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Young Scientists Summer Program

Future scenario of residential hourly cooling energy demand in the United States.

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Program: Energy, Climate, Environment (ECE)
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This report represents the work completed by the author during the IIASA Young Scientists Summer Program (YSSP) with approval from the YSSP mentor.

It was finished by _____ September 30th, 2022__________ and has not been altered or revised since.

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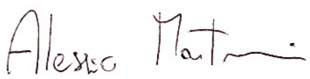

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Abstract

Despite improvements in building and appliance efficiencies, energy use for space cooling has tripled since 1990 and has become the fastest-growing energy service in buildings. Growing cooling demand pushes up electricity demand and creates additional stress on current cooling-related sectors, and will generate more greenhouse gas emissions. Reliable projections on high-resolution temperatures and cooling demand can provide valuable guidance for adaptive planning measures. This study aims to quantify the changes in hourly cooling energy demand with a focus on the U.S. residential sector, accounting for the impacts of warmer air temperatures and socio-economic change. The current report presents the first part of this research where we produced hourly temperature and cooling degree-hours profiles for the mid-century (2040-2050) under a medium scenario (SSP2-45). By comparing the future summer (June, July, August) cooling degree-hours to the historical values (1990-2000), we found a consistent increase in the future daily cumulative cooling degree-hours in the summer months, and the daily cumulative increases mainly resulted from the surge in the daily peak demand. In the future, the historical maxima of both cumulative demand and peak demand will be frequently exceeded, and this may pose enormous challenges for the current cooling-related sector. Our analysis, providing information on future hourly cooling demand, will help AC companies, utility companies, grid systems, and other related cooling sectors be well prepared for future warming and the associated massive cooling needs. Furthermore, the methods of producing future hourly temperature profiles can also be applied in other countries to improve our knowledge of the future cooling demand globally, and explore the potential of energy conservation measures and climate change adaptation responses on a larger scale.

About the author

Gesangyangji, from Tibet, China, is a Ph.D. candidate in the Nelson Institute Environment and Resources Program at the University of Wisconsin-Madison (UW-Madison). She holds an MS in Atmospheric and Oceanic Sciences and a Certificate in Energy Analysis and Policy from UW-Madison. Her research has focused on the impacts of climate change on building design and indoor heating and cooling energy demand. (Contact: gesangyangji@wisc.edu)

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1. Introduction

Space cooling is the fastest-growing component of energy demand in buildings (IEA, 2018). Electric power fans and air conditioning (AC) systems are commonly used to provide space cooling, and as such, the growth of cooling demand is contributing increasingly to the demand for electricity (Dell et al., 2014; McFarland et al., 2015).

Not just the overall power needs, the rising cooling demand also pushes up the generation and distribution capacity required to meet the peak demand (IEA, 2018), and therefore brings enormous strain on current power systems (Denholm et al., 2012). In addition, studies have shown that higher electricity use generates higher emissions (D. Abel et al., 2017; Isaac & van Vuuren, 2009; Meier et al., 2017) and increases the risk of adverse health impacts associated with poor air quality (D. W. Abel et al., 2018).

To slow down the rapid growth of cooling demand and associated impacts, actions must be taken on the demand and supply sides (IPCC, 2018; Mundaca et al., 2019). On the demand side, it is important to improve the efficiency of cooling systems, like AC, to curb energy demand growth (Chen et al., 2020; IEA, 2018). On the supply side, a widely discussed measure is the decarbonization of the electricity sector, from generators (IEA, 2022) to power systems (Denholm et al., 2012; Denholm & Hand, 2011).

Effective implementation of these measures requires a thorough understanding of cooling demand and its variation on multiple time scales (Denholm et al., 2012), especially on an hourly scale (Castillo et al., 2022; Haydt et al., 2011), because hourly cooling data provides an important guide in many of these measures. For instance, the cooling loads during peak hours are an essential threshold for properly sizing AC capacity (ASHRAE, 2013) to ensure system efficiency; hourly cooling demand also plays a key role in balancing the supply of VRE generations with the energy demand (Denholm & Hand, 2011; Haydt et al., 2011).

