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Tourism has been identified as a key economic sector vulnerable to climate change, yet direct empirical evidence is still lacking on the economic gain and loss of the tourism industry due to climate change. Here we find that temperature significantly affects the profits of the hotel industry with both spatial and seasonal heterogeneity. By using a rich dataset of the monthly financial records of more than 1700 hotels in 50 US states during 2016–2018 (approximately 3.2% of hotels nationally), we show that a deviation from 18 °C ~ 20 °C in monthly averaged temperature leads to a decrease in the profit rate. The effect is triggered by fewer customers, less revenue, and higher cost per occupied room partially due to the increased usage of electricity and water. Such an effect can be lasting and is less impactful for higher chain scale hotels. In future GHG emission scenarios, climate change will lead to a loss of profit in most climate zones particularly the southern regions, with higher GHG emissions leading to a more serious effect. This study contributes to the literature on how climate change affects human activities and helps refine the relevant damage function of climate change on tourism in existing climate models.

**Introduction**

The tourism and travel industry is a key sector of the global economy, accounting for 10.4% of GDP and supporting one-tenth of jobs [1]. Tourism boosts the economy not only by directly stimulating the consumption of accommodation, transportation, entertainment, food services, information, and insurance, but also by indirectly encouraging the investment in infrastructure, manufacturing, etc. Yet the tourism sector is sensitive and vulnerable to climate risks and can be drastically affected by global climate change [2, 3]. The change in thermal comfort, attraction of the landscape, and availability of certain activities (e.g. skiing) will lead to a redistribution of tourism resources both spatially and temporally. Such redistribution in turn causes

considerable and geographically heterogeneous effects on the business performance of tourism [4]. Such effect has been evaluated in simulation works at the global level [5] and at the country level [6], while studies also fit statistical models to explore how the historical climate change affects the flow of international travel [7, 8], consumers' choice of destination [9], and the local hedonic value of climate amenities [10]. Most studies report a decrease in the flow of the traveling population when the temperature becomes less comfortable, and document regionally different effects of climate change on the tourism sector. However, previous research predominantly adopts the national average temperature and in/outbound international travel flows, missing the details of the intra-national variation of climate and tourism resources nor providing an estimation of direct

financial indicators. Micro-level estimation of the economic gain and loss is still lacking on the supply side of the tourism industry. As a result, it is hard for hotel owners to evaluate their gains and losses directly due to climate change, and the cost and benefit in practicing adaptation strategies accordingly against the possible risks of climate change in the future.

Here we focus on a major sub-sector of tourism and travel, the hotel industry, and provide high spatial-temporal resolution micro-level empirical evidence on the effect of the changing climate on its business performance. We adopted a comprehensive dataset provided by the M3 Center for Hospitality Technology and Innovation that records monthly financial factors of 1752 hotels in the United States from 2016 January to 2018 December. The dataset records provide monthly averaged occupancy, room rate, and expenses and revenues by department, their chain scale, and location specified in zip code zones. We linked these data to meteorological observations from ground stations in the Global Surface Summary of the Day (GSOD) [11]. Climate factors including daily temperature, wind speed, and relative humidity are averaged and precipitation is aggregated to the month level.

We estimate the variation in profits as a response to climate change following several studies that use 1–3 years of short-term monthly or daily temperature fluctuations to examine the potential impact of climate change on human behaviors and electricity consumption [12, 13]. Since both the pre-existing literature and our descriptive statistics (figure S3 in the supplementary materials available online at [stacks.iop.org/ERL/14/084022/mmedia](https://stacks.iop.org/ERL/14/084022/mmedia)) show a thermal comfort zone deviating from which would lead to less outdoor human activities, we use a semi-parametric model to examine the effect of temperature as well as other climate factors (explained in detail in the Methods section). The panel data enables the control of various confounding factors such as time-invariant individual hotel characteristics and state-wide time-variant factors such as variation in seasonal demand for travel in different regions, and thus add to the validity of our estimations. In particular, our methods ensure that the estimated changes in hotel profits in response to temperature changes are not a result of seasonal differences in climate and travel demand of the same location, but reflect the actual effect of climate factor fluctuations, because we are essentially examining how temperature fluctuations within the same season affect hotels located in the same state through the state-season fixed effects. We also average hotel business records and the climate variables by month of year to include the extensive-margin adaptation behavior as suggested in previous studies [14, 15]. We further discuss the detailed channel of such change via occupancy, revenue, and cost, and detect the heterogeneous effect by the chain scale. Based on these results, we project the change in profit in different

future climate scenarios provided by the Coupled Model Intercomparison Project (CMIP) Phase 5 [16], and map its distribution to identify the losses and gains in various locations.

