. Temperature changes are larger under the higher emission scenarios as compared with the lower ones and for the higher-sensitivity models (HadCM3 and GFDL CM2.1) as compared with the lower-sensitivity model (PCM).

(A2; a heterogeneous world, with regionally oriented development and slower growth), and lower (B1; a convergent world that makes a rapid transition to an information-based rather than a material-based economy) emission scenarios, for the period 2000 to 2099. These IPCC SRES scenarios represent the range of nonintervention emissions futures, with projected 2100 atmospheric CO_2 concentrations ranging from 550 ppm at the lower end to almost 1000 ppm at the higher end.

For each of the nine model/scenario combinations used here, projected California-wide temperature increases were first calculated directly from the AOGCM output (Fig. 1). This coarse-resolution approach tends to cause a slight cool bias because of the proportion of grid cells near ocean waters and mountainous regions. For that reason, we therefore downscaled maximum and minimum daily temperatures to the individual city level using historical model simulations and the long-term daily weather station records from the NCDC daily surface dataset (NCDC 2007).

Statistical downscaling through regression is a common approach that has been well documented in the literature (Wigley et al. 1990; Wilby et al. 1998; Huth 1999; Wilby et al. 2002; Wilby and Dawson 2004). Statistical downscaling procedures have the advantage of being computationally efficient, but because they rely on historical relationships between large-scale climate fields and local variables, partial stationarity over time must be assumed.

For this analysis of temperature extremes, we used a deterministic method to downscale daily maximum, average, and minimum temperatures, as presented in Dettinger et al. (2004). Gridcell values of temperature from the reference period 1976 to 1990 were first rescaled by simple monthly regression relations to ensure that the overall probability distributions of the simulated daily values closely approximated the observed probability distributions at selected long-term weather stations located in five urban centers within the state: San Francisco, Los Angeles, Sacramento, Fresno, and San Bernardino/Riverside. Observed daily maximum, average, and minimum temperatures for each of the five weather stations for the period from 1976 to 1990 were used to train a set of third-order regression equations to transform the large-scale temperature values from the AOGCM simulations into local-scale daily maximum temperatures, preserving the distribution of the observed mean and variance. The resulting model was then verified on the 1961–75 period, with the downscaled time series having a near-exact fit to observations. The ability of this method to reproduce successfully the observed daily temperature distributions is illustrated in Fig. 2, which provides a comparison between the observed and statistically downscaled distributions of maximum daily temperature for Sacramento and Los Angeles. Although the modeled distributions tend to be somewhat smoother than the observed ones, in general the GFDL- and PCM-based