To understand changes in the cooling energy demand under future climate, scientists have been using climate and/or building energy models to project changes in future cooling demand (Dirks et al., 2015; Mastrucci et al., 2021; Shen, 2017; Spinoni et al., 2018; Wang & Chen, 2014; Xu et al., 2012; Zhou et al., 2014). However, few studies are on an hourly scale because of the limitations in related datasets. For example, climate models usually provide data on a daily or monthly scale (Semenov & Stratonovitch, 2010; Shen, 2017), and they are biased in the simulations of the diurnal cycle (Christopoulos & Schneider, 2021; Yin & Porporato, 2017), which affects temperature projections, a key climate variable for cooling demand calculation. On the other hand, behavioral patterns and other dynamics in buildings are underrepresented in building energy models at aa large scale.

The purpose of this research is to fill the gap in the literature and provide a thorough analysis of future hourly cooling demand. We first adjusted a climate data rescaling method (Gesangyangji et al., 2022) to produce future hourly temperature, which is then used to calculate cooling degree hours (CDH), a commonly used indicator that represents the impacts of climate on building cooling demand (ASHRAE, 2013; Shi et al., 2021). Then, CDH will be input through an IIASA-developed energy demand model (Mastrucci et al., 2021), where changes in socio-economic factors like population, building characteristics, and behaviours are also considered for a more realistic energy demand projection.

Our research focused on the United States (U.S.), where virtually all cooling needs are met by electricity (Dell et al., 2014; Zhou et al., 2014). Space cooling shares more than 10.6% of total building final energy use in the U.S., and more than 70% of peak residential electricity demand during extremely hot days (IEA, 2018). We aim to produce reliable projections on hourly cooling demand to support adaptive planning measures in sectors like electricity and AC companies, as well as cooling-related policymaking in the U.S.

This report will present the research we accomplished through the summer of 2022. In this part, we produced summer (June, July, and August) hourly temperatures and CDH over the U.S. for 2040-2050, under a medium pathway of future greenhouse gas emissions (SSP2-45) (O’neill et al., 2016). By comparing the future CDH with baseline CDH (1990-2000), we show how U.S. residential cooling demand will change on summer days and at peak hours.

2. Methods

A widely used method to study climate impacts on energy demand is degree-days (Petri & Caldeira, 2015; Ramon et al., 2020; Spinoni et al., 2018). This method tells the needs for space cooling or heating based on the differences between outdoor temperature and an internal base temperature, as given by equations (2.1) (CIBSE, 2006). However, degree-days are calculated from daily mean temperature ($\overline{\mathrm{T}}_{iday}$), so this method is not able to capture the daily variations in energy demand (figure 1). To preserve the daily variations, we used a cooling degree-hours (CDH) method (equations 2.2) that has a similar definition to cooling degree-days (CDD), except degree-hours is calculated from hourly temperature (T_{ihour}) and a base temperature.

$$\mathrm{CDD} = \sum_{iday=1}^{\mathrm{N}} (\overline{\mathrm{T}}_{iday} - \mathrm{T}_{base}) \quad (2.1)$$

$$\mathrm{CDH} = \sum_{ihour=1}^{\mathrm{N}} (\mathrm{T}_{ihour} - \mathrm{T}_{base}) \quad (2.2)$$