Our results provide the damage function of climate change on the business of the hotel industry at the micro-level for the first time. Although our sample does not cover all the lodging facilities in the United States (According to the estimation from American Hotel & Lodging Association, there are more than 54 200 hotels in the country, of which our sample accounts for about 3.2%), it is indeed diversified in the chain scale and location (figure S1) to reflect the heterogeneous effect of climate factors. The dataset contains hotels of those management companies that are clients of M3 Accounting and is thus not sampled from a nationally representative framework. However, as we compared the key performance characteristics of our sample with the monthly summary of a nationwide collection of hotels from a major market research firm, Smith Travel Research (STR), the two datasets show similar values and trends over time (figure S2). Therefore, our estimates indirectly reflect the responses of hotels in the United States to climate change. We also provide estimates by the chain scale and projections by climate zones to discern the possible heterogeneous effect of the climate so that the (at least rough) estimations can be immediately available if there are more detailed data on the composition of hotel population in the nation available. In this way, our findings can reliably represent the response of hotels in the United States to climate change, and can be referred to for regions characterized by similar climate and socio-economic context.

## Methods

### Linking the data of hotel financial performance and meteorological factors

The M3 hotel database and GSOD records are matched based on their spatial locations. Since the most detailed geo-identifier we have for the hotels is the zip code zone, we geocode each land station and match every hotel with all the stations within a buffer with radius 50 km. After the matching, almost all the buffers of the zip code zones covered at least one station. A map of the distribution of meteorological stations and the hotels are shown in figure S1. In this way, there could be measurement errors since the meteorological factors at the locations of climate stations may not accurately represent the climate of the locations of the matched hotels. Nevertheless, we argue such limitation is not a serious confounding factor for two reasons. First, the climate does not change at the localized level that we focus on. In fact, the variation in climate factors from stations matched with the same hotel is fairly small. Second, even though there might be a slight measurement error due to this

mismatch, such measurement error is likely to be a classical measurement error (random prediction error with a mean of zero) and it would only lead to an attenuation bias toward 0 and thus an underestimation of the effect of climate. Given the significance of our findings, we are at least providing conservative estimations.

### Identification with bins of climate factors

We construct our model following a series of studies documenting the effects of climate factors on human activities [12, 17–21] as:

$$\begin{aligned}
 y_{it} = & \sum_j \alpha_j \overline{TEMP}_{ijt} + \sum_k \beta_k \overline{PRCP}_{ikt} \\
 & + \sum_l \chi_l \overline{WDSP}_{ilt} + \sum_m \delta_m \overline{RHMD}_{imt} \\
 & + \eta_i + \pi_{sq} + \gamma_t + \varepsilon_{it}
 \end{aligned} \quad (1)$$

where  $i$  represents hotels, and  $t$  stands for months over the study period.  $y_{it}$  denotes the business indicator of a hotel. We focus on the monthly profit rate (the total revenue/total cost), and then examine the change of other indicators such as monthly average occupancy, revenue, and cost of the occupied rooms, etc.  $\overline{TEMP}_{ijt}$ ,  $\overline{PRCP}_{ikt}$ ,  $\overline{WDSP}_{ilt}$ , and  $\overline{RHMD}_{imt}$  are a set of dummies showing whether the average temperature, total precipitation, wind speed, and relative humidity falls into a particular interval coded by  $j$ ,  $k$ ,  $l$ , and  $m$  in a particular month of the year,  $t$ , respectively. We include a set of fixed effects to address the possible confounding effects and endogeneity issues because of missing variables.  $\eta_i$  indicate the hotel fixed effect which captures the effect of hotel characteristics such as scale, location, etc.  $\gamma_t$  is the year \* month fixed effect that controls for the temporal confounding effect from the common seasonal variation, macro socio-economic context, holidays, etc. Since the tourism resource in each season can be locally specific, we also include a state \* season fixed effect,  $\pi_{sq}$ , to capture such confounding effects and ensure that our estimation is not a result of seasonal climate differences in the same location, but reflect the actual effect of climate factor fluctuations.  $\varepsilon_{it}$  is the error term.

We balance the flexibility of the model with statistical precision to choose the bandwidth of the bins (2 °C for temperature, 0.5 m/s for the wind speed, 20 mm for the total precipitation, and 5 for the relative humidity). We select the most pleasant interval as the reference groups based on the literature and our visualization of the relationship between each meteorological factor and dependent variable in figure S3 which shows a reverse-U shaped curve for temperature peaking at 18 ~ 20 °C, approximating the most favored temperature of 65 °F in the United States identified in the previous literature [19]. Precipitation and wind speed show monotonic negative effects, and thus we select 0 ~ 20 mm and 0 ~ 1.5 m s<sup>-1</sup> as the reference groups, respectively. Humidity shows a

monotonic positive effect, and we select >80 as the reference group.