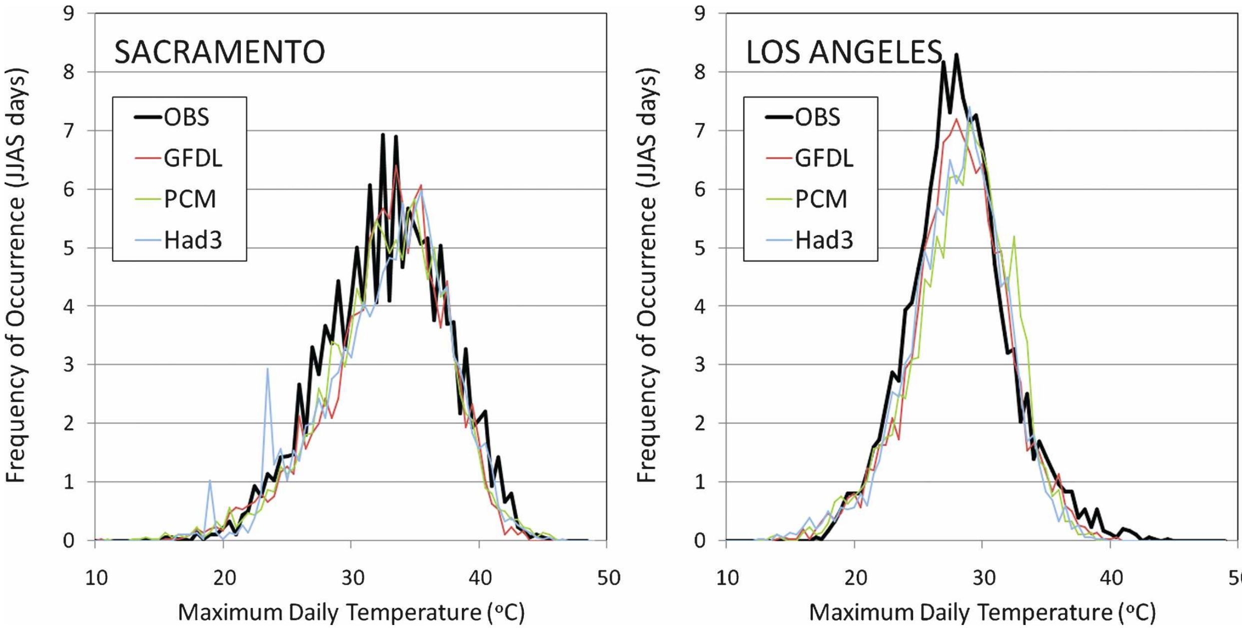

FIG. 2. Comparison of observed and statistically downscaled daily summer (JJAS) temperature distributions for (left) Sacramento and (right) Los Angeles. The statistically downscaled Tmax distribution, binned at 0.5°C intervals, is shown in units of average number of days per year for the period 1961–90. In comparison with the observed distribution, model-simulated distributions tend to show less variance. For Sacramento, the observed standard deviation is 1.94 (range = 6.9), and modeled values are 1.86 (6.4), 1.79 (5.8), and 1.76 (6.0) for GFDL, PCM, and HadCM3, respectively. For Los Angeles, the observed standard deviation is 2.30 (range = 8.3), and modeled values are 2.09 (7.2), 2.05 (7.1), and 2.06 (7.4) for GFDL, PCM, and HadCM3, respectively.

simulations capture a distribution very similar to that observed, whereas HadCM3-based simulations tend to show a slightly broader distribution.

The same regression relations were then applied to future simulations, such that rescaled values shared the weather statistics observed at the five stations. At the daily scales addressed by this method, the need to extrapolate beyond the range of the historically observed parts of the probability distributions was rare even in the future simulations (typically <1% of the future days) because most of the climate changes involve more frequent warm days than actual truly warmer-than-ever-observed days (Dettinger et al. 2004).

Future projections were then averaged for three time periods (2005–34, 2035–64, and 2070–99) to produce climatological near-term, midterm, and long-term projections of daily maximum, average, and minimum temperatures for California on which to base estimates of future shifts in the timing and magnitude of electricity demand.

3. Results

To determine the likely impacts of climate change on temperature extremes and electricity demand under higher and lower emissions scenarios, we calculated projected increases in average daily temperature, the number of future days likely to exceed the historical T90 threshold, and average JJAS CDD values. These projections were then used as the basis for determining changes in statewide and urban demand for electricity for cooling, under assumptions of present-day population and technology. Last, we extrapolated the impacts of upper- and lower-bound population growth and technology advances in California to estimate the likely future range of peak electricity demand and the potential to mitigate the impact of temperature on electricity shortages through adaptation.

a. Projected increases in T90 events

During the historical reference period (1961–90), by definition T90 events occur an average of just over 12 times per year, making up 10% of JJAS days. After deriving state- and city-specific thresholds for defining a T90 event from the historical record (see Table 1 for T90 threshold temperatures), as described earlier, we then evaluate the number of days on which maximum temperatures are projected to exceed this threshold in the future, both at the state level and for the five urban centers examined here.

As temperatures rise, both at the state and city level, we find that the historical T90 threshold will be ex-

TABLE 1. T90 threshold values (°C, determined such that an average of 12 days per year exceed the T90 threshold during the period 1961–90) and projected increased number of days exceeding the 1961–90 T90 threshold for near-term (2005–34), midcentury (2035–64), and end-of-century (2070–99) periods. Values shown are the range given by HadCM3, GFDL, and PCM model simulations for the SRES A1fi (higher), A2 (midhigh), and B1 (lower) emissions scenarios.