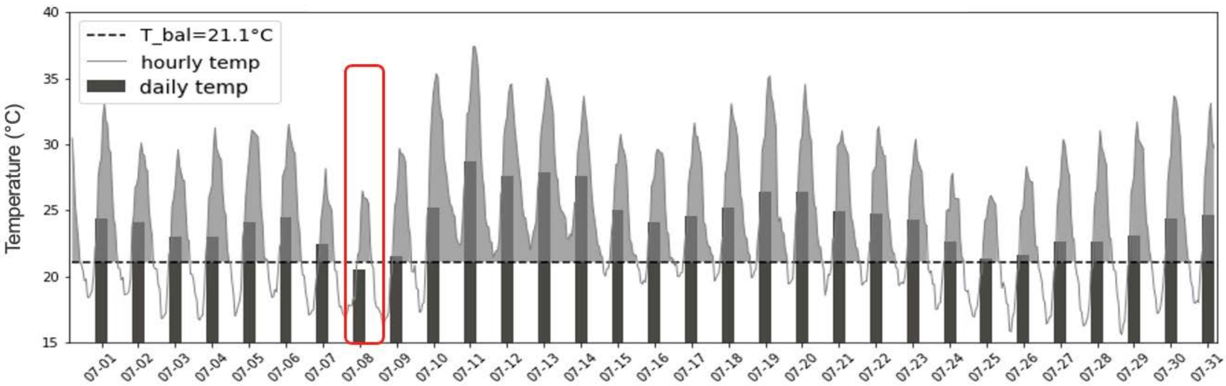

Figure 1. Illustration of differences in cooling degree-days and cooling degree-hours in Los Angeles, California, in July 1990. Bars: daily mean temperature; solid line: the hourly temperature; dashed line: base temperature. Bars above the dashed and the shaded parts are cooling degree-days and cooling degree-hours, respectively. On July 8th (red box circled), the cooling degree-hours method captures the cooling needs during hours in the afternoon, while the degree-days method indicates no cooling needed.

The calculation of CDH requires hourly temperatures, which are available for historical periods from different sources but are not available for future scenarios. To get hourly temperatures for the future scenario, we used the recalling method introduced in (Gesangyangji et al., 2022). The basic idea is to obtain a historical relationship between hourly temperatures and daily maximum and minimum temperatures (T_{max} and T_{min}) (equations 2.3), named hourly fractions (a_{ihour}, see examples in figure 2), and then apply these hourly fractions to projected Tmax and Tmin to produce future hourly temperature profiles on a daily basis (equations 2.4).

$$a_{ihour} = (T_{ihour} - Tmin_{iday})/(Tmax_{iday} - Tmin_{iday}) \quad (2.3)$$

$$T_{ihour} = a_{ihour} \times Tmax_{iday} + (1 - a_{ihour}) \times Tmin_{iday} \quad (2.4)$$

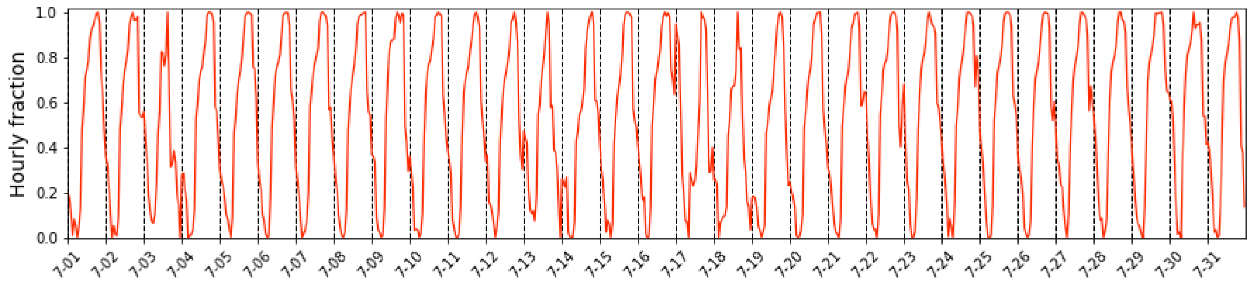

Figure 2. Time series of hourly fractions on a random location in July 1995. Hourly fractions on a day range from 0 to 1, where value 0 and 1 represent the daily minimum and maximum temperature, respectively.

We used historical hourly temperatures during 1990–2015 from the fifth-generation of ECMWF reanalysis ERA5 data and projected T_{max} and T_{min} during 2040–2050 from the NASA Earth Exchange (NEX) Global Daily Downscaled Projects (GDDP) (Bridget et al., 2022). Although NEX provides data from multiple global climate models, we used data downscaled from GFDL-ESM4. Figure 3 illustrates the process of producing future hourly temperatures. Historical hourly fractions are applied to future T_{max} and T_{min} based on a similar daily mean temperature (T_{mean}) (shown in the red boxes). We first created temperature bins (for every 1 °C) from the historical T_{mean} and then averaged corresponding hourly fractions to obtain a representative hourly fraction (RHF) for each bin. We merged the bins that have less than ten days with their nearest bin for the representativeness of the RHF. Afterward, we assigned the projected T_{mean} to each temperature bin, so that each of the future days would find an hourly fraction to produce hourly temperatures. For the future days where the projected T_{mean} exceeds the highest historical T_{mean}, we assigned the RHF of the warmest temperature bin.