Equation (1) approximates climate conditions using its *realization in short-term weather variables*. Such approximation can be imperfect since there is randomness in the weather variables while the climate is more stable [14]. To exclude the possible interruption of such randomness deviating the weather from the general local climate, we average the records of hotels and the climate variables by month during the study period and conduct additional analysis with

$$\begin{aligned}
 y_{ip} = & \sum_j \alpha_j \overline{TEMP}_{ijp} + \sum_k \beta_k \overline{PRCP}_{ikp} \\
 & + \sum_l \chi_l \overline{WDSP}_{ilp} + \sum_m \delta_m \overline{RHMD}_{imp} \\
 & + \eta_i + \omega_p + \pi_{sq} + \varepsilon_{ip}
 \end{aligned} \quad (2)$$

where  $y_{ip}$  denotes the averaged business indicator of a hotel in month  $p$ , and  $\overline{TEMP}_{ij}$ ,  $\overline{PRCP}_{ik}$ ,  $\overline{WDSP}_{il}$ , and  $\overline{RHMD}_{im}$  are a set of dummies showing whether the average temperature, total precipitation, wind speed, and relative humidity by month falls into a particular interval coded by  $j$ ,  $k$ ,  $l$ , and  $m$ , respectively. The hotel fixed effect,  $\eta_i$ , month fixed effect,  $\omega_p$ , and the season \* state fixed effect,  $\pi_{sq}$ , are introduced.

Equations (1) and (2) are able to capture the short-term response of hotels but rules out the effect of their possible adaptive actions at a longer time scale. The medium- and long-term adaptation behaviors can take place in many ways. Individuals may reschedule their travel plans across months to avoid unpleasant weather, usually within a season. In the long term, technical advances will facilitate a lower cost of operation for hotels, e.g. higher energy efficiency can reduce the expense of electricity in extreme heat/cold days. The reallocation of climate resources may trigger new attractions (e.g. a warmer climate suitable for flower blossoming), and the room rates can eventually be adjusted to reflect the shadow price of such amenities while new business models in tourism can emerge for higher profits. Hotels can also choose to locate (for new lodging facilities) or relocate (for the existing facilities) to match the emerging demand of tourism. In this way, equations (1) and (2) capture the upper-bound effects of the climate change. To capture the change in the seasonality of travel, we rerun equation (2) but use seasonal averaged data. As for the long-term adaptation, inclusive estimates can be retrieved from cross-sectional regressions [15], in which the difference in profit across hotels is a result of their adoption of specific techniques, room rates, business models, locations, etc. We thus conduct such cross-sectional analysis by running equation (2) with  $\eta_i$  excluded. Despite that such strategy is likely to suffer from endogeneity issues raised by missing variables [22], we compare results from multiple identifications to examine if this is a serious issue that threatens the validity of our results.

### Spline regression model

We construct the spline regression model following previous works [13, 17] as:

$$y_{it} = \sum_j \beta_{1j} f_j(temp_{it}) + \beta_2 prcp_{it} + \beta_3 wdsp_{it} + \beta_4 rhmd_{it} + \eta_i + \pi_{sq} + \gamma_t + \varepsilon_{it}. \quad (3)$$

The  $temp_{it}$ ,  $prcp_{it}$ ,  $wdsp_{it}$ , and  $rhmd_{it}$  indicate the monthly average temperature, total precipitation, wind speed, and relative humidity, respectively. The functions  $f_j(\cdot)$  define the splines. The rest indicators are defined as in equation (1). Then we determine  $j$  (the number of splines) using 10-fold cross-validation. In the validation, we first pick the value of  $j$ . Next, the sampled hotels are split into 10 folds with 9 used for model training and the left 1 for testing. The process is rotated for each fold, and the mean of the mean-square error for each fold of the testing fold is then calculated as CV statistics [23]. We randomize the split of the sample with 1000 trials for different values of  $j$ . Finally, we pick the  $j$  with the lowest CV statistics as summarized in figure S4. To include the long-term adaptation behavior, we also conduct an analysis using the monthly average model and the cross-sectional model using a similar demean method as that used for the bin model.

### Climate projection

The projection is conducted using the CMIP Phase 5, 1 km grid climate data (available at <https://adaptwest.databasin.org/pages/adaptwest-climatena>). This dataset provides monthly averaged temperature and total precipitation in the RCP4.5 and RCP8.5 scenarios for the year of 2020 s (average of years 2011–2040), 2050 s (average of years 2041–2070), and 2080 s (average of years 2071–2100). We aggregate these climate factors to the zip code zone level by taking their average to match with our sample of hotels and plug them into our spline regression model to predict the monthly profit rate and in the future climate scenarios. The spline model specified by the monthly average data is adopted to both match the nature of the monthly average of the CMIP data and exclude the effect of annual randomness of the weather variables. We chose not to use the cross-sectional model since the long-term adaptation behaviors may not be extrapolated from the historical records, e.g. the technical progress and the adjustment of room rates can be non-linear. In this way, the projection depicts the upper-bound of changed profitability in the future climate scenarios.