	T90 threshold (°C) 1961–90	Scenario	No. of days exceeding T90 threshold 2005–34	2035–64	2070–99
Statewide	35	A1fi	19–34	32–66	69–88
		A2	18–30	29–47	53–76
		B1	21–26	27–39	39–52
San Francisco	27	A1fi	20	32–46	70–94
		A2	13–28	20–48	40–91
		B1	17–23	23–35	37–49
Los Angeles	33	A1fi	24	34–50	63–93
		A2	16–24	23–48	39–98
		B1	19–24	27–36	38–45
Sacramento	38	A1fi	20	33–46	70–78
		A2	15–36	25–49	47–89
		B1	17–23	26–42	40–52
San Bernardino	40	A1fi	21–23	31–46	63–78
		A2	13–27	20–46	36–87
		B1	20–27	26–36	36–45
Fresno	40	A1fi	19–21	33–45	69–75
		A2	15–35	25–51	46–93
		B1	16–27	26–42	40–52

ceeded more frequently. Moreover, T90 events are expected to be more intense (i.e., hotter), to last longer, and to occur earlier in the season relative to the 1961–90 reference period.

For California as a whole, with a T90 threshold of 35°C, the total number of T90 days is projected to *double* relative to a historical mean of 12 days per summer to an average of 23–24 days per summer as early as 2005–34, regardless of the emissions scenario followed. By midcentury (2035–64), we see 27–39 days (B1), 29–47 days (A2), and 32–66 days (A1fi) exceeding the T90 threshold. By the end of the century (2070–99), the statewide number of JJAS T90 days are projected to increase to an average of 4 times (B1), 5.5 times (A2), and 6.5 times (A1fi) the historical average (Table 1; Fig. 3).

T90 threshold values for the urban locations vary from a low of 27°C for San Francisco up to 40°C for Fresno and San Bernardino (Table 1). Using city-specific T90 threshold values, similar increases in the number of JJAS T90 days are projected for the five urban locations (Table 1). By 2005–34, in most cities the number of days also doubles relative to the historic reference period. By the end of the century, there are projected to be 3.5–4 times as many T90 days under B1, 5.5–6 times as many T90 days under A2, and 6–7 times as many T90 days under the higher A1fi scenario, depending on the city.

As for the statewide projections, increases for individual urban areas are proportionally larger under the higher emissions scenarios (A1fi and A2) relative to the lower B1. Furthermore, coastal cities (Los Angeles and San Francisco) are projected to see changes of more than 90 T90 days by the end of the century under the A1fi and A2 scenarios, as compared with slightly lower projections of 70–80 T90 days per year for inland areas.

b. Projected increases in CDD values

Statewide, annual CDD values based on an 18°C (65°F) mean temperature threshold average 400°–500°C days per year for the period 1961–90. For California as a whole, average CDD values are projected to increase to 600°–1000°C days by midcentury. By the end of the century, the difference between emissions scenarios becomes clear, with CDD values for California ranging from 650° to 1000°C days under the lower B1 scenario up to 800°–1250° and 1000°–1500°C days under the higher A2 and A1fi scenarios, respectively. These increases are from double (B1) to triple (A2 and A1fi) the historical values.

Perhaps even more relevant to electricity supply is the average CDD value during a T90 event, when the electric power demand peaks. California currently has a CDD value of approximately 20°C days per day during summer heat episodes. For each degree above the base comfort per day (°C days), an additional amount of energy will be required for cooling.

