

1     **Role of Clouds in the Urban Heat Island and Extreme Heat: Houston-**  
2                     **Galveston metropolitan area case.**

3                     **John F. Mejia<sup>1</sup>, Juan Jose Henao<sup>2</sup>, Ebrahim Eslami<sup>3</sup>**

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5     **1. Division of Atmospheric Sciences, Desert Research Institute, Reno, Nevada.**

6     **<https://orcid.org/0000-0001-6727-5541>.**

7     **2. Escuela Ambiental, Facultad de Ingeniería, Universidad de Antioquia, Medellín,**  
8     **Colombia.**

9     **3. Houston Advance Research Center, The Woodlands, Texas. [https://orcid.org/0000-0002-](https://orcid.org/0000-0002-7721-6534)**  
10    **7721-6534**

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12    Corresponding author: John F. Mejia ([john.mejia@dri.edu](mailto:john.mejia@dri.edu)); 2215 Raggio Parkway, Reno, NV  
13    89512.

14    **Key Points:**

- 15       • Urbanization correlates with the presence of shallower cumulus clouds.
- 16       • Urban clouds are driven by the enhanced sensible heat and dynamic drag imparted by the  
17       urban landscape.
- 18       • Urbanization cloud enhancement emerges as a crucial pathway responsible for reducing  
19       the afternoon Heat Index values.

20 **Abstract**

21 The study and simulation of the Urban Heat Island (UHI) and Heat Index (HI) effects in the  
22 Houston-Galveston metropolitan area demand special attention, particularly in considering moist  
23 processes aloft. During the warm season, the afternoon sea breeze phenomenon in this coastal  
24 city acts as a natural air conditioner for city residents, facilitating the dispersion of pollutants,  
25 moisture, and heat. To delve into the intricate relationships among urbanization, clouds, and  
26 land-sea interaction, we conducted cloud- and urban-resolving simulations at a 900 m grid  
27 resolution. Results show that urbanization correlates with the presence of shallower cumulus  
28 clouds, cloud bases at higher altitudes, and increased cloud duration over the Galveston-Houston  
29 region compared to rural areas. These urban clouds benefit from the enhanced sensible heat and  
30 dynamic drag imparted by the urban landscape, thereby intensifying vertical mixing and  
31 moisture flux convergence. This dynamic interplay uplifts heat and moisture convergence,  
32 contributing to the enhancement of moist static energy that sustains the additional urban  
33 convection. Interestingly, our findings suggest that urbanization augments the mean HI while  
34 mitigating its afternoon high. An urban circulation dome emerges, overpowering the influence of  
35 land-sea circulations. Contrary to expectations, urbanization doesn't seem to promote a stronger  
36 sea breeze that would favor moist and cooler air mass to the city. Instead, the influence of  
37 urbanization on cloud enhancement emerges as a crucial pathway responsible for reducing the  
38 afternoon HI values. Moreover, uncertainties in SSTs are closely linked to the sensitivities of  
39 land-sea circulations, which in turn modulate UHI and extreme heat indicators.

40 **Plain Language**

41 Urbanization influences the meteorology by creating a warmer environment, which enhanced the  
42 excessive heat during the summer. Additionally, the warmer environment and the urban  
43 buildings increase friction leading more mixing and in turn favoring the development of low-  
44 level clouds. We developed computer simulations aiming to understand these processes and  
45 further include the role of the sea-breeze in this coastal city. We found that these clouds help  
46 ameliorate the excessive heat during the afternoon.

47

48 **Keywords:** Urban clouds, Urban Heat Island, Urban Circulation, Sea Breeze, Heat Index.

# 49 1 Introduction

50 This study is motivated by the need to characterize and better simulate excessive heat in  
51 urban environments. Increasing population in urban areas make cities more vulnerable to  
52 extreme weather events, climate variations and warming trends. It is likely that some of these  
53 changes will be outside of the range of historical extremes (Simolo et al. 2011; Trenberth 2012)  
54 and are expected to cause changes not only in mean, but also in extreme weather episodes  
55 (USGCRP, 2018). While there is relatively high confidence in the direction of changes in  
56 extreme temperature episodes, decision-makers require more quantitative and detail information  
57 to make better and more concrete adaptation plans to improve resilience in natural resources  
58 management (Rosenzweig et al. 2014) and health related risks (Guo et al. 2018; Ebi et al. 2021).  
59 The exposure of cities to extreme heat appears to be more critical under climate change scenarios  
60 and is exacerbated by the high solar absorption of the urban environments (i.e., the Urban Heat  
61 Island effect, hereafter UHI) (Fischer and Schär 2010; Schubert et al. 2012). High-resolution  
62 meteorological models are important tools for both weather forecasts and the development of  
63 adaptation and mitigations strategies aiming to make cities more resilient to climate-related risks  
64 (Cady et al. 2020; Zonato et al. 2021; Resilient Houston 2020; Houston Climate Action Plan  
65 2020). Hence, understanding the processes modulating the extreme temperature and related  
66 uncertainty in the models is a necessary step to add value and gain confidence in forecast  
67 products and the climate risk management process.

68 Recent studies have found that the urban environments not only modulate the temperature  
69 via the UHI effect, but also clouds and precipitation (Loughner et al. 2011; Theeuwes et al. 2019;  
70 Fan et al. 2020; Doan et al. 2023; Vo et al. 2023). Vo et al. (2023) used long-term satellite  
71 clouds retrievals to show that cities enhance clouds. During the daytime, observations (Theeuwes

72 et al. 2019) and numerical simulation (Loughner et al. 2011; Fan et al. 2020; Theeuwes et al.  
73 2021) have shown that the urban environment enhance warm non-precipitating clouds (i.e., low-  
74 level shallow cumulus clouds) and even extreme precipitation (Fan et al. 2020; Doan et al. 2023),  
75 which we argue can work as a self-cooling mechanism by blocking the incoming solar radiation  
76 and increasing evaporative cooling. During the night, however, Vo et al. (2023) suggested that  
77 clouds can block outgoing longwave radiation and exacerbate the UHI by suppressing the  
78 nighttime cooling. The role of the urban environment on simulated warm non-precipitating low-  
79 level clouds needs a more systematic and deeper assessment as it can be influenced by the  
80 geography and climate of the region (Theeuwes et al. 2021; Vo et al. 2023; Chiu et al. 2022). Vo  
81 et al. (2023) observed, however, that urbanization near Gulf Coast coastal cities tend to show  
82 enhanced clouds during the summer. For a single storm event, Fan et al. (2020) simulated the  
83 individual and combined effects of the urban land-use/land-cover and aerosols on convective and  
84 a storm evolution and intensity. In agreement with Theeuwes et al. (2019, 2021), Fan et al.  
85 (2020) showed that Houston urban area is related to earlier occurring and more persistent clouds  
86 due to a stronger urban heating and sea-breeze circulation. They also showed that the aerosol-  
87 cloud interaction effect can develop deeper convective mixed-phase clouds and more intense  
88 storms than the effect of the urban land-use/land-cover alone.

89         How Houston urban morphology, local circulations, and climate regimes impact the city  
90 cloud patterns remain poorly understood. This study focuses on better understanding urban-  
91 induced clouds in the Houston area. The local land-ocean sea breeze circulations can invigorate  
92 clouds and precipitation (Loughner et al. 2011; Zhong et al. 2017) and overwhelm the signals  
93 related to urbanization, dispersion of pollutants (Loughner et al. 2011; Ngan et al. 2013; Caicedo  
94 et al. 2019) and aerosol-cloud interaction effect (Fan et al. 2020). Furthermore, Zhong et al.

95 (2017) showed that under some synoptic conditions, the ACI can overwhelm precipitation  
96 processes directly produced by the land-use/land cover and limit the understanding of the  
97 interaction between non-precipitation clouds and urban climate. Neglecting aerosol cloud  
98 interactions (ACI), we hypothesize that urban-induced clouds can have a significant net surface  
99 cooling effect impacting extreme heat indicators.

100 In this study, we carried out cloud-resolving simulation experiments using the Weather  
101 and Research Forecasting (WRF) model coupled with Urban Canopy Modeling focused over the  
102 Houston-Galveston area to assess the impact of non-precipitation clouds on the extreme heat  
103 indicators during the modeling period. Moreover, we assess some model uncertainties by  
104 contrasting cloud and extreme heat indicators sensitivities to low-level moisture fluxes related to  
105 sea surface temperature biases.

## 106 **2 Data and Methodology**

### 107 **2.1 The regional climate model coupled with the Urban Canopy**

#### 108 **Model**

109 We used the Weather Research and Forecasting model (WRFv4.3.2; Skamarock et al.  
110 2008) coupled with the Urban Canopy Model (UCM) to perform urban- and cloud-resolving  
111 simulations for 1-16 August 2020 . We implemented the UCM based on the multi-layer building  
112 effect parameterization (BEP) scheme coupled with the Building Energy Model (BEM; Salamanca  
113 et al. 2010). This UCM option considers three-dimensional mass and momentum mixing and heat  
114 transfer between buildings and provides a realistic and accurate representation of near-surface  
115 energy fluxes and air temperature in mid-latitude cities (Cady et al. 2020; Jin et al. 2021). We  
116 would like to stress that this is not an instance of model calibration, but an attempt to assess and

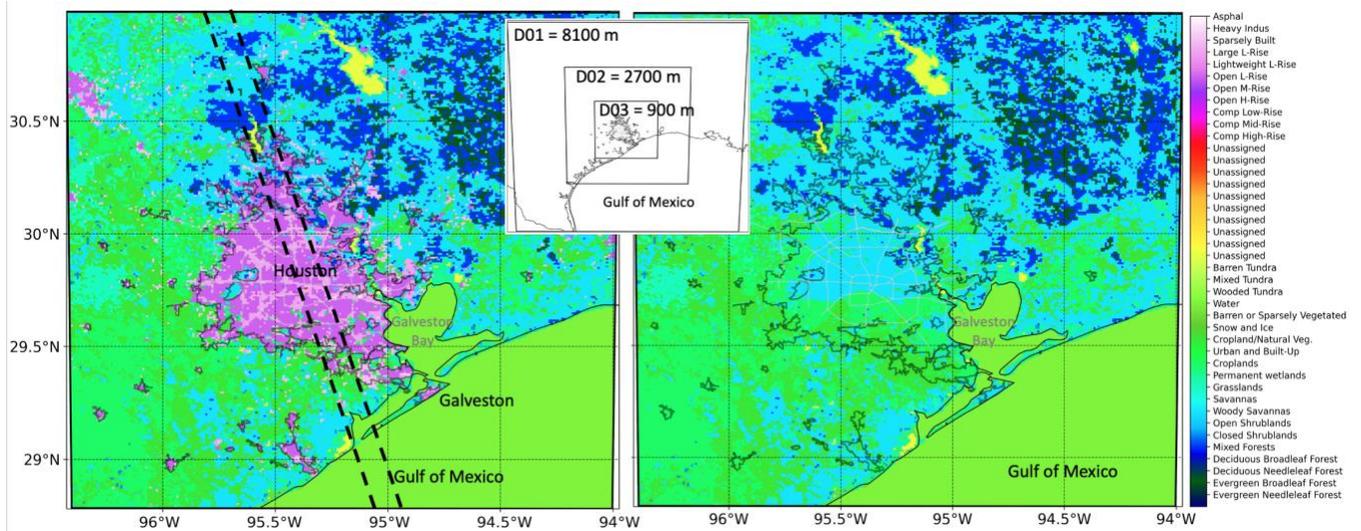
117 understand the UCM's capabilities and related uncertainties. We used this UCM option, among  
118 others available, because it incorporates 11 Local Climate Zones (LCZ), and it can be coupled with  
119 a solar photovoltaic-panel and green roof parameterization schemes (Zonato et al. 2021) that will  
120 be implemented in an urban heat mitigation assessment.