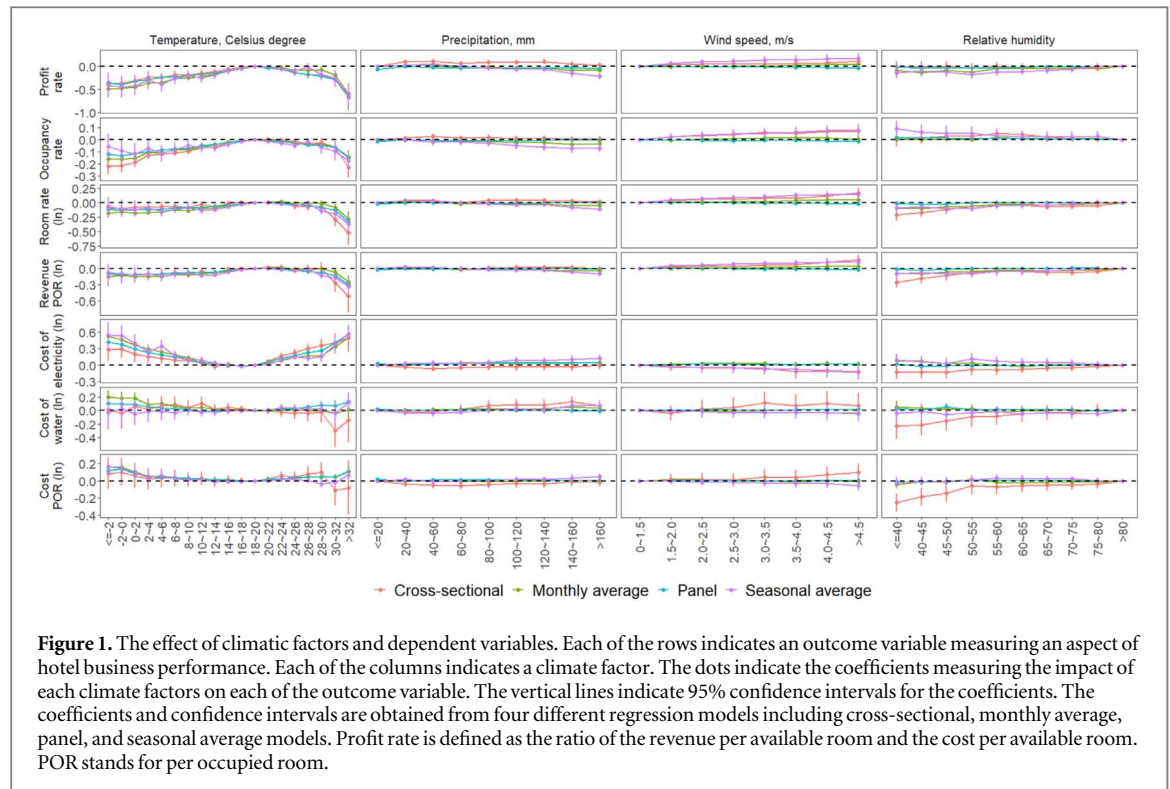
We summarize the results by the International Energy Conversation Code (IECC) Climate zones (The division is available at <https://basc.pnnl.gov/images/iecc-climate-zone-map>) as shown in figure 2. We further use our estimation to project how the gross profit per available room would change in all the zip code zones. To do so, we first retrieve the coefficients from the spline model to predict the monthly gross

profit per available room (GOPPAR) in both the RCP4.5 and RCP8.5 scenarios for the years 2020 s, 2050 s, and 2080 s. Then, we regard 2020 s as the reference year and calculate the difference between it and the results of 2050 s and 2080 s. Finally, the differences are summed to show the annual change in profit. The results are mapped in figure 3. Although our sample does not cover every zip code zone, these maps can still help to identify the most vulnerable areas that call for attention in decision making and business management plans.