By midcentury, the seasonal average CDD values for

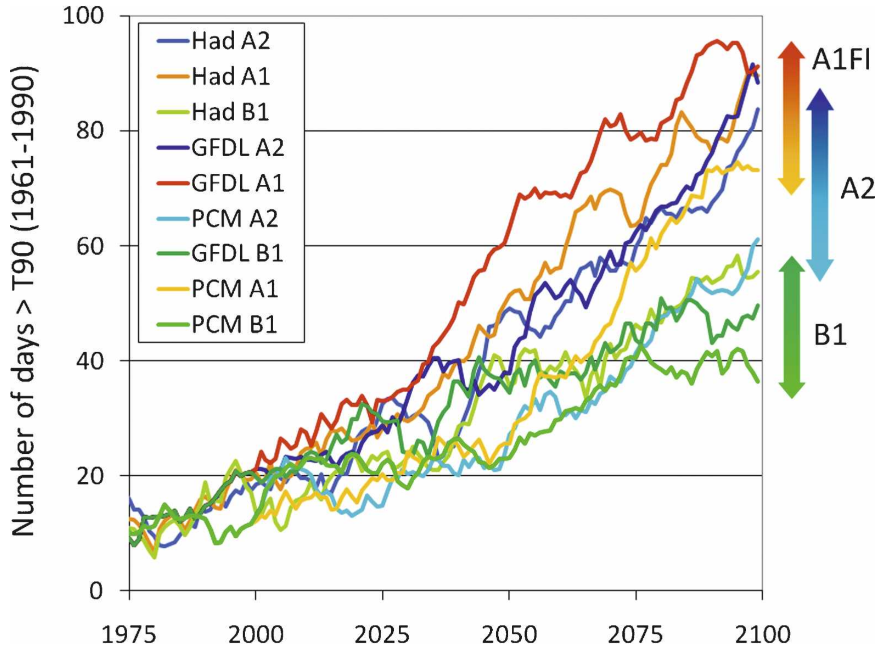

FIG. 3. California-wide projected average number of JJAS T90 days per year from 1975 to 2100. Year-to-year variations have been smoothed using a 10-yr running mean to show long-term trends. Projected values are shown for the HadCM3, GFDL, and PCM models. Shaded arrows indicate the end-of-century range for simulations corresponding to the SRES A1fi (higher; red/orange), A2 (midhigh; blue), and B1 (lower; green) emission scenarios.

T90 days alone is projected to increase from the historical average of 20°C days per day up to approximately 100°C days per day. By the end of the century, daily CDD values during T90 events exceed 150°C days under most scenarios (Fig. 4). Together, the impact of projected increases in T90-day frequencies and duration (with more such events occurring closer together or even consecutively) act to enhance daily average CDD values as well as JJAS totals, likely increasing peak electricity demand.

At the urban scale, similar increases in CDD values are seen for the five cities examined here (Table 2). Resolving individual urban centers also shows that there are significant inland and coastal differences in the T90 values and the corresponding CDD values, with projected increases being greatest in the southern and inland locations. Additional projected CDD increases for cities farther north and south (Crescent City and El Centro; not shown) confirm a north-to-south gradient of increasing T90 and CDD values. Also, in contrast to the T90 analysis, interscenario differences are more evident before the midcentury, with projected increases for 2035–64 ranging from 60°C days per year up to 90°C days per year under B1 and up to 150°C days per year under A1fi for the more northerly San Francisco. As the CDD values increase toward the end of the century, even greater increases are seen under the higher A1fi and A2 emission scenarios relative to the lower B1 emission scenario (Table 2). By the end of the century, the projected increase in CDD values under the A2 and A1fi scenarios range from 140°C days per year in San Francisco up to 750°C days per year in the south (Riverside/San Bernardino) and are 1.2–2.5 times that projected under B1.

c. Projected increase in electricity demand

Peak electricity demand and temperatures in California are strongly correlated. For temperatures above 28°C (82°F), California peak electricity demand exhibits a linear increase at a rate of 700 MW $°F^{-1}$ (DOE 2004; CEC 2002). In 2005, the 1-in-10 (T90) California JJAS peak electricity demand outlook was 61.8 GW, indicating an operating reserve of 3.3% (CEC 2005). Spot market imports are used to meet peak demand during periods of low resource margins. For statewide mean daily temperatures above 86°F, electricity demand capacity can be less than 5%, depending on resource outages and availability of imports, resulting in stage-II electricity emergency-response programs being put into effect. When only 3% of the reserve margin is available, a stage-III emergency alert is proclaimed, accompanied by rolling blackouts.