121 We acknowledge that it is difficult to find a model configuration that is superior under  
122 different flow regimes and the large variety of geography and urbanization settings. In this study,  
123 we used a three nested domain configuration (8100 m, 2700 m, and 900 m) centered in Houston,  
124 with 61 vertical levels up to 100 hPa. To allow the innermost model domain to relax towards the  
125 scenario settings, we designed the borders to be at least 80 km away from the suburban areas of  
126 Houston. Our initial modeling tests showed significant numerical diffusion noise highlighted as  
127 non-physical wind street patterns and thermal fields in the mixing layer with a spatial scale of two  
128 times the grid size. This problem is relatively common in high-resolution simulations during weak  
129 wind conditions and weak or unstable stratification (Knievel et al. 2007; Crosman et al. 2012).  
130 We imposed a spatial filter based on an explicit 6th-order numerical diffusion scheme with a non-  
131 dimensional rate of 0.12. Despite the potential over smoothing of surface processes, the explicit  
132 diffusion treatment notably improved simulations, and results were resistant and insensitive to its  
133 implementation. Additionally, we combined our experience and literature reports to determine  
134 other configurations and selection of physical parameterizations implemented in our model. For  
135 parameterization of moist processes, we used the Thompson double-moment microphysics,  
136 whereas convection and clouds parameterization are resolved explicitly in all our model domains,  
137 except for the coarser grid (8100 m) where we used the Kain–Fritsch scheme. Additionally, we  
138 used the Dudhia and RRTM as shortwave and longwave radiation schemes, respectively; Noah-  
139 MP, Monin-Obukhov and YSU as land-surface model, surface layer, and planetary boundary layer

140 (PBL) schemes, respectively. YSU PBL scheme was used for its simplicity, low computational  
141 cost and recognized good performance (Hendricks et al. 2020). The first 6 hours of simulations  
142 were not considered to allow for the model spin up. We used the NCEP GDAS/FNL 0.25 Degree  
143 Global Tropospheric Analyses and Forecast Grids (hereafter "FNL") as initial and boundary  
144 conditions data, with SST skin temperature updated as bottom boundary condition SSTs every 6  
145 hours.

## 146 **2.2 Land Use/Land Cover and Urban Characterization**

147 An important consideration in urban canopy modeling is the characterization of the Land  
148 Use/Land Cover (LULC) and urban categories. Most LULC products rely on remote sensing  
149 surveys with urban classification that are either outdated, such as the National Urban Database  
150 and Portal Tool (NUDAPT - 2009) or lack details even in major urban composition features,  
151 such as the World Urban Database and Access Portal Tools version 2 (WUDAPT - 2016;  
152 Brousse et al. 2016; Ching et al. 2018; Demuzere et al. 2021, 2022). Additionally, differences in  
153 the algorithms used to characterize urban categories and different data sources may result in  
154 different urban coverage. We opted to implement the 100 m global WUDAPT data (Demuzere et  
155 al. 2022) for the following considerations, including: WUDAPT (2016-2018) data is more  
156 modern than NUDAPT (2006) and captures a more recent snapshot of the urban growth with  
157 better resolution; and LCZ adaptation to WUDAPT favors the implementation of the UCM  
158 BEM+BEP for 11 different urban categories, contrasting only three urban categories in the  
159 NUDAPT data.



160

161 **Figure 1.** (left panel) Model inner domain (900 m) Land Use/Land Cover (LULC) based on WUDAPTv2 using  
 162 Local Climate Zones for the urban areas and MODIS for rural areas; dash lines show the location of the cross-city  
 163 transect shown in the analysis. (right panel) LULC after removing the urban areas and replacing them with  
 164 surrounding predominant rural vegetation. Inset shows the nested domain configuration. Dark grey contours  
 165 indicate urbanization boundaries as of 2010 (Houston-Galveston Area Council, H-GAC; [https://www.h-](https://www.h-gac.com/Home)  
 166 [gac.com/Home](https://www.h-gac.com/Home)) and light grey show location of major intraurban highways. For reference, inset in the middle  
 167 shows all model domains.

## 168 2.3 Surface Station and Upper-air Winds

169 We used all available, reliable, quality-controlled surface station regular monitoring sites  
 170 in the Houston area and surrounding rural land. Information was downloaded via the MesoWest  
 171 portal (<https://mesowest.utah.edu/>) but provided by the National Weather Service, Remote  
 172 Automated Weather Station, and Texas Commission on Environmental Quality (TCEQ)  
 173 Continuous Ambient Monitoring Station (CAMS) network. A total of 150 stations passed our  
 174 quality assurance/quality control filters (e.g., less than 5% of missing data after removing  
 175 outliers, visual inspection, atypical diurnal cycle of temperature and relative humidity) with 117  
 176 sites located in urban (112 in Open L-Rise; 4 in Large L-Rise; and 1 in Open H-Rise) and 31 in  
 177 rural land use/land cover categories. These surface observation data helped further constrain the  
 178 model in its diurnal evolution behavior in temperature, relative humidity, and winds, while

179 augmenting the information to examine derived parameters such as: low temperature (Tmin);  
180 high temperature (Tmax); Urban Heat Island (UHI) effect, estimated as the difference between  
181 representative urban minus rural sites; and Heat Index, following Rothfusz (1990) formulation.  
182 We acknowledge the potential of siting uncertainties in the urban networks and sensors (117  
183 sites), some of which are designed for air quality monitoring purposes (e.g., TCEQ sites). We  
184 assessed the confidence in the model by estimating the model bias, root-mean-square-error  
185 (RMSE) and Pearson correlation coefficient statistics. To partly address the uncertainties related  
186 to the relatively short simulations (e.g., dominance of any synoptic settings) and the potential  
187 effect of diurnal mesoscale constrains or geographical heterogeneities (e.g., sea-land circulations,  
188 distance from the coast and Galveston bay), we performed a bootstrapping with replacement  
189 approach any time it was possible.

190 To evaluate the performance of the simulated low-level winds, we used the Cooperative  
191 Agency Profilers wind profiler observations at La Porte (LPTTX; Cooperative Agency Profilers  
192 <https://madis-data.noaa.gov/cap/>), located near the coast at the northern shores of Galveston Bay.  
193 When the model is contrasted against the observations, we excluded the initial 6 hours due to  
194 model spin-up issues. To isolate the effect of the intermittent and scattered summer showers, we  
195 constrained the error analysis to days without significant observed precipitation events (< 5 mm)  
196 in the Houston-Galveston area; showers were mostly concentrated during Aug 1-3 (not shown).

## 197 **2.4 Model Experiment Design**

### 198 **2.4.1 SST Sensitivity**

199 The city's proximity to the Gulf of Mexico and the complex coastal shape of Galveston  
200 Bay warrants a careful look at the SST data used by the model as bottom boundary conditions  
201 (Hawbecker and Knievel 2022). An effort to improve the simulated thermal gradients will be the

202 careful implementation of the remotely sensed NOAA-SNPP VIIRS SST dataset (available daily  
203 at 4 km grid size; several snapshots per day; Bouali and Ignatov 2014). We carried simulations  
204 using the SST fields as they are provided by the FNL bottom boundary conditions (hereafter  
205 'biased' SSTs). From these untreated SSTs, we performed a time-space bias correction using the  
206 remotely sensed and buoys data. When comparing measurements from these platforms and  
207 default fields used by the model, we found an average offshore FNL SST cold bias of nearly -  
208 1°C (SFig. 1). We implemented a Barnes interpolation approach with successive correction  
209 using a Gaussian weight function departing from the background field (the biased SSTs) until  
210 optimizing the agreement between the interpolated function and the measurements (the unbiased  
211 SSTs).

#### 212 **2.4.2 Clouds, Urbanization and Weather Sensitivity**

213 To isolate the intricate role of the synoptic effect, sea-breeze, and cloud effects from that  
214 of the urbanization effect, we performed several simulations. The influence of moist processes  
215 (clouds and precipitation) is important in characterizing the temperature and relative humidity in  
216 Houston. Cloudy afternoon and showers forced by the sea-breeze can make a significant  
217 difference in the UHI environment (Morris et al. 2001). However, due to the relatively short  
218 simulations (15 days) and the intermittent nature of the moist processes (clouds and  
219 precipitation), we performed a set of simulations that isolate the influence of clouds and showers  
220 in the area. Simulations without clouds helped us produce an upper boundary in surface  
221 radiation conditions but mesoscale dynamical changes in relation to the clear sky environment  
222 are still expected. Additionally, during the simulation period, different meteorological regimes  
223 could have modulated sea-breeze related convection invigoration: 1-3 Aug a pre-trough regime,  
224 4-5 Aug a post-trough regime and 5-16 Aug the Bermuda high anticyclone was more pronounced

225 (Want et al. 2022; <https://earth.nullschool.net/>). Hence, we developed a clear sky simulation  
 226 (e.g., fully turning off microphysics and convection) to help analyze the results. Hence,  
 227 simulations with (Baseline) and without (hereafter 'Clear sky') clouds and precipitation were  
 228 performed and combined with model realizations similar to Baseline but perturbing the offshore  
 229 bottom boundary conditions using bias corrected SSTs fields (hereafter 'Biased SSTs) or  
 230 removing all urban areas in the domain (hereafter 'No City'). Table 1 shows a summary of the  
 231 simulations that were performed in this study, as well as their related description and  
 232 justification. All references to the model simulation are related to the All sky-Baseline scenario  
 233 (hereafter 'Baseline'), unless otherwise stated.

234 **Table 1.** Description of model scenarios simulated in for this study.

<i>Scenario name</i>	<i>Description</i>	<i>Justification</i>
<b>Baseline</b>	<i>Baseline with simulation of cloud and convective processes (moist processes) and bias correction of offshore SSTs</i>	<i>Full physics simulation using outlined parameterizations and state-of-the-art LULC categories from LCZ. Systematic biases associated with offshore SSTs are removed.</i>
<b>Clear Sky</b>	<i>Same as Baseline but without clouds and moist convective processes.</i>	<i>Isolate the role of clouds and precipitation relative to Baseline.</i>
<b>Biased SST</b>	<i>Same as Baseline but with biased offshore SSTs</i>	<i>Assess the sensitivity of Baseline to SST perturbations or refinements (e.g., bias corrections).</i>
<b>No City</b>	<i>Same as Baseline but removing the urban LCZ categories and replacing them for representative vegetation in the region.</i>	<i>Isolate the role of the urbanization in the meteorology.</i>

## 235 **3 Results**

### 236 **3.1 Model Evaluation**

237 Figure 2 shows the observed and simulated diurnal patterns of surface temperature,  
 238 relative humidity, Heat Index, and zonal and meridional winds, corresponding to urban and rural  
 239 sites in the domain. In general, the model adequately follows the diurnal median patterns for all  
 240 the evaluated parameters, but several biases are apparent with the model showing a systematic