Finally, with the hourly fractions and Tmax and Tmin for the given future day, we produced future hourly temperatures. The rescaling process in figure 3 was performed on each summer month and each grid cell (0.5 by 0.5) for entire U.S.

With the hourly temperatures, we calculated CDH (equation 2.2) on a base temperature of 21.1 °C (Mehregan et al., 2022). Summer months CDHs are compared between historical (1990-2000) and future scenario (2040-2050, SSP245) to present how U.S. cooling demand will changes by the mid-century.

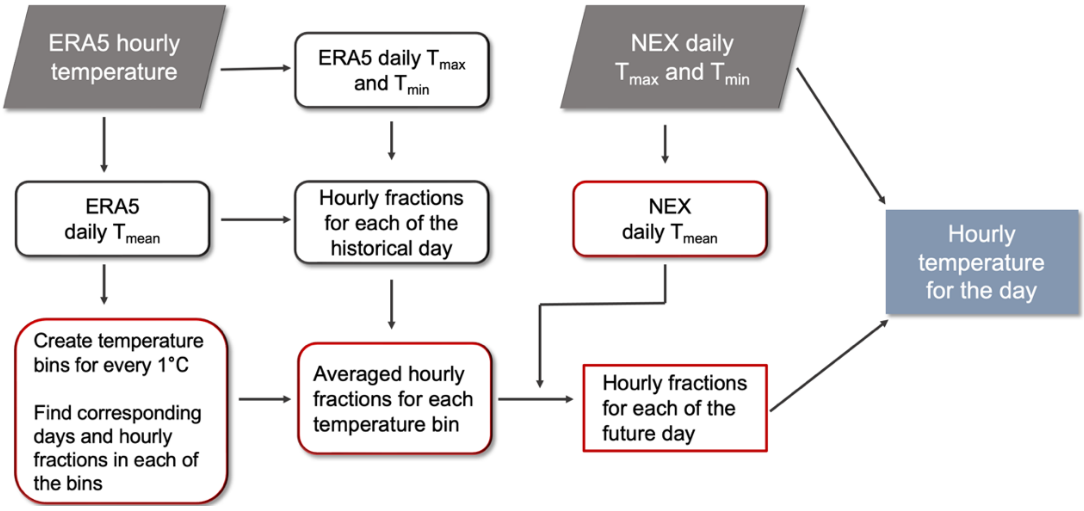

Figure 3. Schematic diagram of the method used to produce future hourly temperatures. Two grey boxes are the original dataset we used; black boxes indicate steps for producing historical hourly fractions using equation 2.3; red boxes indicate the steps for applying historical hourly fractions for future days.

3. Results

3.1 Cumulative cooling degree hours

Our first results show the changes in cumulative CDH (CCDH: sum of the CDHs for a given day), indicating the overall cooling demand on a summer day. Figure 4 presents the averaged CCDH over the U.S. for historical (blue bars) and future (orange bars) scenarios, and dashed lines are the monthly means. Overall, higher CCDH is projected for every single day of the summer months, with a more prominent increase in July and August (about 50%) than in June (around 30%). In the future, CCDH in about half of the days in June (late June) will exceed the historical maximum value, while future CCDH in July and August will far exceed the historical maxima. In addition, in June, monthly variations in CCDH will become larger as more increases are seen in late June than in early June. Increases in August CCDH also show monthly variations, more increase in early August than in late August, but not as significant as in June. CCDH and increases in CCDH in July are relatively flat, with monthly minimum variations.

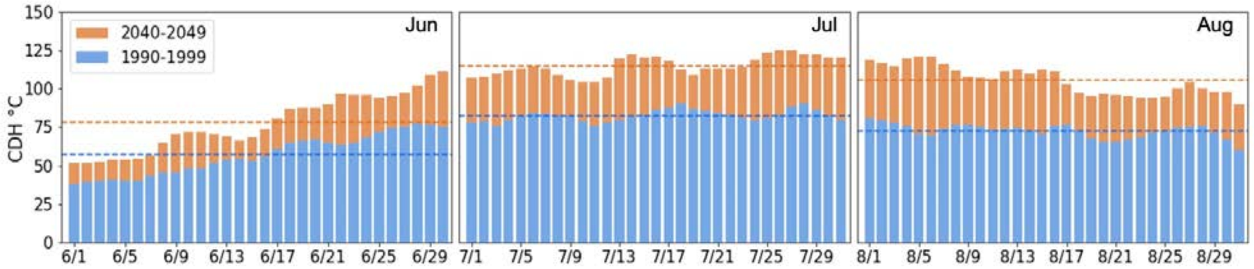

Figure 4. U.S. daily cumulative CDH for June (left), July (middle), and august (right). Blue bars: historical scenario; orange bars: future scenario. Dashed lines: monthly mean.