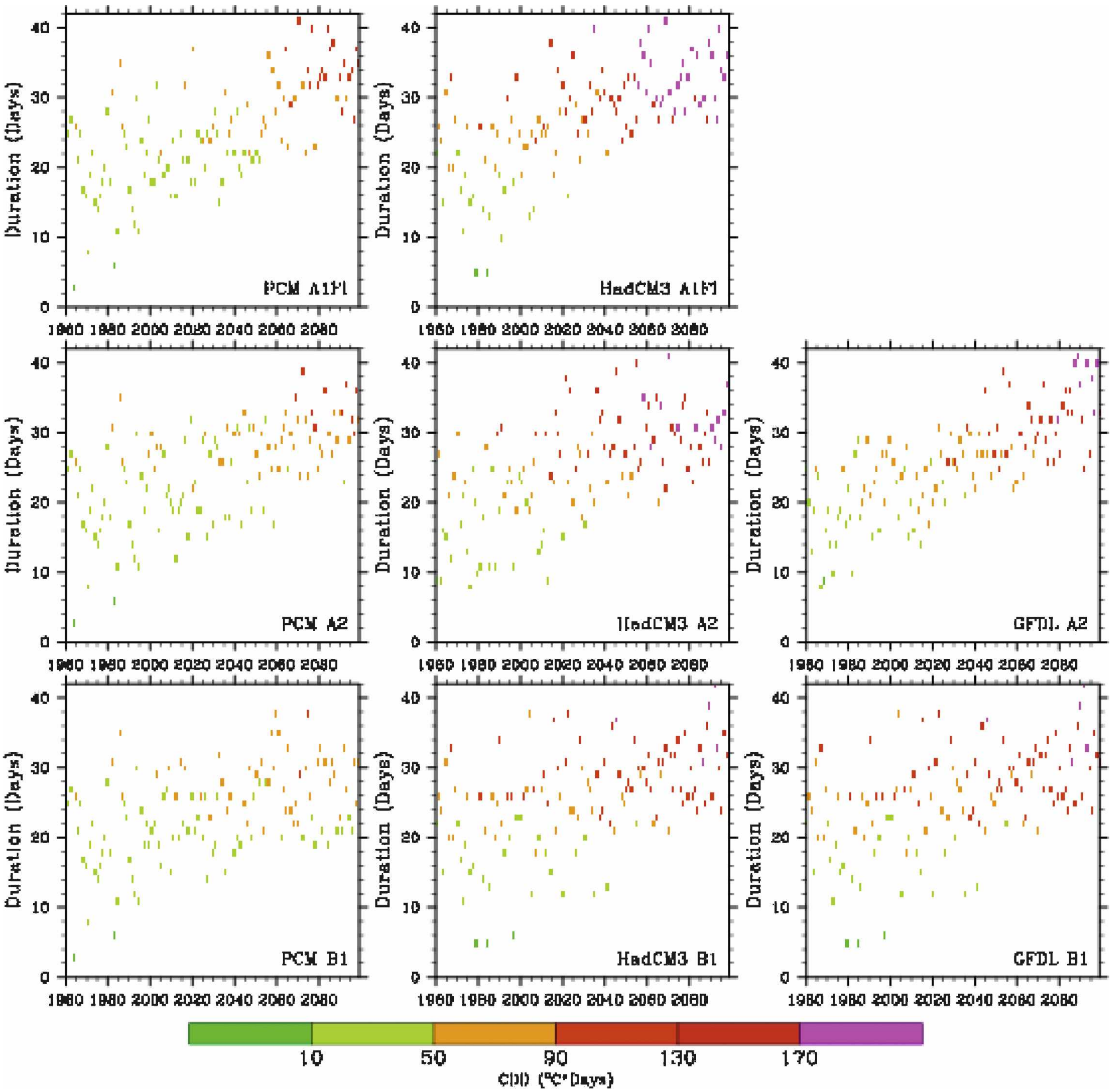

FIG. 4. California-wide duration and intensity for JJAS T90 events from 1960 to 2100 as simulated by the HadCM3, GFDL, and PCM models for the SRES A1fi (higher), A2 (midhigh), and B1 (lower) emission scenarios, as labeled. Note that GFDL A1fi simulations were not available at the time of calculation.

In our demand analysis, we hold the gross state product and aggregate population constant at today's level to isolate the effect of the increased frequency of extreme-heat days on peak electricity demand. Based on this approach, the increases in aggregate demand arise only from temperature-induced increases in the per capita rate of electricity consumption. CEC (2005) forecasts reflect a growth of aggregate peak electricity demand essentially matching population growth.