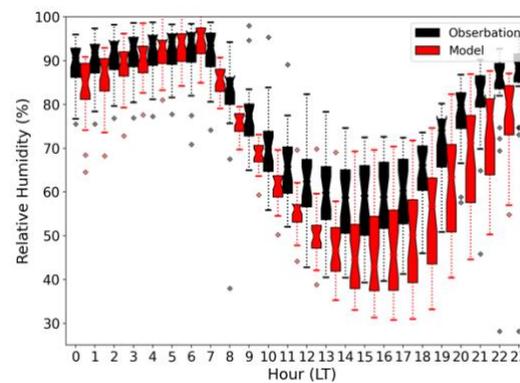
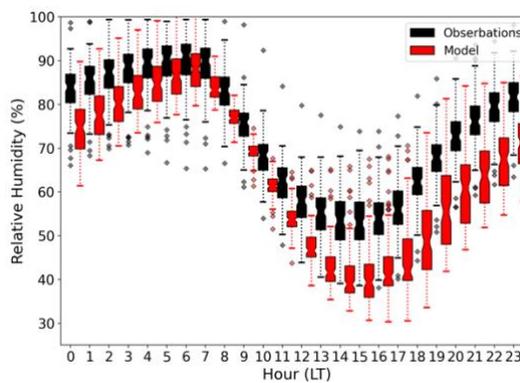
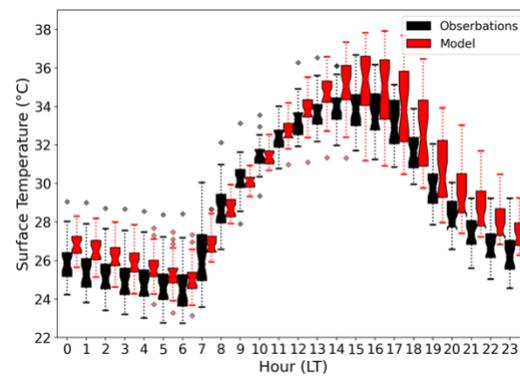
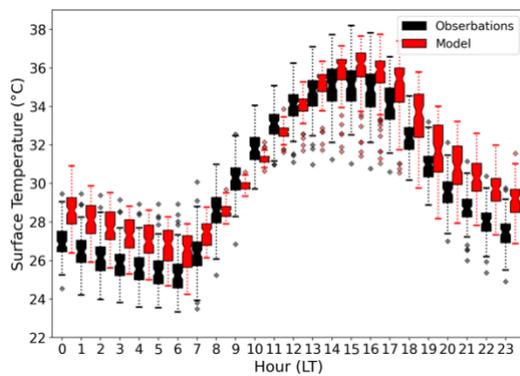
241 dry bias (also exhibited in the water vapor mixing ratio, not shown) that is more intense during  
242 the afternoon and nighttime. The model surface temperature shows an in-phase diurnal evolution  
243 with a warm bias in the late afternoon and during the nighttime. Of note is that model nighttime  
244 temperatures biases are even warmer in urban sites compared to rural sites. Intercomparison  
245 between the urban and rural sites is only possible because we performed a bootstrapping  
246 approach with replacement to assess the uncertainty of the results with respect to the distance  
247 from the coast and its land-sea interaction effects. Relative to Houston, the stations included  
248 contained nearly equal number of sites closer to the coast and further inland.

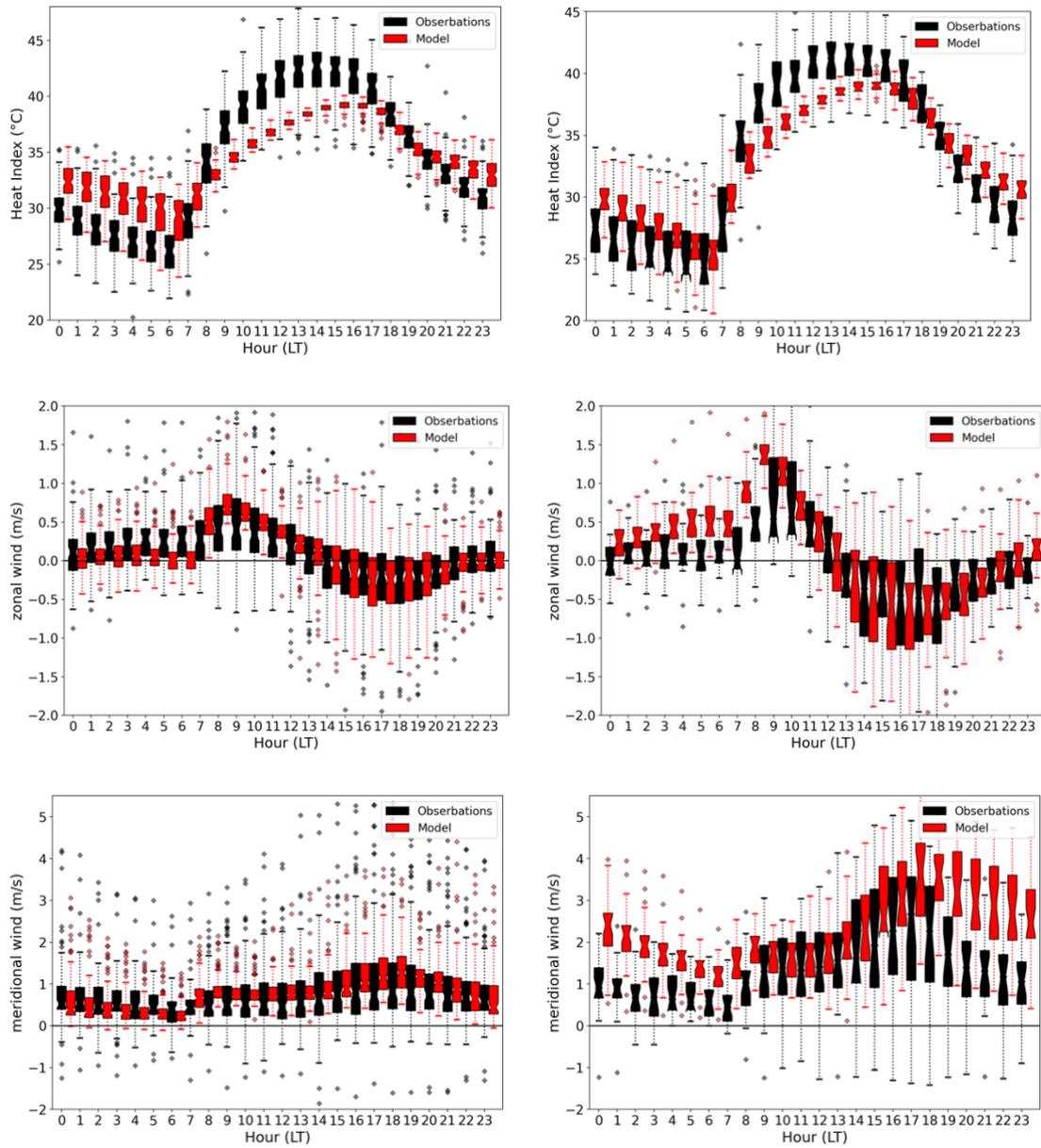
249 To evaluate the model performance of the low-levels ( $< 3$  km) circulation, we used  
250 surface stations and La Porte wind profiler observations. Fig. 2 shows that the diurnal  
251 distribution of the simulated zonal winds closely follows the observations, with shifting from  
252 relatively calm southeasterlies in the morning to stronger southwesterlies in the afternoon and  
253 nighttime. Part of the wind shifting feature is typically a result from the planetary boundary layer  
254 diurnal inertial oscillation (Blackadar 1957); diurnal variability at this region can also be driven  
255 by the land-sea circulation. A striking surface circulation feature is that wind speeds are stronger  
256 over rural areas compared to urban areas (Fig. 2). This urban-rural wind speed differences are  
257 overemphasized by the model: the simulated winds show a slightly stronger southerly wind bias  
258 in urban sites, whereas it almost doubles the observed southerly wind in rural sites. Fig. 3 shows  
259 low-level winds at La Porte, highlighting an observed peak at midnight and between 250-500 m  
260 above the ground, whereas the model shows a deeper maximum at 01-02 LT and centered  
261 between 300-400 m above the ground. In agreement with the evolution of the surface diurnal  
262 pattern, the model overemphasizes the low-level winds and shows an earlier (15 compared to 12  
263 LT) southwesterly wind increase in the afternoon. During the evening and nighttime, the low-

264 level flow further accelerates until early in the morning. This nocturnal acceleration is connected  
 265 to the prevailing summertime Great Plains Low-level Jet circulation that extends to the Gulf  
 266 coast in eastern Texas (Pu and Dickinson 2014). Early in the morning, the land breeze and  
 267 vertical mixing decelerates the nocturnal jet. In intensity, this nocturnal jet shadows the diurnal  
 268 variability related to the local land-sea breezes. Ngan et al. (2013) showed similar model biases  
 269 patterns and intensities irrespective of different land surface and PBL parameterizations.

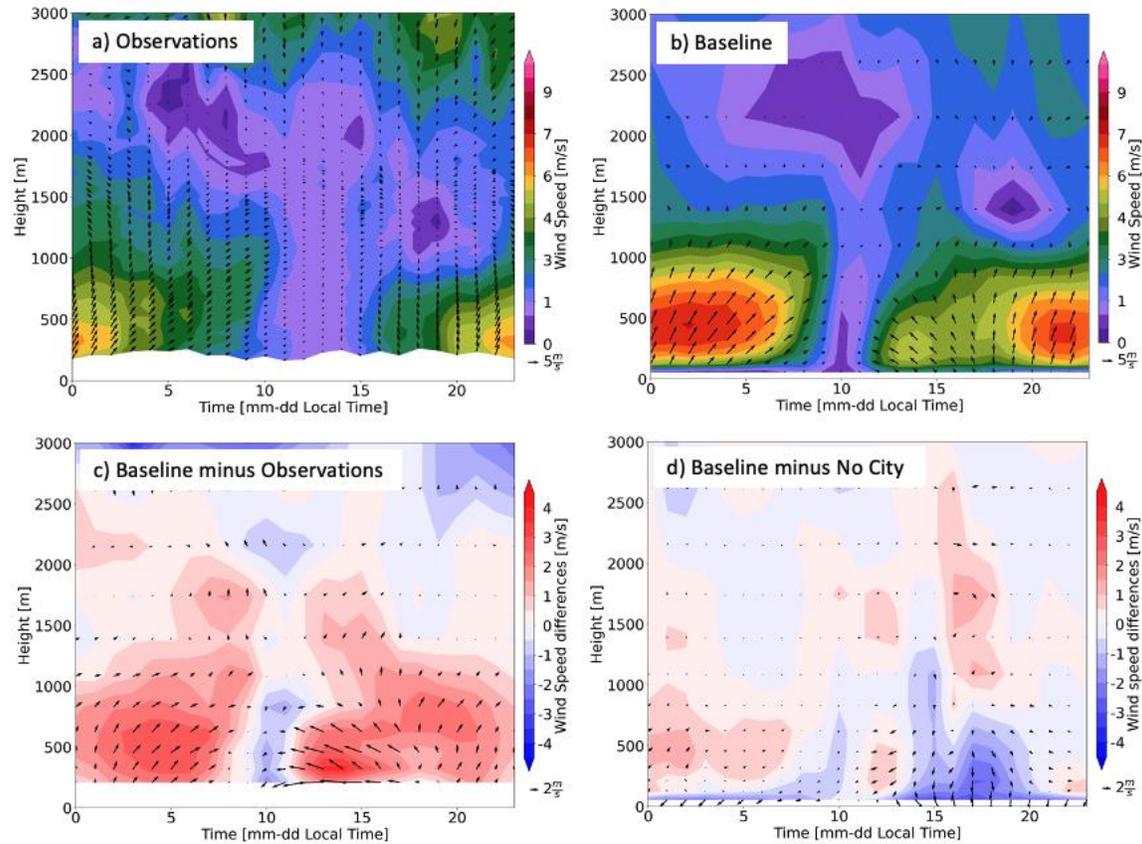
Urban stations (117)

Rural stations (31)





270 **Figure 2.** Baseline model and observed diurnal cycle distribution of (top to bottom panels) surface temperature,  
 271 relative humidity, and zonal and meridional wind components for stations in the Houston urban (115 sites; left  
 272 panels) and rural regions (31 sites; right panels).



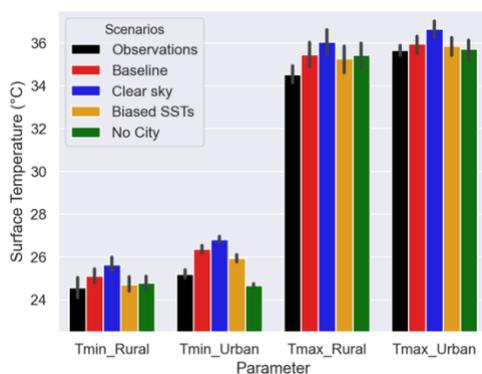
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274 **Figure 3.** Low-level-diurnal mean horizontal wind speed (contours) and wind vectors (with the north direction  
 275 pointing upwards) for (a) La Porte Wind profiler observations, (b) Baseline model winds, (c) Baseline minus  
 276 observations differences and (d) Baseline minus No City differences.