Figure 5 presents the spatial distribution of mean CCDH for June, July, and August. Three rows are for the historical and future scenarios, and their differences, respectively. From the top two panels, we see that the spatial pattern of CCDH will remain in the future, with larger demand required in the south than in the north. The maximum and minimum CCDH are seen in the southwest (border of southern California and Arizona) and the Rocky Mountain area, respectively.

Though the monthly CCDH shows a consistent pattern throughout the summer months, and the pattern will remain in the future, changes in CCDH (the bottom panel) show spatial and monthly variations. In general, higher CCDH is expected over most of the U.S. except the coastal area in California, where cooling demand will decrease because marine influences can overcome regional global-warming effects (Lebassi et al., 2010). Increases in the CCDH are more prominent in the central area than in the west and east. In June, the central Great Plains see more increases than the rest of the area, while in July, it will extend to the northern Great Plains and Midwest area. In August, CCDH will increase most in the south-central area, crossing through Texas, Oklahoma, and Kansas.

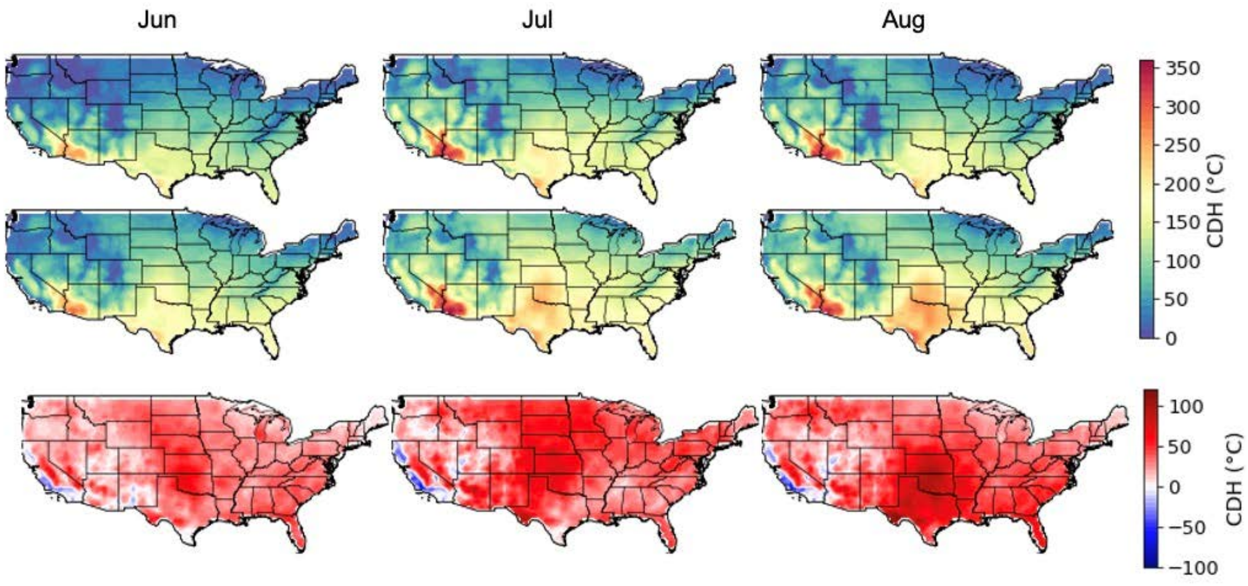

Figure 5. Spatial distribution of mean daily cumulative CDH in June (left), July (middle), and august (right), for historical scenario (first row), future scenario (second row), and their difference (bottom row).