Using the above temperature–demand relationship, statewide JJAS peak electricity demand increases under all projections of future climate change, because of the increased frequency of days warmer than 28°C (82°F). Residential peak electricity demand at midcentury is projected to increase by 3.4%–10.0% under the A1fi and A2 scenarios and by 2.8%–7.7% under the B1 scenario.

Because these estimates are growth in energy demand due to heat events only and do not include popu-

TABLE 2. Historical (1961–90) simulated and projected future change in annual CDD relative to the historical average for five California cities, listed from low to high present-day CDD values. Values shown for the SRES A1fi (higher), A2 (midhigh), and B1 (lower) emission scenarios for the range simulated by downscaled projections from the HadCM3, GFDL2.1, and PCM models.

	1961–90 (absolute value)	2035–65			2070–99		
		A1fi	A2	B1	A1fi	A2	B1
San Francisco	60	+90–150	+90–100	+60–90	+260–340	+140–220	+110–150
Los Angeles	570	+190–340	+210–310	+150–200	+410–590	+260–550	+230–310
Sacramento	690	+310–400	+270–360	+220–280	+630–720	+310–630	+330–410
San Bernardino/Riverside	800	+250–430	+200–410	+190–270	+520–750	+240–750	+290–390
Fresno	900	+320–410	+200–370	+220–310	+640–730	+250–670	+340–410

lation and economic growth, we can compare these with anticipated growth rates in per capita demand by planners. The assumed 0.05% per capita annual growth rate assumed by the CEC (2004) is equivalent to an increase in peak demand for this period of 2.3% over 2000 levels. The difference between the simulated and anticipated peak demand of 0.5%–7.7% will have to be covered by expansion of installed capacity, electricity imports, demand-side management efforts, or strict conservation. By the end of the century, this demand will increase by 6.2%–19.2% under the A1fi and A2 scenarios and by 4.0%–11.2% under the B1 scenario. This would result in a difference ranging from 1.9% to 14.2% under these scenarios. Much of this increased peak demand is projected to occur simultaneously across the state because extreme-heat events are of a regional rather than local nature, raising concerns about the reliability and structural stability of the energy grid to supply the needs of all sectors and regions simultaneously, including industrial, residential, and emergency services.

Of course, it is not only the increased frequency of extreme-heat days that drives up peak demand. Economic growth of California's economy measured by increasing the gross state product is another main determinant of electricity demand. Although per capita electricity use in California has been flat since 1975 because of aggressive energy-efficiency programs, further technological advances will have to offset increases from both of these factors to grow electricity supply at the same rate as population growth.

4. Discussion

Projected increases in extreme temperatures characterized by a T90 threshold, cooling degree-days, and direct estimates of electricity demand all suggest that electricity demand in California is likely to continue to rise over this century even without considering likely population growth. Although California's installed electricity capacity will also continue to grow over time, its current rates of growth suggest summer electricity shortages may occur as early as 2020. This scenario is particularly likely for southern California, where the electricity operating reserve has already dropped below the 5% reserve margin during multiple hot days in recent years. By the end of this century, all model/scenario combinations indicate an increase in regionwide extreme temperature conditions of a severity associated with electricity shortages under the current configuration of the electric power system and patterns of demand.

Population estimates suggest a large influx along major transportation corridors in the California Central Valley, a region that is already very hot during the JJAS season, requiring air-conditioner use. If we were to impose a doubling and a quadrupling of the population within the Central Valley during this century, then the demand side will also increase proportionally and supply will consequently need to be doubled or quadrupled as well. As mentioned earlier, technological advancement is highly unpredictable; however, there is always the possibility of breakthroughs.