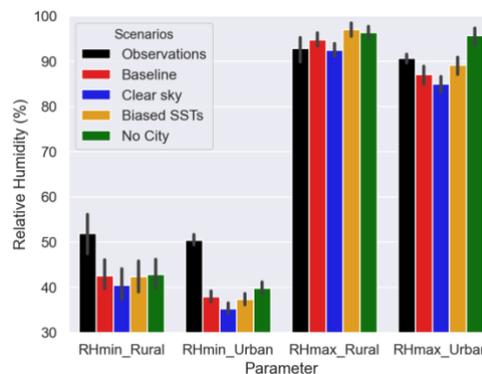
277 Figure 4 shows the observed and all simulated model scenarios (Table 1) and simulation  
 278 biases evaluated at all available surface station sites (see SFig. 2 for evaluation of the RMSE and  
 279 Pearson correlation coefficients). In general, model errors are small and well within the model  
 280 typical behavior in perturbed sensitivity experiments (Ancell et al. 2018; Wang et al. 2023), but  
 281 some systematic error signals emerged as a function of the scenario simulations and by  
 282 compositing rural and urban areas. Over both urban and rural areas, the Baseline simulation  
 283 shows a systematic warm bias for T<sub>min</sub> and T<sub>max</sub>. Not surprisingly, over the urban areas the No  
 284 City scenario shows a relatively colder bias when compared to all the urbanized scenarios. The  
 285 role of clouds in the model performance is apparent. Notably, during the daytime the biases are

286 warmer (and drier) for the Clear sky scenario, as the lack of clouds increases the incoming solar  
 287 radiation, balanced by more sensible and ground heating. At night, the warmer biases of the  
 288 Clear sky scenario relative to Baseline biases suggest that the outflux ground heating dominate  
 289 the faster longwave radiation cooling (Fig. 5). When comparing the Baseline to the Biased SSTs  
 290 scenario, refining the offshore SSTs towards a warmer SSTs have a significant warming effect,  
 291 with larger differences during early morning. Therein, a surprising result is that bias differences  
 292 between Baseline and Biased SSTs during the daytime are smaller than those during early  
 293 morning; the direct sea-breeze advection of warmer maritime surface temperature during the  
 294 daytime does not develop significant sensitivity in Tmax in comparison to Tmin. Therefore, the  
 295 model biases highlight that the surface temperature sensitivity between the Baseline and Clear  
 296 sky simulations (-0.56 °C difference) are significantly larger than that between the Baseline and  
 297 Biased simulations (0.25 °C difference; see also SFig. 2). By construction, the bias trends in this  
 298 model evaluation procedure are somehow expected, but some potential non-linear impacts  
 299 related to changes in cloudiness and circulation, which motivates the main objective of this  
 300 study, are not as apparent.

a) Surface temperate

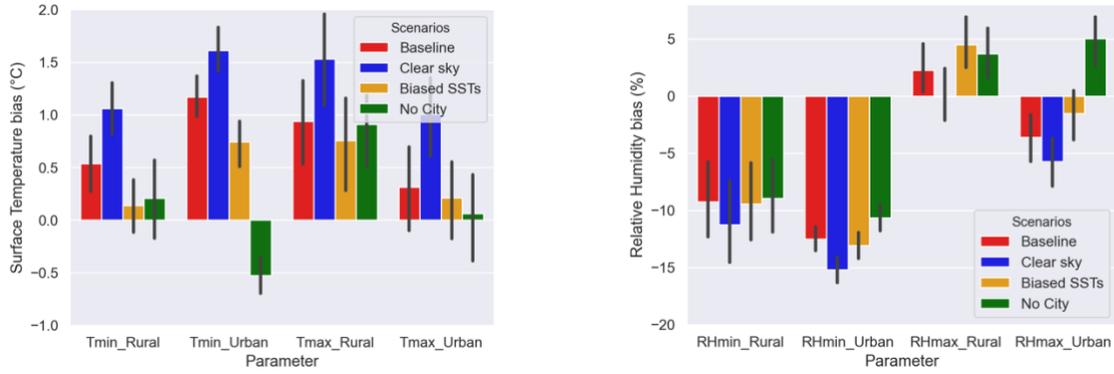


b) Relative humidity



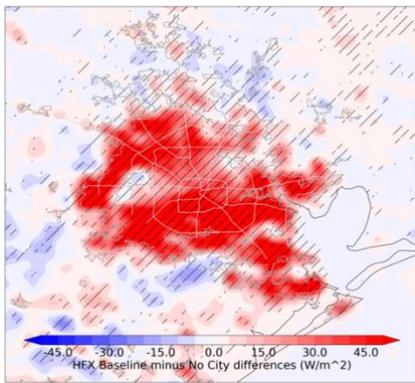
c) Surface temperature bias

d) Relative humidity bias

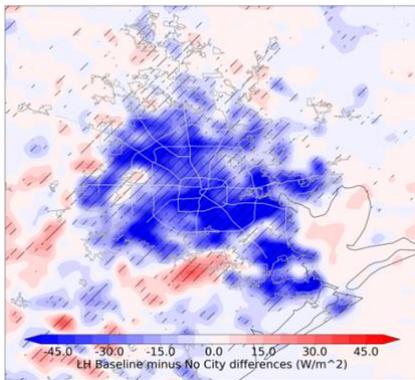


301 **Figure 4.** Observed and different model scenarios (Table 1) evaluated at surface station sites for low and high (a)  
 302 surface temperature and (b) relative humidity, and corresponding (c, d) bias distribution. Surface station sites are  
 303 categorized as Urban or Rural according to MODIS/WUDAPTv2 land use/land cover types. Evaluation period is 1-  
 304 16 August 2020. Analysis constrained to non-rainy periods as described in the text.

a) Sensible heat flux

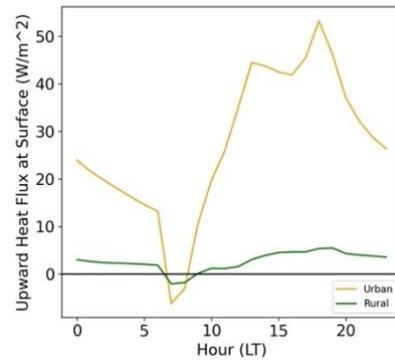


c) Latent heat flux

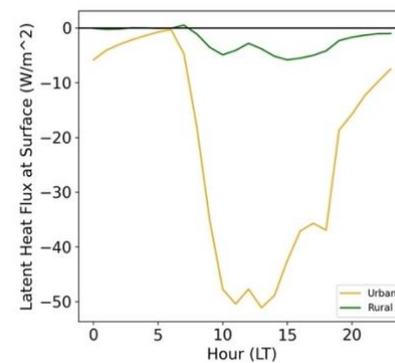


e) Ground heat flux

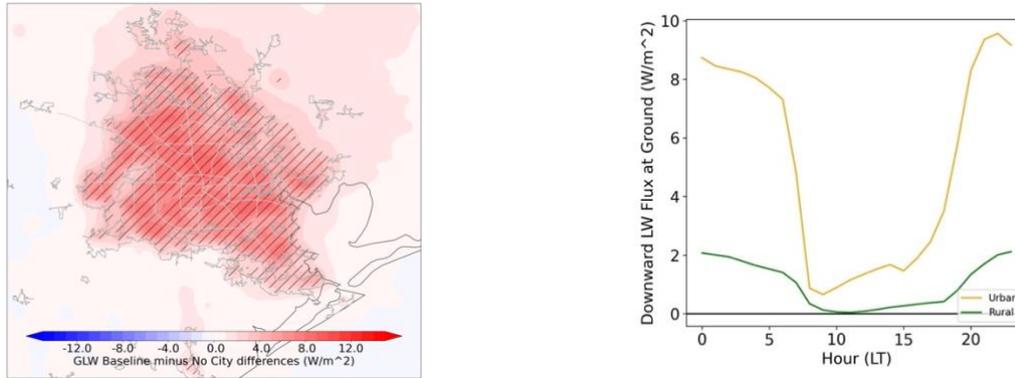
b) Sensible heat flux



d) Latent heat flux



f) Ground heat flux



305 **Figure 5.** Mean Baseline minus No City differences for (a) sensible, (c) latent, (e) ground heat fluxes. Hatched areas  
 306 indicate that differences are significant with a 95% confidence level. Dark grey contours indicate urbanization  
 307 boundaries as of 2010 (Houston-Galveston Area Council, H-GAC; <https://www.h-gac.com/Home>) and light grey  
 308 show location of major intraurban highways. Spatially averaged diurnal (b) sensible, (d) latent and (f) ground heat  
 309 fluxes for Baseline minus No City differences composited by urban and rural areas.

### 310 **3.2 Urban Heat Island**

311 Table 2 compares surface station observations and corresponding simulations composited  
 312 as a function of the rural and urban categories. The UHI was estimated as the mean of the mean  
 313 of the stations in the urban minus rural sites. Since the distance from the coast (i.e., from the  
 314 station to the nearest simulated ocean grid point) can have an impact in the UHI estimates, we  
 315 balanced the number of sites located near the coast with those far from the coast. Observations  
 316 show a more pronounced UHI effect during the  $T_{max}$  times than during the  $T_{min}$  times. When  
 317 contrasting the model at sites with surface station data, the Baseline model is overemphasizing  
 318 nighttime and early morning UHI effect and underemphasizing that of the afternoon; herein, no  
 319 effort was made to examine and evaluate the timing of the  $T_{min}$  and  $T_{max}$ . Earlier, however, we  
 320 showed that the mean cycle of temperature in the model is in-phase with the observations (Fig.  
 321 2). Table 2 also shows that the Baseline simulation is related to a stronger early morning and  
 322 milder afternoon UHI than the Clear sky scenario. This is not surprising due to the role of clouds  
 323 in the long and short wave radiative balance (Brenquier et al. 2000). Biased SST simulation

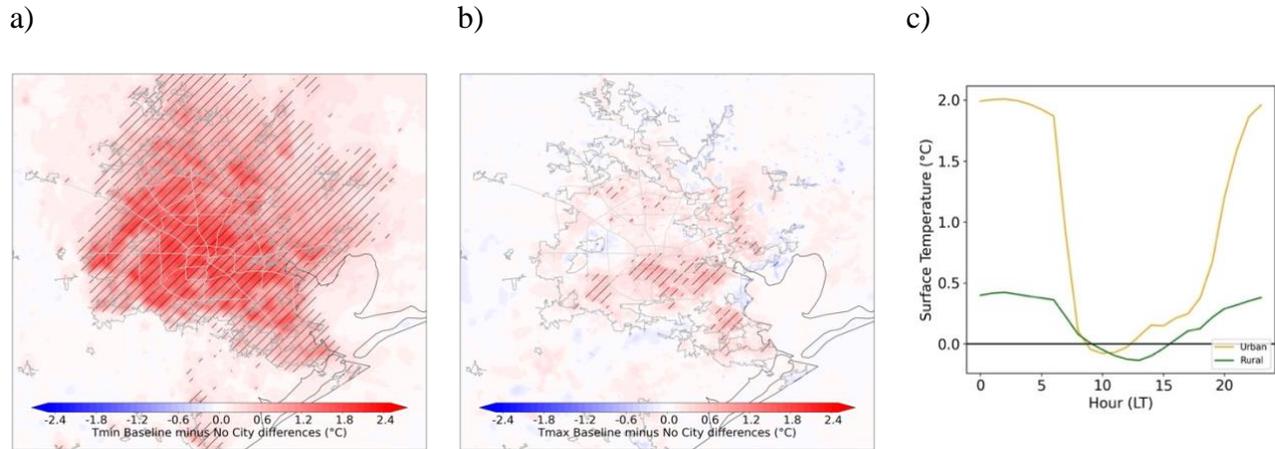
324 yields a similar and more intense early morning and afternoon UHI, respectively. Finally, the  
 325 relatively small UHI effect based on the No City simulation shows that the composited UHI are  
 326 linked to urbanization.