## Results

### The effect of climate on the hotel business

Travelers usually plan their trips beforehand based on the weather forecast for destinations. As a result, their decisions can be affected by the forecast weather. Since the historical forecast data is unavailable, we use the actual current climate as a proxy given that the weather forecast predicts the actual climate with decent accuracy and likely random error. The regression results are displayed in figure 1 with the coefficients reported in table S2. The temperature shows a significant and non-monotonic effect on the profit rate. A temperature reading deviating from 18 ~ 20 °C results in significantly less profit (table S2, Column 1). Meanwhile, the marginal effect of turning hot and cold is different. For a mild deviation, a colder climate results in a greater loss of profit. A temperature reading between 16 °C and 18 °C decreases the profit rate by 4.8%, while the slippage is 3.2% for 20 ~ 22 °C. Given the average profit rate of 174.1%, this indicates a reduction to 169.3% and 171.9%, respectively. However, with more extreme temperatures such as above 26 °C, the increase in temperature starts to lead to a larger decrease in profit rate compared with colder readings of below 12 °C. This indicates that Americans would rather pay more on the margin to avoid excess heat than cold, consistent with findings from other studies [19]. Wind speed shows a significantly negative effect, indicating less profit in windier months. The effect is almost linear: the coefficients of all the bins are of similar magnitudes. Precipitation also demonstrates a negative effect, and heavier rain tends to reduce profitability: total monthly precipitation of 120 ~ 140 mm and >160 mm reduce the profit rate by twice and three times as much as the 40 ~ 60 mm, respectively. The relative humidity has a non-monotonic and small effect on profit. Compared with the reference group (relative humidity > 80), only a few bins show significantly less profit. Smaller humidity tends to benefit the occupancy. Overall, the magnitudes of the coefficients are small. These results approximate the observations in the previous study on how climate change alters human outdoor physical activity [17].



**Figure 1.** The effect of climatic factors and dependent variables. Each of the rows indicates an outcome variable measuring an aspect of hotel business performance. Each of the columns indicates a climate factor. The dots indicate the coefficients measuring the impact of each climate factors on each of the outcome variable. The vertical lines indicate 95% confidence intervals for the coefficients. The coefficients and confidence intervals are obtained from four different regression models including cross-sectional, monthly average, panel, and seasonal average models. Profit rate is defined as the ratio of the revenue per available room and the cost per available room. POR stands for per occupied room.

The monthly average, seasonal average, and cross-sectional regressions report similar results in tables S3–S5, respectively. The results based on monthly and seasonal average approximate the results based on panel data, except that the coefficients for  $20^{\circ}\text{C} \sim 22^{\circ}\text{C}$  become insignificant for almost all the dependent variables. In the cross-sectional regressions, profit rate and occupancy decrease toward extreme heat deviating from  $18^{\circ}\text{C} \sim 20^{\circ}\text{C}$ , while the consumption of electricity increases. The effect on room rate almost disappears except in bins above  $30^{\circ}\text{C}$ , while the cost per occupied room and water consumption are almost irresponsive. Overall, the magnitudes of the cross-sectional results approximate those of the panel regressions with a considerable overlap of the interval estimations as shown in figure 1, indicating mild missing variable issues.

It is possible that the businesses of neighboring hotels are affected by the same local factors (i.e. economic conditions). As a result, the error terms of the hotels at the same location are correlated. Ignoring such a correlation would lead to an over-estimation of t statistics. We address this issue by clustering the error term by zip code zone, city, and county to test if the significances still hold. Although such an effect may also exist for hotels matched with the same ground station, clustering the standard errors at the station level is not feasible since our observations of climate factors are organized at the hotel level as an average of the data obtained for several nearby ground stations. Nevertheless, clustering at other levels largely covers this effect. The results in tables S10–S18 show that all the statistical significances barely change.

Such profit loss can be explained by both revenue and cost channels. First, revenue may decrease due to reduced occupancy and income from each occupied room. The flow of visitors may decline when the weather becomes less comfortable, even if hotels lower room rates to attract customers. Table S2 examines these possibilities and shows that a less comfortable temperature or more precipitation reduces the occupancy of hotels (Column 2), while wind and humidity do not seem to have an effect. Such findings still hold even after accounting for room rate changes (Column 3), despite that hotels indeed reduce room rates in days with uncomfortable temperature or rain (Column 4). A lower willingness to pay thus leads to a further decrease in the revenue from each occupied room (Column 5). Meanwhile, the cost per occupied room may increase in unpleasant weather (Column 8). This is possibly a result of the lower occupancy which results in a larger proportion of the fixed expenses of running hotels per occupied room. The utility costs can also rise since customers may increase the usage of energy or water for cooling or heating in a less comfortable temperature, or stay in the hotel longer on rainy or windy days which further increases the energy use. These possibilities are verified by Column 6 (positive significance of higher/lower temperature, more precipitation, and stronger wind for electricity cost) and 7 (positive significance of higher/lower temperature for water cost) in table S2. Although utilities account for only a small proportion of the total cost (table S1) and thus may not be the main driver of the increased cost, these results indicate the adverse effects of unpleasant climate in terms of resource use. These results can also

be seen in figure 1. Profitability in the hotel industry is driven by location rents. In the long-term, deviations from the mean due to climate change might cancel out: revenues of the hotel industry might go down due to unpleasant climate but the costs might also go down when the location is experiencing lower economic growth. However, our cross-sectional analysis shows that the long-term deviations still cause a lower profit, possibly due to an uneven rate in the change of the revenue versus the cost side.