3.2 Daily distribution of cooling degree hours

After noticing significant increases in CCDH on summer days, we want to know how these increases are distributed throughout a day. Figure 6 shows the historical (blue) and future (red) hourly CDH (averaged over the U.S.) in the summer months. In the U.S., we found that maximum and minimum cooling demand have occurred around 3 pm and 7 am, respectively, and this pattern will remain in the future. Diurnal cycle of CDH is relatively consistent through July and August but is divergent in June, especially at peak hours in June. The significant divergence at peak hours may be responsible for the notable monthly variations in cooling demand in June (Figure 4).

Moreover, summer cooling demand in the U.S. will expect larger intra-day variations. This is because although increases in CDH are seen throughout a day, most increases will occur at peak hours. Historical peak demand, occurring at a single peak hour, will become more frequent. In the half of the days in June, future CDH will exceed the historical maxima (7.1°C at 4 pm) for about 5 hours per day (1–6 pm). In July and August, the historical peak CDH (8 and 7.2 °C around 3–4 pm) will be far exceeded by future CDH from around 12 pm to 7 pm on each day. These additional demands, especially at peak hours would put a huge strain on the current grid systems.

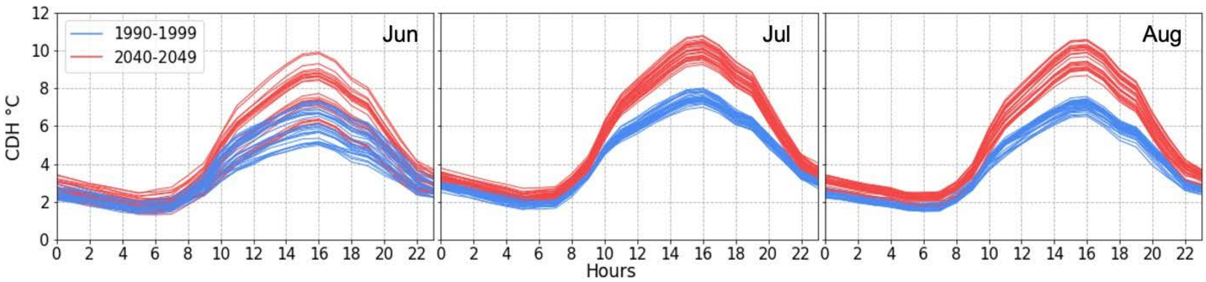

Figure 6. Daily distribution of CDH in June (left), July (middle), and august (right), for historical scenario (blue lines) and future scenario (red lines). Each line represents a day in the given month during the 10 years of the given scenarios.

3.3 Peak cooling degree hours

From the previous section, we learn that CDH would increase the most at peak hours. In this section, we show the spatial distribution of the peak CDH. Figure 7 presents the spatial distribution of peak CDH for June, July, and August. Three rows are for the historical and future scenarios, and their differences, respectively. The top two panels show that spatial patterns of future peak CDH will remain the same as the historical pattern: higher value in the south than in the north; maxima and minima over the southwest and Rocky Mountain area, respectively. Regarding the changes (the bottom), positive changes are seen in most U.S. except in the west coastal area, with relatively more increases in the central U.S.

In fact, the spatial pattern of peak CDH and its changes in the summer months are well consistent with the patterns of cumulative CDH (section 3.1). This indicates that the changes in overall cooling demand across the U.S. can be largely attributed to the changes in the peak demand. Such changes will pose a great problem to local cooling systems and electrical systems as many of these systems are sized and designed to handle present peak demand (ASHRAE, 2013). As future demand continues to surpass the historical peak value, the limits of systems will be frequently exceeded, and the capacity of systems will be challenged. Knowledge of the future hourly demand can deliver helpful information and guide on adaptation planning of these systems.