327 Another method to reveal the intensity of the UHI is by comparing the Baseline and the  
 328 No City scenarios. Fig. 6 shows the UHI effect spatial patterns during Tmin and Tmax times as  
 329 estimated by the Baseline minus the No City simulated differences. The nighttime and daytime  
 330 UHI differences are striking, highlighting a very pronounced and significant early morning UHI  
 331 effect and a less intense afternoon UHI effect (Fig. 6c). The urbanization intensity and intra-  
 332 urban vegetation islands are related to some of the cool UHI patches within the city (Fig. 1);  
 333 albeit that differences can also be a function of the distribution of the underlying vegetation  
 334 assigned in the No City scenario instead of the urbanized LCZ. Notably, the Baseline minus the  
 335 No City differences remain significant downwind and to the north and northwest of the city  
 336 boundary (Fig. 3). Since some stations are located downwind of Houston, this advection of UHI  
 337 can reduce the actual UHI intensity estimates shown in Table 2. Hence, the overemphasis of the  
 338 early morning UHI can be partly attributed to the overestimation of surface temperature in the  
 339 urban areas.

340 **Table 2.** Observed and simulated mean Tmin and Tmax at surface station locations composited by rural (31 sites)  
 341 and urban (115 sites) locations. Urban Heat Island effect is estimated as the urban minus rural difference. Urban and  
 342 rural categories are assigned following MODIS/WUDAPT and LCZ designation in the model.

	Rural	Urban	Rural	Urban	UHI (Urban minus Rural)	
	Tmin [°C]		Tmax [°C]		Tmin [°C difference]	Tmax [°C difference]
<b>Observations</b>	24.56	25.18	34.52	35.65	0.62	1.13
<b>Baseline</b>	25.10	26.35	35.46	35.96	1.25	0.50
<b>Clear sky</b>	25.62	26.80	36.05	36.65	1.18	0.60
<b>Biased SSTs</b>	24.70	25.93	35.28	35.86	1.23	0.58
<b>No City</b>	24.77	24.66	35.43	35.71	-0.11	0.28

343

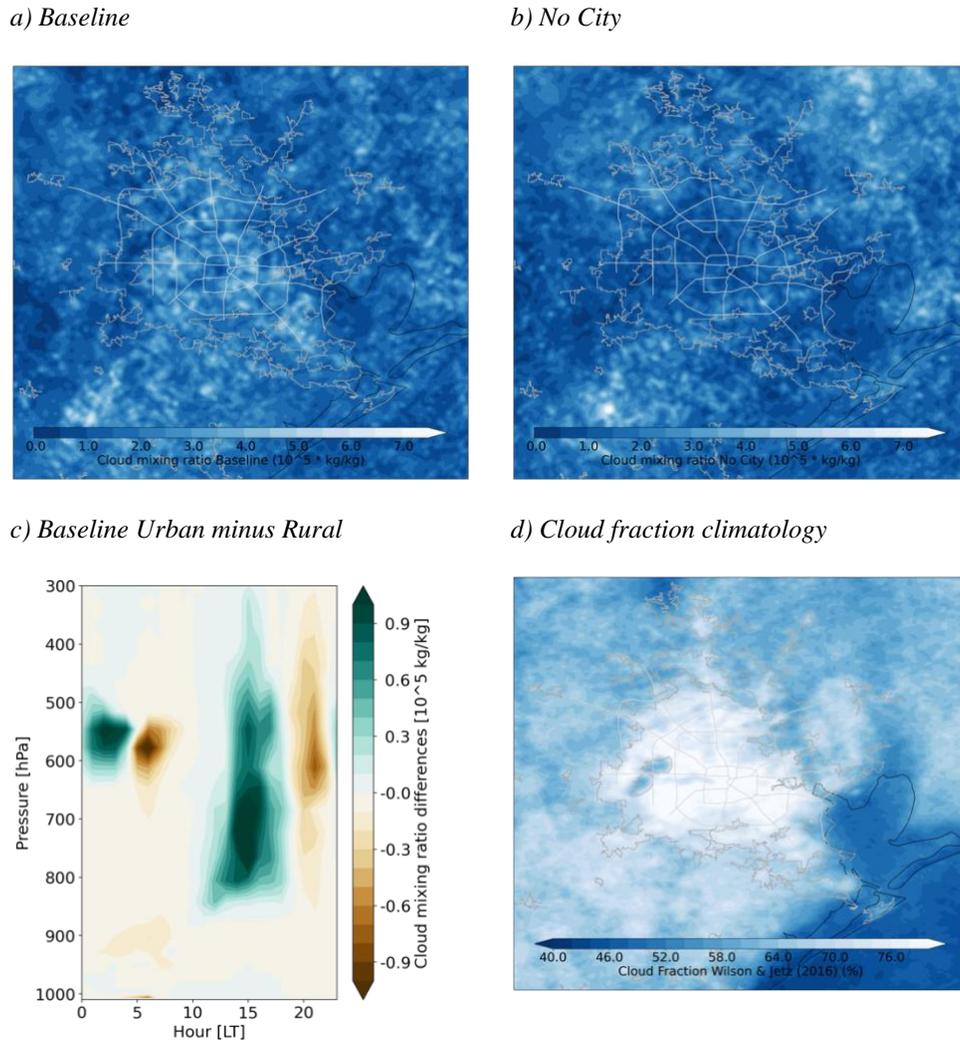


344 **Figure 6.** Mean Baseline minus No City differences for (a) Tmin and (b) Tmax. Hatched areas in (a) and (b)  
 345 indicate that differences are significant with a 95% confidence level. Dark grey contours indicate urbanization  
 346 boundaries as of 2010 (Houston-Galveston Area Council, H-GAC; <https://www.h-gac.com/Home>) and light grey  
 347 show location of major intraurban highways. (c) Spatially averaged diurnal surface temperature for Baseline minus  
 348 No City differences composited by urban and rural areas.

### 349 **3.3 The Role of Shallow Cumulus Clouds**

350 Figures. 7a and 7b show the mean vertical maximum cloud mixing ratio for the Baseline  
 351 and No City scenarios, respectively. The Baseline urbanized area exhibits thicker and more  
 352 abundant clouds compared to the urban area in the No City scenario, primarily attributed to  
 353 afternoon shallow cumulus clouds (Fig. 7c). In contrast, the No City scenario shows less  
 354 abundant cloud cover with less apparent differences across the domain. The impact of  
 355 urbanization in the cloud patterns is complex and can vary temporally and spatially. It is  
 356 important to note that the patchy cloud structures are a result of the relatively short simulation,  
 357 limiting a point-by-point comparison between these scenarios. However, extending the model  
 358 integration over a longer duration is expected to reveal more robust and discernable differences.  
 359 For instance, the cloud frequency climatology by Wilson and Jetz (2016) unambiguously  
 360 demonstrates that urbanization-related clouds are more frequent than clouds in the surrounding  
 361 rural areas. This cloud climatology, developed at a 1 km grid size, further reveals intraurban

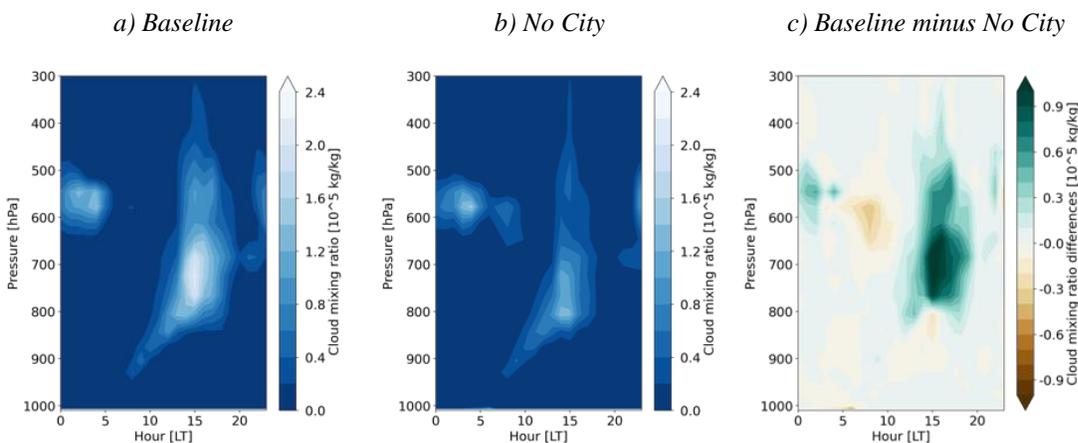
362 variability in cloud frequency dependent on urbanization intensity and urban green  
 363 infrastructures, as observed in the less cloudy areas over the vegetated Addicks and Barker flood  
 364 control reservoirs in the west of Houston (Fig. 1).



365 **Figure 7.** Mean vertical maximum cloud mixing ratio for (a) Baseline and (b) No City scenarios, and (c) Baseline  
 366 diurnal-pressure urban minus rural composites. (c) Wilson and Jetz (2016) cloud fraction climatology based on 15  
 367 years of twice-daily Moderate Resolution Imaging Spectroradiometer (MODIS) satellite images. Dark grey contours  
 368 indicate urbanization boundaries as of 2010 (Houston-Galveston Area Council, H-GAC; [https://www.h-](https://www.h-gac.com/Home)  
 369 [gac.com/Home](https://www.h-gac.com/Home)) and light grey show location of major intraurban highways.

370 The impact of urbanization in the clouds is more apparent by averaging their properties in  
 371 space. Fig 8 presents the spatially averaged diurnal-pressure cloud mixing ratio for both the  
 372 Baseline and the No City scenarios. In general, inland shallow cumulus clouds begin forming

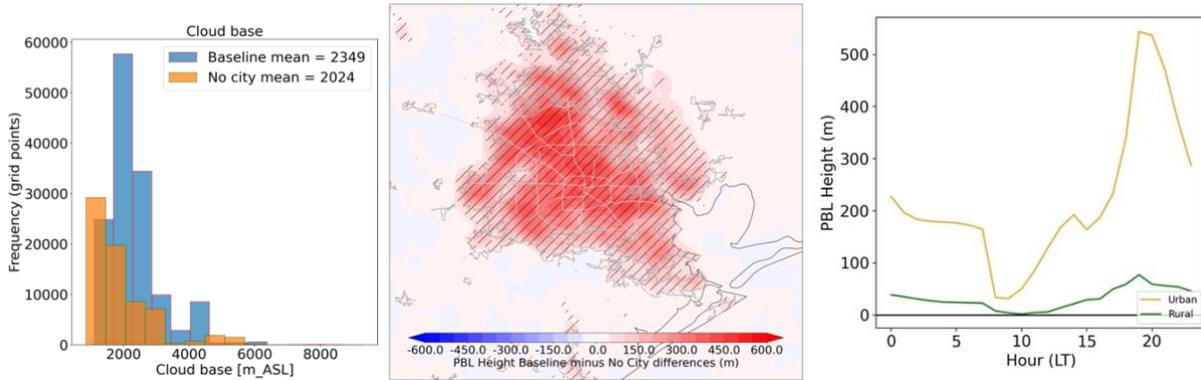
373 early during the daytime, growing deeper and more abundant around 15 LT. The Baseline  
 374 simulation shows that these clouds are more abundant in the urban areas than in the rural areas,  
 375 while Baseline minus No City differences further confirm that over the urban areas these shallow  
 376 cumuli are more abundant, grow deeper and last longer. Although smaller differences are  
 377 observed when comparing clouds between the Baseline and No City scenarios in rural areas,  
 378 some cloud mixing ratio differences are simulated, likely due to the advection of UHI effects  
 379 downstream into rural regions (Fig. 6). Other contributing factors may include changes in  
 380 mesoscale land-sea circulation, evident from offshore cloud mixing ratio differences (Fig 8), or  
 381 potential numerical noise effects.