Past climate conditions may also play a role in affecting the performance of the accommodation facilities. Impressions on the past local climate affect individual beliefs and behaviors, e.g. people living in areas turning cold are more likely to doubt whether the earth is warming [24, 25], and individuals are capable of adjusting their expectation of and response to the future climate by learning from the past [26]. Therefore, the past climate may also affect the hotel business: unpleasant weather in the past may lead to a loss of visitors and lower room rates, and thus a reduction of revenue and profit. We display such an effect using the climate factors at the same time of the prior year in figure S5 with coefficients included in table S6, respectively. The climate factors of both the last month and the same month of the prior year show similar significance as the current climate but with smaller magnitudes. These results indicate that the individual decision to travel can be affected by the climate in the past.

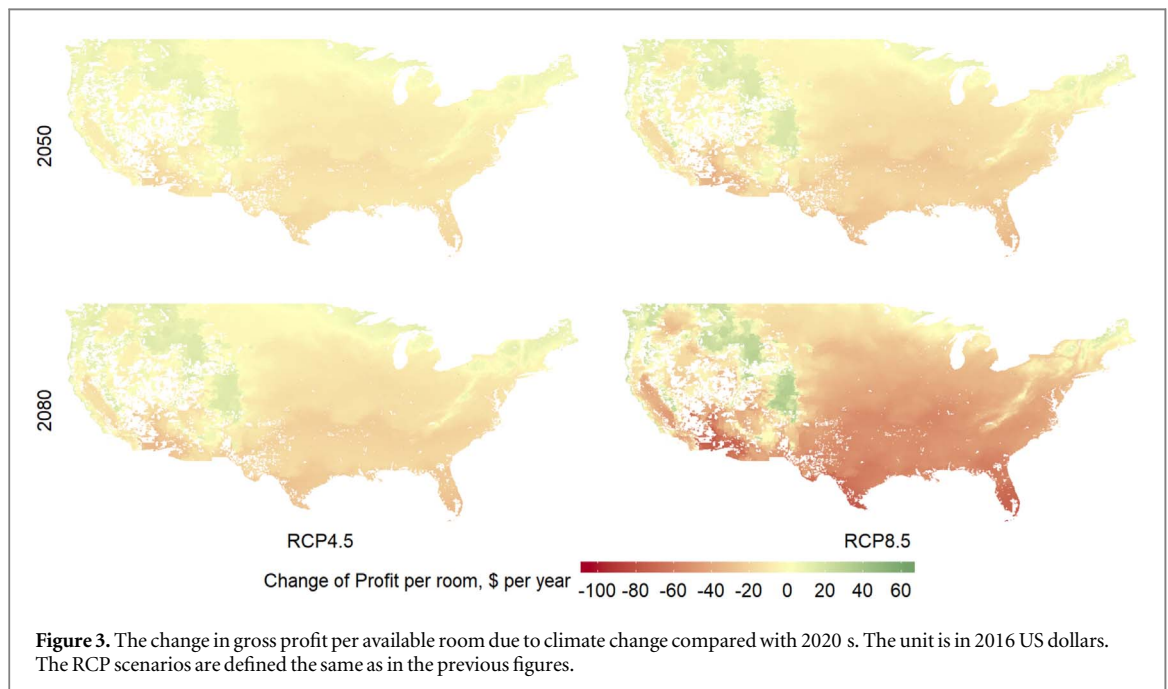
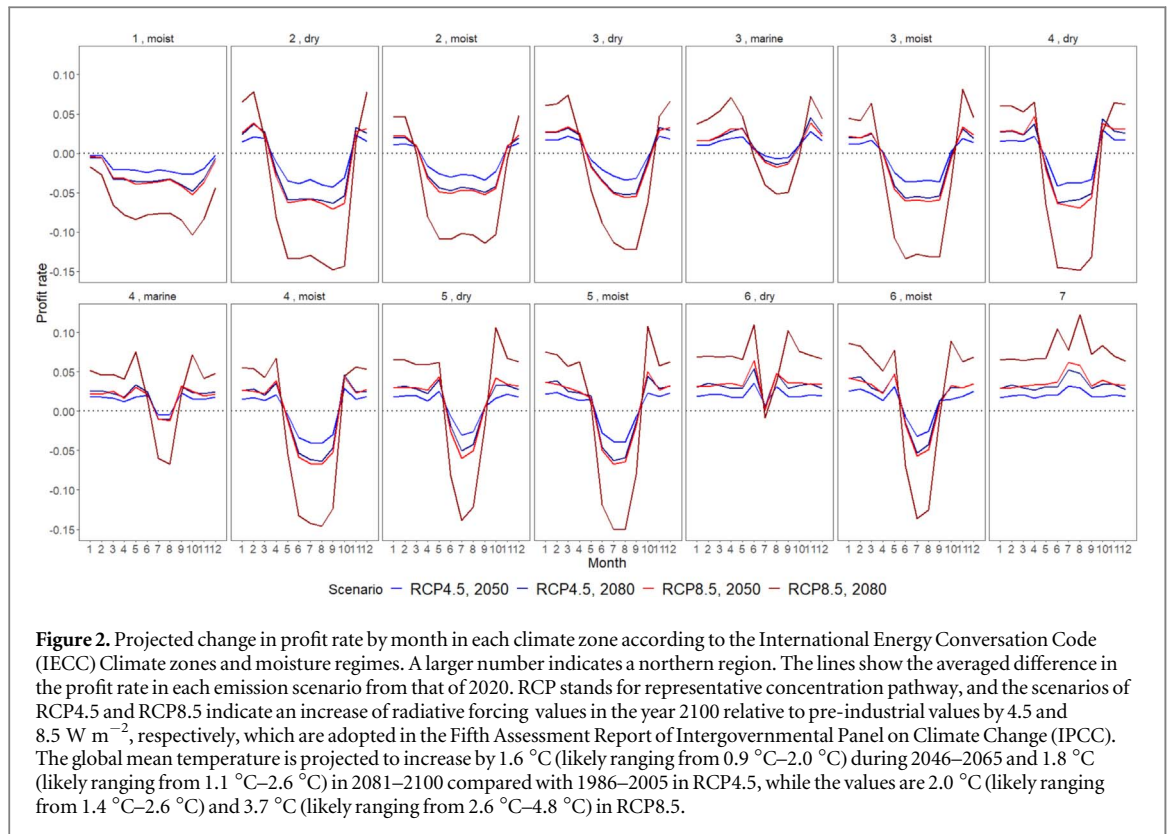
The effect of climate factors can also be heterogeneous depending on the characteristics such as the chain scales of the hotels. The consumers that can afford accommodations in higher scale chains (which are of higher room rates as shown in table S1) may be wealthier and thus have more capability in adapting to the changing climate during the trip such as driving or taking a taxi on hot days. Therefore, it is possible that higher scale hotel chains are less affected. To testify this hypothesis, we interacted the indicator variables of the STR hotel chain scales (available at <http://hotelnewsnow.com/Media/Default/Images/chainscales.pdf>) with all the interval dummies of the climate factors and conduct a regression analysis. The chain scales of the hotel brands are determined based on the previous year's annual system wide (global) average daily rate by STR, which can be correlated with our dependent variables and result in endogeneity. To deal with this issue, we use the chain scale in 2016 (predetermined by the room rates in 2015). We also conduct the analysis with monthly average and cross-sectional data. The results shown in table S7 (on panel data) and table S8 (on monthly average data) show a significantly smaller profit loss for upper upscale and upscale hotels when the temperature becomes less pleasant, indicating that low-end lodging is more sensitive to temperature and precipitation, and can be more vulnerable to climate change. The estimates of cross-sectional data in table S9 show almost no significant difference in profitability across hotels of different chain scales,