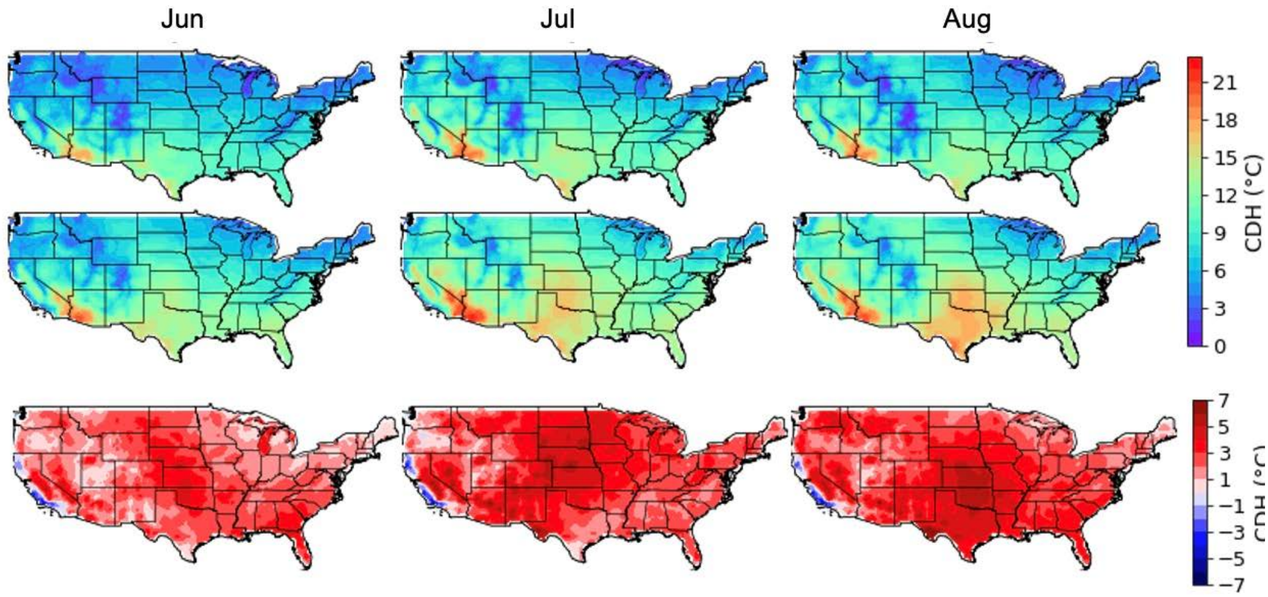

Figure 7. Spatial distribution of peak CDH in June (left), July (middle), and august (right), for historical scenario (first row), future scenario (second row), and their difference (bottom row).

Not only the changes in the amount of peak CDH, we also want to know if the peak demand will occur at the same hours. Although figure 6 shows that, in the U.S. as a whole, the peak cooling demand will occur around 3 pm, figure 8 indicates an irregular spatial heterogeneity in the time for peak demand. In general, peak cooling demand will occur around 2–3 pm over most central U.S., around 2–4 pm in the east, and around 2–5 pm in the west. In general, the spatial pattern is similar through the three months and does not show a significant difference between historical (top panel) and future scenarios (middle panel). The shifts of the peak hours at each location are given in the bottom panel of figure 8. For most of the area, peak cooling demand is projected to occur at the same hours. However, some areas in the Rocky Mountain and the Northeastern U.S. may expect the peak cooling demand to occur one or two hours earlier, while some areas in the Southeastern U.S. (and Northeastern in June) may have their peak demand delayed for one or two hours.