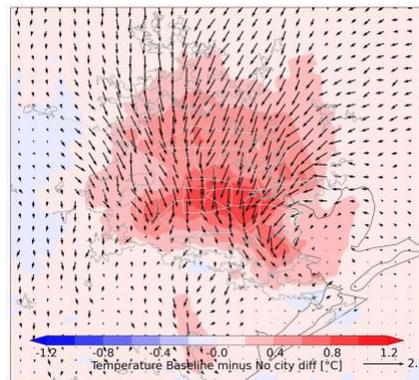
382 **Figure 8.** Diurnal-pressure mean cloud mixing ratio for a) Baseline, b) No City and c) Baseline minus No City  
 383 scenarios spatially averaged over urban categories according to MODIS/WUDAPTv2 land use/land cover types.

384 Figure 9 shows that the cloud base is significantly higher and thicker in the urban mixing  
 385 layer dome. Compared to the rural areas, an increase in cloud base height is expected in  
 386 environments with lower relative humidity (Williams et al. 2015) or higher Bowen ratio (Chiu et  
 387 al. 2022). Additionally, it is possible that the thicker mixed layer is favored by enhanced sensible  
 388 heat flux (Fig. 5) and by the increased urban aerodynamic roughness exhibited as a flow  
 389 slowdown over the urban area (Fig. 3). The low-level flow deceleration of the predominant  
 390 south-southeasterly wind, as it flows over the urban area, is apparent in Fig. 10. Notably, the

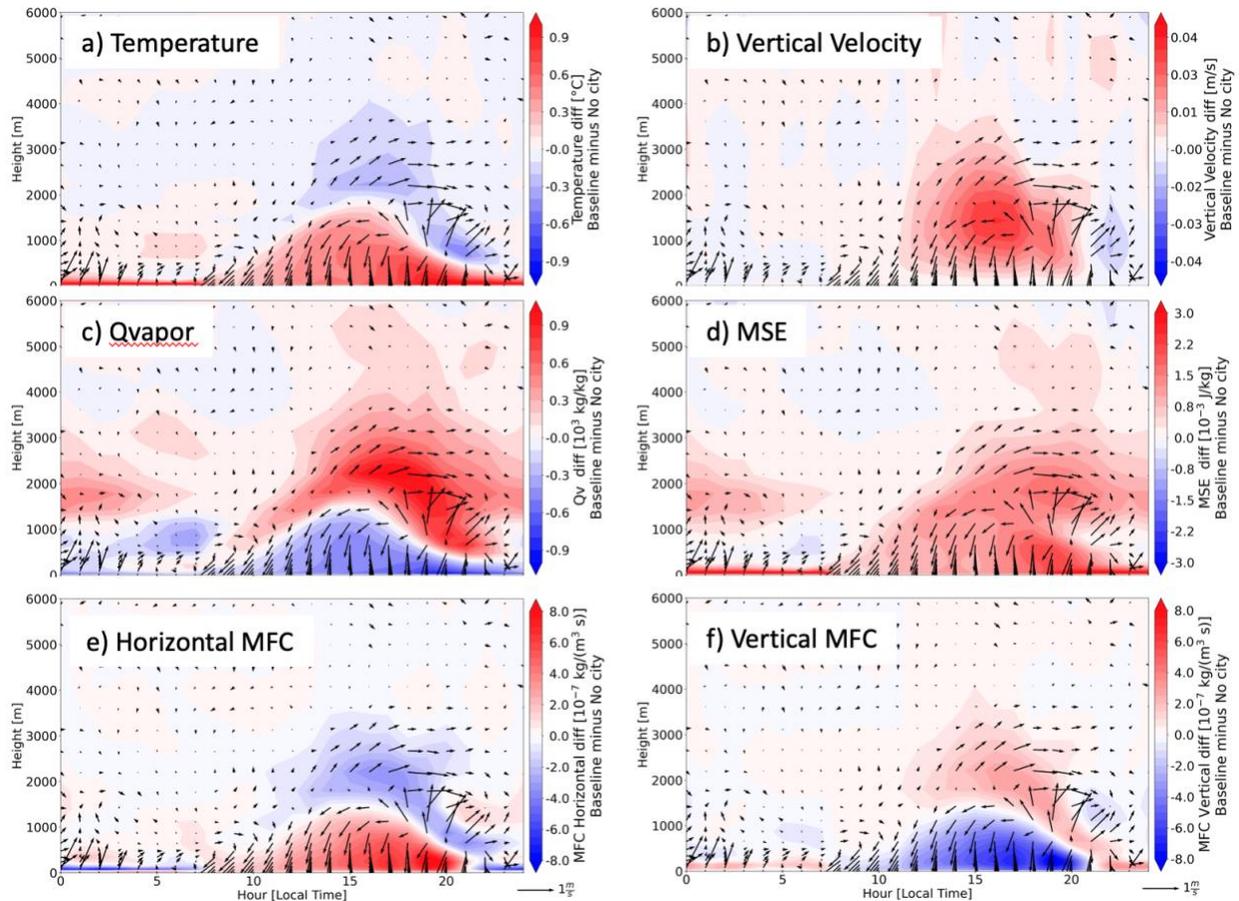
391 urban PBL diurnal differences are damped around the time of maximum shallow cumulus (~15  
 392 LT), in which the enhanced clouds control a transient surface cooling effect, hence temporarily  
 393 reducing the vertical mixing.



394  
 395 **Figure 9.** (Left panel) Cloud base distribution for Baseline and No City scenarios as occurring over the urbanized  
 396 area. Student's t-test and Kolmogorov–Smirnov test indicate that means and distributions are significantly different  
 397 with 99% confidence level. (Middle panel) Baseline minus No City PBL height differences with hatched areas  
 398 indicating that differences are significant with a 95% confidence level; Dark grey contours indicate urbanization  
 399 boundaries as of 2010 (Houston-Galveston Area Council, H-GAC; <https://www.h-gac.com/Home>) and light grey  
 400 show location of major intraurban highways. (Right panel) Baseline minus No City PBL height differences averaged  
 401 over urban and rural areas.



402  
 403 **Figure 10.** 500 m ASL temperature and wind vectors for Baseline minus No City differences averaged between  
 404 noon and 18 LTC. Dark grey contours indicate urbanization boundaries as of 2010 (Houston-Galveston Area  
 405 Council, H-GAC; <https://www.h-gac.com/Home>) and light grey show location of major intraurban highways. ).  
 406 Wind vectors are plotted only every 6 grid points to avoid cluttering.



407

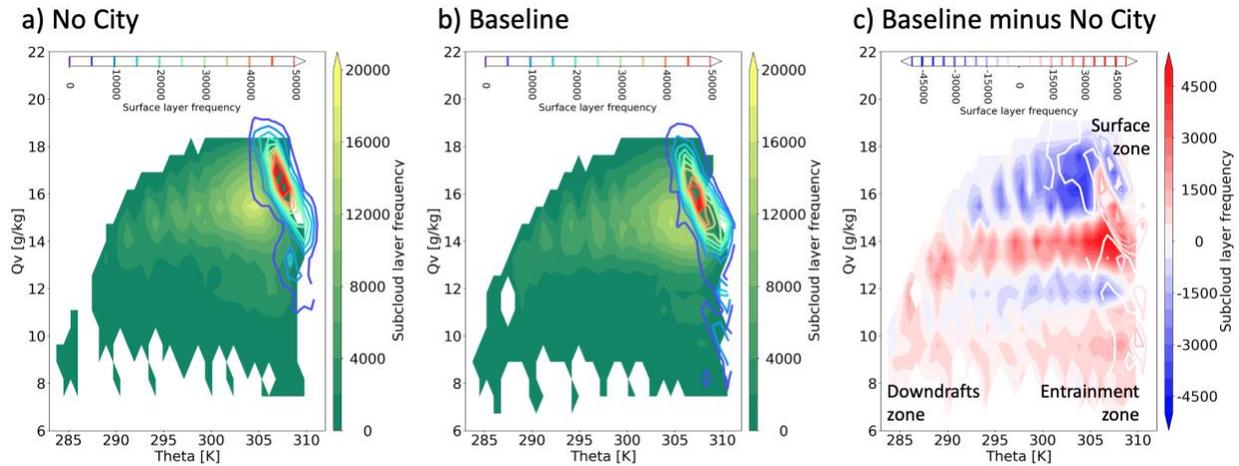
408 **Figure 11.** Diurnal-height Baseline minus No City scenario differences spatially averaged over the urban areas for  
 409 (a) temperature, (b) vertical wind component, (c) water vapor mixing ratio, (d) moist static energy (MSE), (e),  
 410 horizontal moisture flux convergence, and (f) vertical moisture flux convergence. Vectors in each panel correspond  
 411 to the horizontal wind, with the north direction pointing upwards. In the vertical, wind vectors are plotted only every  
 412 6 grid points to avoid cluttering.

413 To better understand the factors driving enhanced clouds over the urban dome, we  
 414 examined the diurnal-height urbanization impacts for various dynamical and thermodynamical  
 415 parameters (Fig. 11). Synchronous with enhanced afternoon uplift, the urban dome extends  
 416 higher with a dipole of warmer and drier air mass over the city and cooler and moister air mass in  
 417 the upper-mixing layer. A significant feature in Fig. 11 is that the mixed layer air entering the  
 418 clouds is related to enhanced Moist Static Energy (MSE), likely supported by the increased  
 419 sensible heat and warmer temperature near the surface, as well as enhanced moisture in the

420 upper-mixed layer. Dynamically, this air mass is sustained by the enhancement of both  
421 horizontal moisture flux convergence at low-levels and upward moisture flux convergence in the  
422 upper-mixed layer. Additionally, an urban-induced circulation cell with northerly low-level and  
423 south-southwesterly upper-mixed layer circulation disturbance (and enhanced moisture flux  
424 divergence) is apparent. This circulation pattern in the urban dome resembles the self-contained  
425 UHI circulation described by Fan et al. (2017). Moreover, Fig. 10 clearly highlights the  
426 horizontal extent of the low-level branch of this circulation, impacting beyond the urban area and  
427 well downstream of the city.

428         It is possible that shallow cumuli and enhanced precipitation (not shown) moisten the  
429 cloud and subcloud layers, further favoring more cloud development. Fig. 12 displays a bulk  
430 mixing line analysis with the thermodynamical structure of conserved variables (potential  
431 temperature and water vapor mixing ratio) in the subcloud layer. The enhanced frequency in the  
432 Baseline entrainment and downdrafts zones further suggests a more active cloud dynamics.  
433 Notably, when compared to the No City simulation, the Baseline simulation shows that surface  
434 fluxes predominantly provide a warmer and dryer mixing lines, with enhanced downdrafts  
435 moistening and cooling the subcloud layer. The enhanced cloud downdrafts help explain the  
436 layer of relatively cool air above the urban heat island dome shown earlier (Fig. 11a).  
437 Furthermore, the Baseline simulation also shows more air masses with warming and drying  
438 turbulent entrainment from the free atmosphere into the subcloud layer. Thermodynamically, the  
439 enhanced MSE in the subcloud layer (Fig. 11d) is then predominantly maintained by enhanced  
440 enthalpy from the surface zone, and partly enhanced by evaporation of the downdrafts and  
441 turbulent entrainment. An MSE budget can reveal the proportion of MSE fluxes from each zone,  
442 but we refrained to further diagnose the zone contribution fraction because by construction the

443 non-local closure PBL scheme used in our modeling setup limits a detail characterization of the  
 444 mixing lines within the mixed and subcloud layer.