denoting that such a distinction may disappear in the long term. The results of multiple regressions are also compared in figure S6.

Our main specification identifies the effect of changing climate following the approach widely used in the literature [12, 17–21] that uses bins of climate factors. This method is however limited in nature as it cannot capture the effect of intra-bin climate change. In order to both test whether this impacts our key findings and conduct a more accurate forecast of hotel business based on the future climate, we fit a linear spline relationship to the data which allows a linear effect of the independent variable within bins following the method found in the existing literature [13, 17] (details are included in the Methods section). We locate the knots at equally spaced quantiles with the number of knots determined by ten-fold cross-validation. The function forms of the other climate factors are simplified as linear since we observed a monotonic and almost linear relationship in both the descriptive statistics and the results of the main specifications. As shown in table S19, the results closely mirror what is uncovered by our primary specifications. The profit increases first as the temperature rises, with the marginal increase becoming smaller as the temperature approaches the most comfortable interval. The temperature–profit curve becomes almost flat at  $17.43\text{ }^{\circ}\text{C} \sim 21.42\text{ }^{\circ}\text{C}$ , overlapping with the  $18\text{ }^{\circ}\text{C} \sim 20\text{ }^{\circ}\text{C}$  interval identified in our main specification, and then starts to go down as the temperature increases further, showing a reduction of profit during hot days. The results for other dependent variables also resemble those of the bin models. The analyses of the monthly average and cross-sectional data in tables S20 and S21 show similar results.