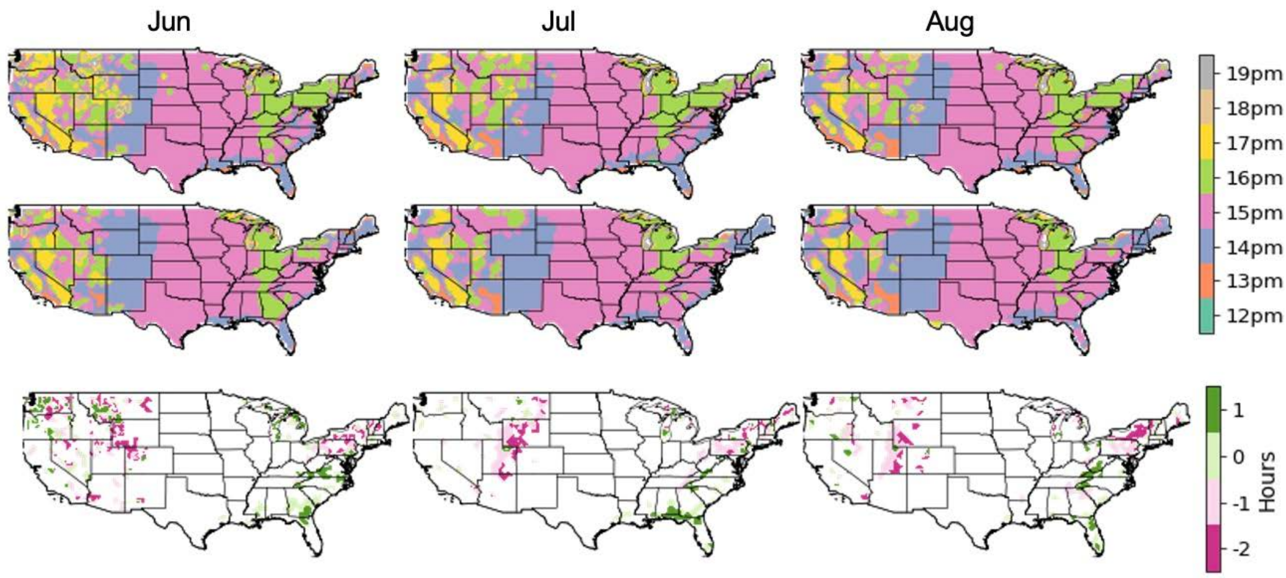

Figure 8. Top two panels: the peak hour for CDH in June (left), July (middle), and august (right) for the historical scenario (first row) and future scenario (second row). Bottom panel: time difference for historical and future peak demand occurrence. Positive: future peak demand will occur x hours later; negative: future peak demand will occur x hours earlier.

4. Discussion & Conclusion

To support adaptive planning measures and achieve our climate goals, this research aims to produce a reliable projection of future cooling demand by using climate projections and an energy demand model. The research is designed in two parts: 1) producing future hourly temperature and CDH profiles and 2) calculating actual energy demand by adding socio-economic components. This report presents the first part. We introduced a rescaling method to produce future hourly temperatures from daily climate projections and discussed changes in future CDH, an indicator representing the impacts of climate change (temperature change) on hourly cooling demand. We focus on the U.S. residential summer (June, July, August) cooling demand during 1990-2000 and 2040-2050 under a medium scenario (SSP2-45).

Key findings show a consistent increase in the U.S. daily cumulative CDH (CCDH) in the summer months. The historical maximum value of the month will be exceeded by future CCDH in late June and through the whole month of July and August. Spatially, more increases are expected in the central U.S. than in the west and east, but the spatial pattern of the CCDH will remain the same. Zooming into a day, we found the largest increase in CDH at the peak hour. Historical maximum CDH that occurs at a single hour of a day is projected to occur more frequently in the future, around 5 hours in days of late June and around 7 hours in days of July and August. The spatial pattern of peak CDH and their changes are well consistent with those of CCDH, which means that changes in the peak demand will dominate the changes in the overall demand. Most of the U.S. will expect their daily peak demand at the same hours, except around the Rocky Mountain and the Northeastern where peak hour may occur one to two hours earlier while some of the Southeastern area will have their peak hours occur one or two hours later.

In this context, our results showing that the increase in cooling demand is mainly attributed to the increase in peak demand, have a variety of implications for many U.S. cooling-related sectors. The historical peak demand being often breached and exceeded will become a great challenge to current cooling systems, like AC, because the system capacity is usually sized for the peak load from the past 25 years (ASHRAE, 2013). In addition, utility companies may need to provide more peaking power, or will use their peaking units more often, or will even have to build more peaking plants to meet the peak demand (Zhai & Helman, 2019). With projected high-resolution cooling demand, these sectors can be well prepared for the warming future. AC companies may consider upgrading system capacity to future peak demand to ensure cooling is efficiently provided under the warmer climate. Grid systems and utility companies can also develop adaptation plans for balancing peak demand to avoid blackouts when cooling is most needed. Grid systems may also use the information to improve grid flexibility for high penetration of VRE (Denholm & Hand, 2011).

Due to the time limits, we have not included the impacts of socio-economic factors here, yet our results show a thorough analysis of how temperature rising will affect the future hourly cooling demand. For the next step, we will incorporate factors like population, building characteristics, and behaviours to yield a more realistic projection of future hourly cooling energy demand.

By using datasets that are globally available, we also aim to make the rescaling method of producing hourly future temperatures applicable to the rest of the world for relevant studies and contribute to the achievement of energy conservation and climate goals.

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