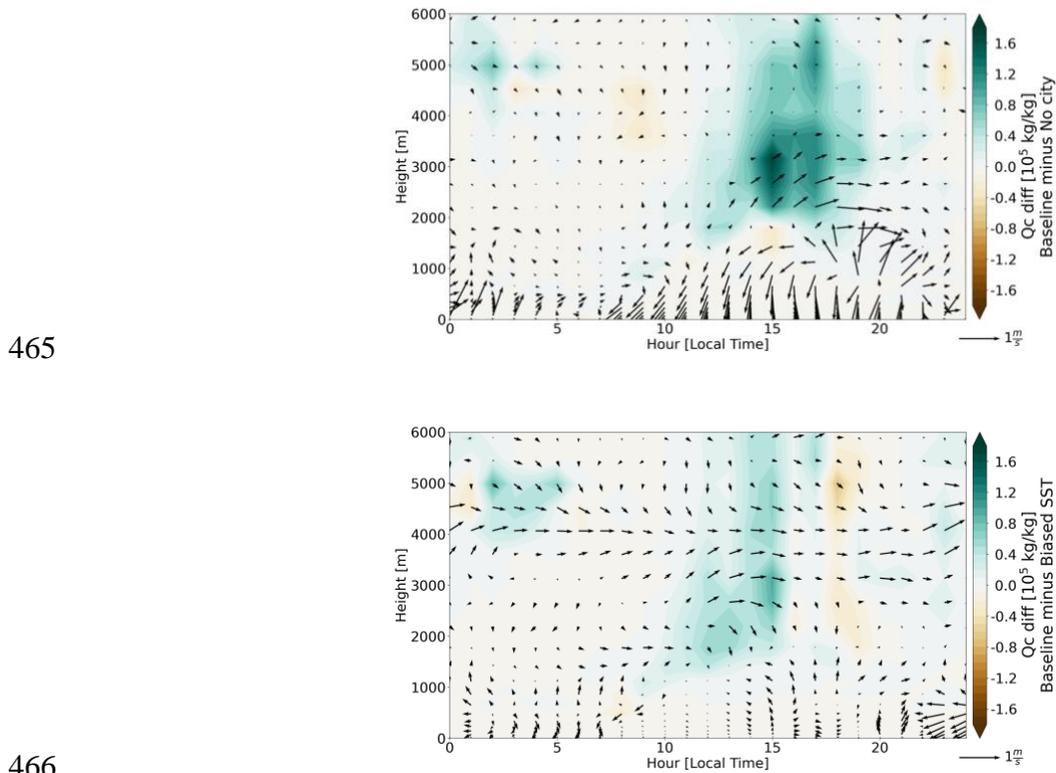
445

446 **Figure 12.** Potential temperature and water vapor mixing ratio (shaded contours) subcloud and (contours) surface  
 447 layers mixing line distribution analyses over the urban area for (a) No City, (b) Baseline and (c) Baseline minus No  
 448 City. Only urban grid points in the 12 to 16 LT period were considered.

### 449 3.4 SSTs Sensitivity

450 To test the sensitivity of the urban clouds against regional sources of moisture and mesoscale  
 451 circulations related to the land-sea contrast, we compared the Baseline with the Biased SST  
 452 simulations. Fig. 13 shows that the warm SSTs adjustment in the Baseline simulation favors  
 453 more shallow cumulus clouds. The effect of urbanization, however, is still dominant when  
 454 compared to the warm SSTs adjustment. Notwithstanding is that the warm SSTs adjustment also  
 455 increases clouds over the rural areas (not shown). By construction, the warmer SSTs develop a  
 456 warmer low-level atmosphere, with increased latent heat and water vapor, that in turn, are  
 457 advected by the predominant southerly and southeasterly flow (Fig. 3). Fig. 14 shows evidence  
 458 of warming and moistening over the city with some striking asymmetries in relation to the  
 459 changes in local circulation and the clouds themselves. The enhanced water vapor differences  
 460 and temperature is related to the more intense MSE signal favoring a thermodynamical pathway

461 for the enhanced clouds with a more unstable lower troposphere, with an enhanced, but weaker  
 462 relative to the Baseline minus No City, horizontal MFC support. Notably, the urban area shows  
 463 a low-level cooling and moistening signal in relation to the enhanced clouds, further displaying  
 464 the role of the urban clouds and subcloud layer processes in the daytime UHI effect.



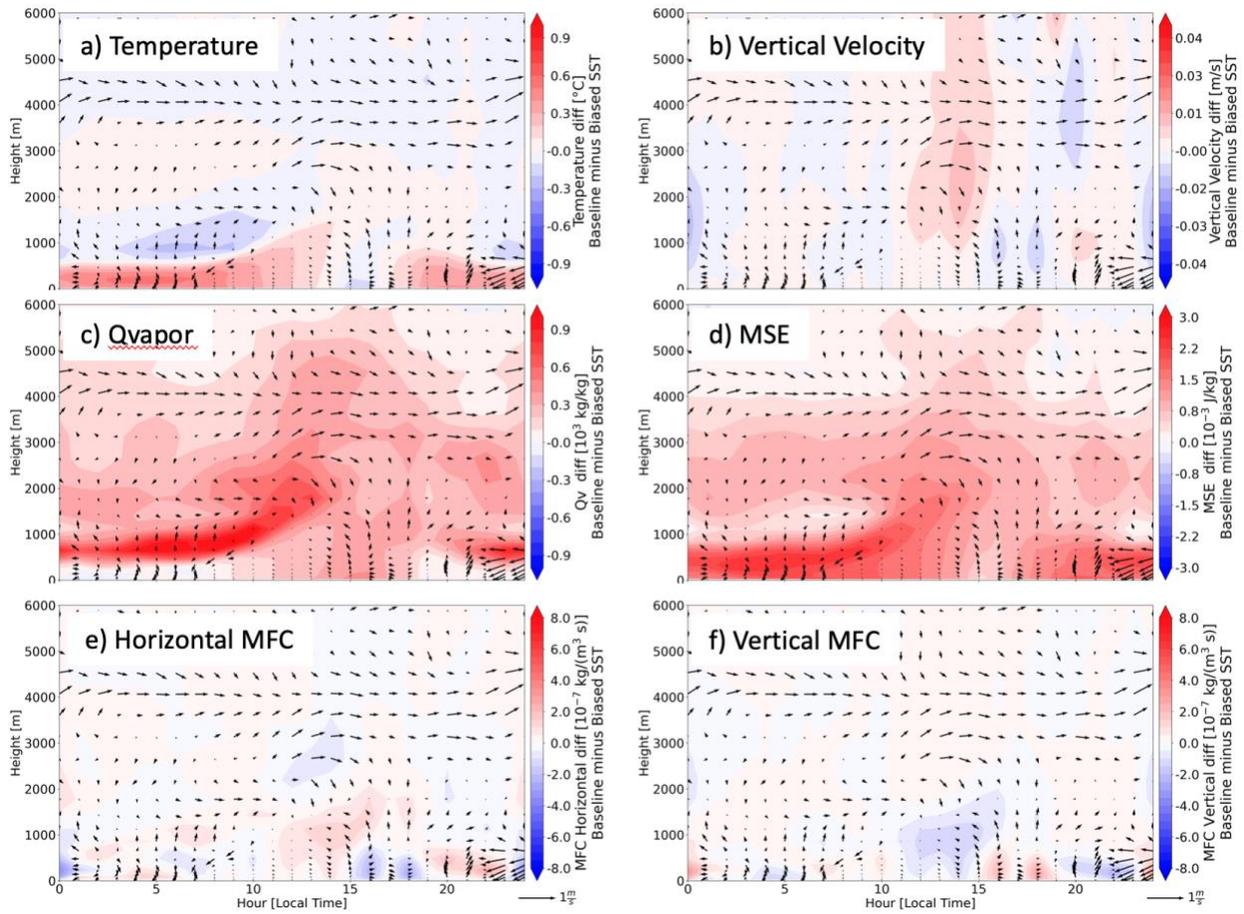
467 **Figure 13.** Diurnal-height Cloud mixing ratio and wind vector differences spatially averaged over the urban areas  
 468 for (top panel) Baseline minus No City and (bottom panel) Baseline minus Biased SST. Vectors in each panel  
 469 correspond to the horizontal wind, with the north direction pointing upwards). Wind vectors are plotted only every 6  
 470 grid point to avoid cluttering.

471 To better display the impact of the No City and Biased SSTs in the mesoscale  
 472 circulations, Figs. 15 and 16 show 6-hour averaged diurnal time slices for both interpolated fields  
 473 at 500 m height and latitude-height slices across the city (Fig. 1). The Baseline minus No City  
 474 differences show that the urban circulation dome is emphasized as the warm blob collocated with  
 475 the northerly wind differences. Earlier results showed that this urban circulation dome is favored  
 476 by the enhanced sensible heat flux, increasing the urban-rural thermal gradient and vertical

477 mixing over the city, and the dynamic frictional drag. Of note is that urbanization imposes  
478 anticyclonic and cyclonic differences to the west and east of the city core, with a horizontal scale  
479 as large as the urbanization scale and extending vertically as high as 3500 m ASL (Fig. 15; Fan  
480 et al. 2017). The urban circulation dome seems to dominate the circulation difference obscuring  
481 impacts on the bay- and sea-breeze circulation reported in the literature (Ryu et al. 2016; Shen et  
482 al. 2018; Fan et al. 2020; Wang et al. 2023).

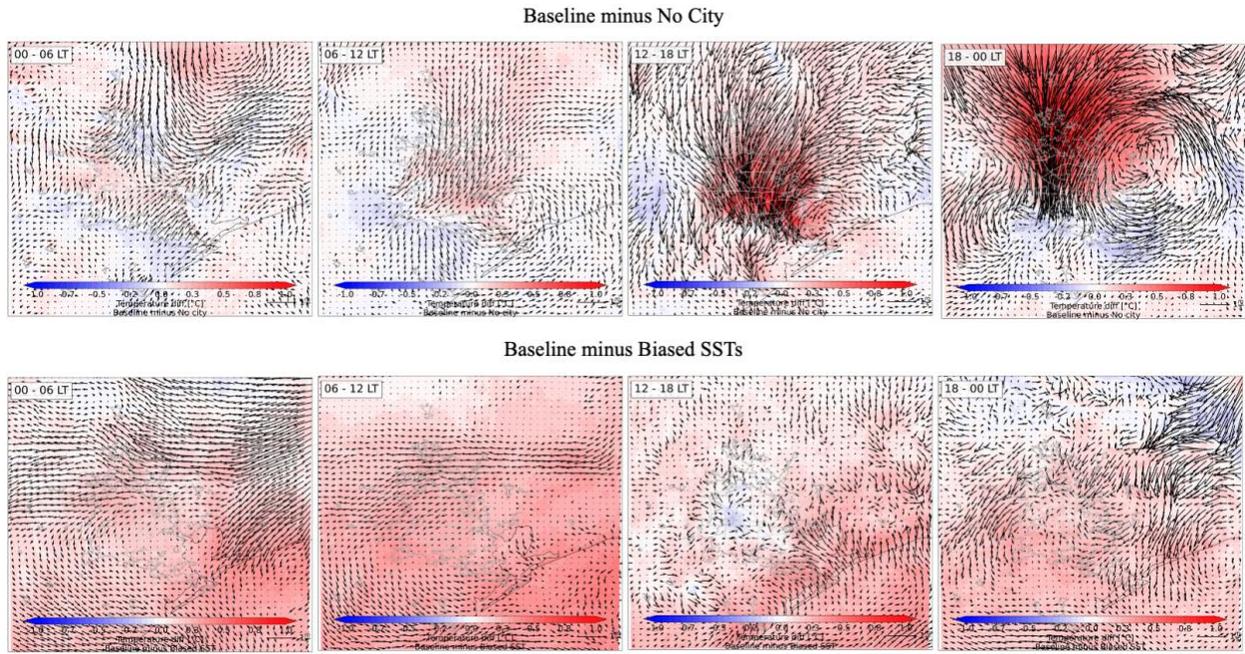
483         The impact of warmer SSTs in the Baseline simulation shows an enhancement of the  
484 evening-to-morning land-breeze and a weaker sea-breeze (Fig. 15), which agrees with previous  
485 SST sensitivity studies (Ryu et al. 2016; Chen et al. 2011). Characterizing the timing and  
486 intensity of the sea breeze in the Houston-Galveston area is complicated by the costal shapes and  
487 SST differences with a relatively warmer Galveston Bay compared to the Gulf of Mexico (Salas-  
488 Monreal et al. 2018). However, Fig. 16 shows that the weaker sea breeze cell favors the weaker  
489 moisture transport near the surface and augment the southerly-southeasterly flow in the return  
490 branch of the cell, which help describe the moist difference over the urban area (Fig. 14c).  
491 Additionally, the enhanced offshore sensible and latent heat fluxes in the Baseline simulation  
492 help develop a deeper and moist MBL (not shown), further enhancing transport of water vapor

493 by the background wind and in the return branch of the sea-breeze.