### Gains and losses in future climate scenarios

We project the seasonal change of business performance of our sample under various climate scenarios using the spline model. The results shown in figure 2 indicate that the profit rate in most climate zones would decrease during the summertime as the temperature becomes higher, further away from the most comfortable interval of  $18\text{ }^{\circ}\text{C} \sim 20\text{ }^{\circ}\text{C}$ . In the meantime, a warmer climate encourages tourism and increases profits during early spring (March to May) as well as in late autumn (September to November). In the winter which is the off-season for tourism in most zones, the profit rate also slightly increases, although not as much as in the other seasons. The change in profit rate is also spatially heterogeneous. Its reduction during the summer turns out to be larger for zones with lower latitudes such as Zones 1 and 2 not only because the temperature increases from a point further away from the comfortable interval and thus leads to larger marginal effects, but also because summer in these regions lasts longer. Such a decrease is lower for northern regions such as Zone 6, and the



northernmost area, Zone 7, would even experience an increase in profit rate due to a warmer and thus more pleasant summer. Scenarios of high greenhouse emissions (RCP8.5) trigger a larger change in profit rate during each season because of both hotter summers and warmer springs, autumns, and winters.

We further project the change in annual profit per available room based on the climate information of each zip code zone as shown in figure 3. Most regions would experience a slight reduction in profit.

Referring to figure 2, this indicates that the increased profit during spring and autumn cannot compensate for the decline during hotter summers. The southern area (mostly Zone 1 and Zone 2) turns out to lose the most customers because of its summer, while already scorching, would become even less thermally pleasant. By contrast, the West Coast (primarily Zone 4 with marine climate), Midwest area (Zone 6 with dry climate), as well as the Great Lakes region (Zone 7) would benefit from climate change in their accommodation



sectors since the spring and autumn become warmer and more suitable for travel.

## Discussion

Our estimation helps refine the damage function of climate change in existing climate models with high spatial and temporal resolution. Such estimates are useful for policymakers and agents affected in the hotel industry to evaluate more precisely the costs and benefits of adaptation. For the mature investment, practitioners should inspect ways of lowering the additional operating costs resulting from climate change. The climate-related change in utility costs imply a potential future benefit of green building and green lodging programs for hotels located in areas with less thermal comfort. The benefit of green building programs, while estimated for both commercial and residential buildings [27, 28], has yet to be examined for lodging facilities in which consumers may be predominantly driven by hedonic values during travel and thus behave differently in consuming energy as compared with at home or work [29]. Meanwhile, green lodging programs have been proved to help hotel owners save on energy and water expenditure, either via the supply-side change such as the modification of the energy or water supply system or demand-side intervention such as increasing the visibility of electricity consumption information to customers [30]. Entrepreneurs may also think of possible new attractions and innovative business models as the current ones may become obsolete as climate conditions change. As most existing studies focus on small-scale cases, a more comprehensive nationwide evaluation of the benefits of the program is called for regarding the heterogeneous change in occupancy, energy use, and water consumption by location.

Our findings also provide implications for location decisions of new accommodation enterprises. As the future climate becomes different from the status quo, climate in some regions, such as the South Central, can lead to lower profitability. As a result, practitioners in the hotel industry should reconsider suitable locations for the construction of new facilities. Although our estimation does not cover all the sub-sectors of travel and tourism, the response of hotel business can at least partly reflect the economic impact of climate change on the whole industry because the hotel sector is closely connected to other parts of the tourism industry. This would provide knowledge and implications for decision makers to form the future climate actions concerning tourism and travel, especially for places where it is a pillar industry of the state economy, such as Wyoming, Vermont, and Nevada [31, 32], to face the challenges and take the opportunity to redistribute tourism resources due to the changing climate. Our results also have implications

globally especially for regions already experiencing similar or warmer climate as South Central US does. Based on the recent Travel & Tourism Competitiveness Report by the World Economic Forum, countries in warmer regions such as those in Southeast Asia, Central America, and warm Mediterranean regions tend to be highly reliant on tourism [33]. Our results imply that climate change will impose threats to an important economic pillar—the tourism industry—for these countries.

It should be noted however that climate change may affect the hotel business not only through different meteorological conditions but also via changes in the frequency and severity of extreme weathers. As our meteorological variables capture at least partly the effects of some events such as extreme heat, storms, and cold waves, others such as tornadoes, floods, hails, etc. are not included in our analysis due to limited data availability on their location, frequency, and intensity in future climate scenarios. We thus leave it for future research.

Meanwhile, the effect of long-term adaptation should be further examined. As we try to include the long-term adaptation using cross-sectional analysis, the validity of our estimates relies on the small effect of missing variable issues. Further research should resort to methods that rely on fewer assumptions and are thus more likely to be exempt from the missing variable issues such as the long difference applied in previous literature [34]. Also, even though we averaged out the randomness in weather variables to some extent in the monthly average model and the cross-sectional model, 3-year means may still be an imperfect analogy of the climate, which can only be improved with data for longer periods. Meanwhile, the location/relocation effect is not fully captured in our cross-sectional model since our dataset does not contain any information on the entry and exit of the hotels. Future research may also examine such an effect if data on the accounts of lodging facilities at a fine geographical scale are available.

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