The natural conclusion arising from projections such as these is that electricity production must be significantly increased. However, in future years, meeting California's demand for electricity—including peak power—will most likely require a combination of new supplies, improved transmission and distribution facilities, and further enhancement of the demand-side policies and programs that are already in place. In particular, adaptation to future change through widespread adoption of conservation and passive-cooling strategies may have the potential to reduce significantly the projected increase in future electricity demand. By raising the average temperature threshold at which air conditioning is commonly turned on through adaptation strategies, such as the use of fans and flow-through ventilation, less electricity would be required for cooling under a given temperature regime. This is not unheard

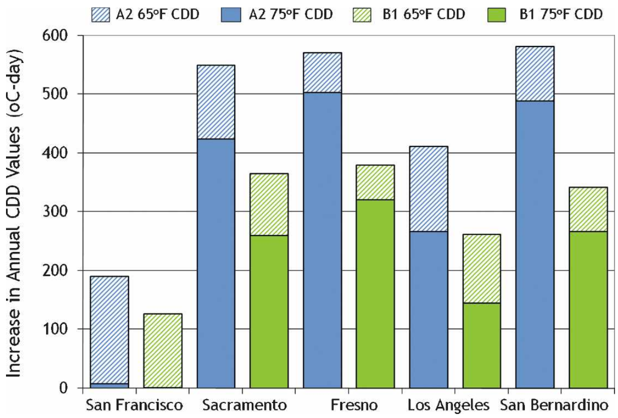

FIG. 5. Projected increase in annual CDD values for a 65°F (solid) vs a 75°F (hatched) average temperature threshold for 2070–99 relative to 1961–90. Results shown are the averaged projections from the HadCM3, GFDL, and PCM models for the SRES A2 (midhigh; gray) and B1 (lower; black) emission scenarios for five California cities. Comparison of the projected change based on a higher vs a lower threshold value for CDD calculation illustrates the adaptation potential for mitigating projected future energy demand, which appears to be greater for coastal cities (San Francisco and Los Angeles) and less for inland areas (Sacramento, Fresno, and San Bernardino).

of in California; during the 2000–01 electricity crises, Californians responded to an imposed electricity efficiency and demand program that resulted in a reduction of approximately 6000 MW, representing 10% of the peak demand (CEC 2004). During the summer of 2000, there were 29 days for which electricity demand exceeded 40 000 MW. Although the summer of 2001 was as hot as 2000, there was a substantial reduction in demand, with only 6 such days occurring. This reduction was due to a combination of price increases and voluntary reduction of electricity use.

Some measure of the adaptive potential for reducing projected increases in CDD and the subsequent rise in residential and commercial electricity demand can be obtained through comparing projected increases in CDD values calculated based on the standard 65°F threshold with CDD values calculated using a higher threshold of 75°F. Raising the CDD threshold by 10°F through more efficient cooling with fans and ventilation would greatly reduce the projected increase in CDD values and related electricity demand—in particular, for coastal cities (Fig. 5). Using this simplified assumption provides us with a sense of potential savings through adaptation. For San Francisco, raising the CDD threshold to 75°F would result in end-of-century CDD increases of less than 15°C day per year, effectively eliminating any increases in projected demand under both the A1fi/A2 and B1 scenarios. Figure 5 shows that Los Angeles has potential reductions of 40%–55% in projected CDD increases relative to the 65°F threshold while inland cities (San Bernardino, Sacramento, and Fresno) indicate an adaptive capacity ranging from 10% to 40%.

Considering that significantly higher CDD values and related electricity demand result from higher emission scenarios, as compared with lower emission scenarios, and that most affordable near-term options for increasing electricity supply via fossil fuels also involve simultaneous increases in greenhouse gas emissions, these estimates of adaptation potential have important implications for decision making at the city and state level.

5. Summary and conclusions

All indicators point to increases in summer electricity demand in California, even when confounding factors such as increased population and market saturation of air conditioning are disregarded. Through calculation of projected increases in extreme heat and electricity demand, we are able to quantify the difference in potential impacts resulting from lower and higher emissions scenarios. Model uncertainties notwithstanding, extreme heat and associated human health risks and electricity demands under the B1 lower emissions scenario are considerably lower than those projected to occur under the A2 and A1fi higher scenarios. Calculations of electricity demand under a range of human comfort levels also highlight the potential for adaptation to play a major role, reducing projected increases in electricity demand by roughly one-third for inland cities and by as much as 95% for cooler coastal cities.

In conclusion, the influence of climate change on extreme heat and electricity demand in California and other similar air-conditioned regions is likely to challenge current-day providers and to raise questions regarding the potential for mitigation to reduce projected increases through following a lower emissions pathway worldwide.

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