494

495 **Figure 14.** Same as Fig. 11 but for Baseline minus Biased SST scencario differences. Vectors in each panel  
 496 correspond to the horizontal wind, with the north direction pointing upwards. Wind vectors are plotted only every 6  
 497 grid point to avoid cluttering.



498

499

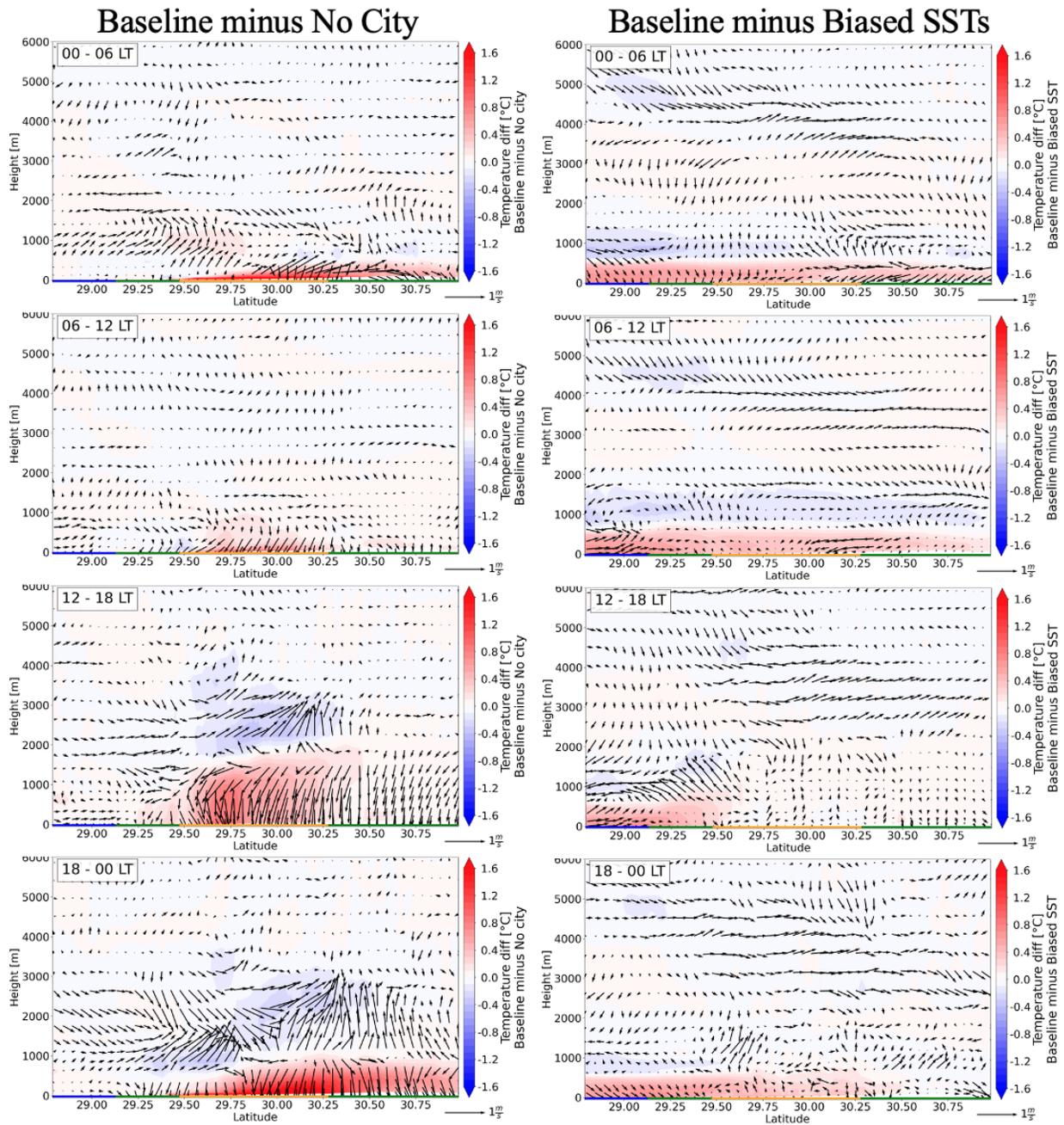
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**Figure 15.** Temperature (contours) and horizontal circulation (vectors) for Baseline minus No City and Baseline minus Biased SSTs differences diurnally averaged over 6-hour time slices (upper left corner in each panel; Local Time). Wind vectors are plotted only every 6 grid point to avoid cluttering. Horizontal analyses show interpolated fields at 500 m height; Dark grey contours indicate urbanization boundaries as of 2010 (Houston-Galveston Area Council, H-GAC; <https://www.h-gac.com/Home>) and light grey show location of major intraurban highways.



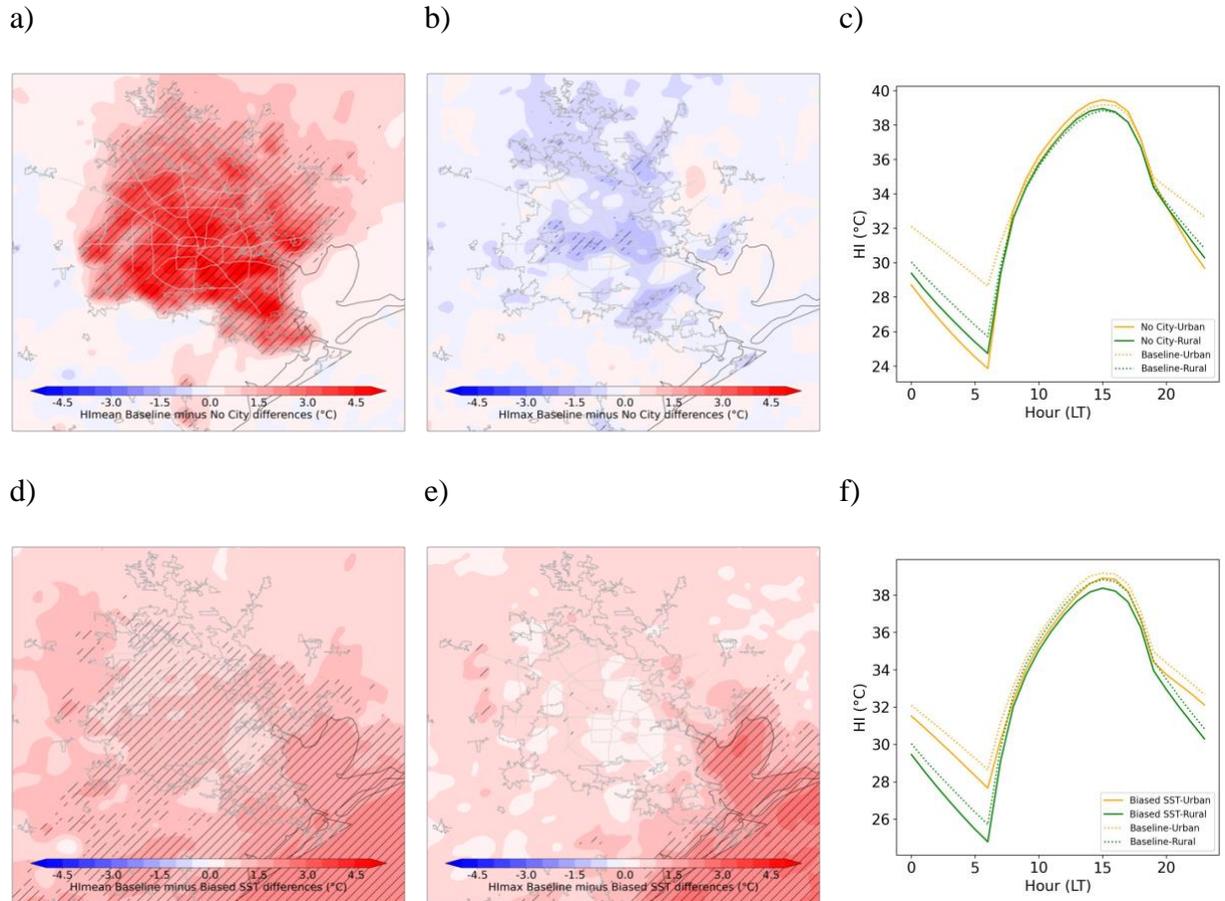
504

505 **Figure 16.** Diurnal evolution (top to bottom) of latitude-height temperature and wind vectors for Baseline minus No  
 506 City and Baseline minus Bias SST analyses along transect displayed in Fig. 1 with blue, green, and orange lines at  
 507 the bottom of the panels indicating the location of the water (blue line), rural (green lines), and urban areas (orange  
 508 line), respectively. Vectors in each panel corresponde to the horizontal wind, with the north direction pointing  
 509 upwards.

### 510 **3.5 Heat Index Sensitivity**

511 Here, we examine the role of urbanization, clouds, and SST uncertainties in the Heat  
512 Index. Fig. 2 shows that the model has some limitations in simulating the amplitude of the  
513 diurnal cycle of the HI over both rural and urban areas, overemphasizing the HI during the  
514 nighttime and underemphasizing the HI during the daytime. Although these diurnal biases can  
515 be traced to a low performance in simulating the relative humidity, more work is needed to  
516 assess the model limitations and sources of uncertainty in estimating the HI. By contrasting the  
517 model simulation scenarios, however, we can partly cancel these biases (i.e., linearizing the  
518 potential effect of internal feedbacks) and retain the signal related to urbanization, clouds and  
519 SST in the diurnal evolution of the HI.

520 Figure 17 shows the sensitivity of the HI to urbanization and SST adjustments. On the  
521 mean, the UHI has a significant influence in increasing the HI mostly during the nighttime and  
522 early morning. During high HI times (around 15 LT), however, urbanization is related to weaker  
523 HI compared to the rural areas, due to the competing impact of air temperature and relative  
524 humidity on the HI. Over the city, the weaker high HI is due partly to the urban dry island effect  
525 (Fig. 5), and partly due enhanced clouds and its surface temperature cooling effect (Fig 8),  
526 limiting high temperatures in the city (Fig. 6). The sensitivity of the HI to moisture is also  
527 shown when contrasting Baseline with the Biased SST simulation. Fig. 17 also shows that the  
528 warmer SSTs ( $\sim 1^\circ\text{C}$ ) impact the mean HI with a more intense effect near the coast and over the  
529 urbanized areas. During high HI, the HI impact of the warmer SSTs over the urban area is less  
530 apparent, likely due to the cloud surface cooling effect balancing the warmer and moist sea  
531 breeze (Fig. 14).



532 **Figure 17.** Mean and diurnal maximum Heat Index (HI) differences for Baseline minus No City (a, b, respectively)  
 533 and Baseline minus Biased SST (d and e, respectively), with hatched areas indicating that differences are significant  
 534 with a 95% confidence level; Dark grey contours indicate urbanization boundaries as of 2010 (Houston-Galveston  
 535 Area Council, H-GAC; <https://www.h-gac.com/Home>) and light grey show location of major intraurban highways.  
 536 HI diurnal variability composited by rural and urban areas is also added for (c) Baseline and No City and (f)  
 537 Baseline and Biased SST.

## 538 4 Discussion and Conclusion

539 To better understand the effect of urbanization in meteorology, this study developed 900  
 540 m grid size simulations using a cloud- and urban-resolving atmospheric model that includes a  
 541 Building Energy Model coupled with Building Effect Parameterization, over the Houston-  
 542 Galveston area, between 1-16 August 2020. The study investigates the intricate interplay of  
 543 clouds in local weather, considering various influencing factors. Several model realizations were

544 developed to isolate the role of the urban environment and to address SST biases in the complex  
545 Galveston Bay and Gulf of Mexico coast and its effect in the land-sea circulations known to  
546 affect the urban climate (Chen et al. 2011; Ngan et al. 2013; Fan et al. 2020). By excluding local  
547 anthropogenic aerosols and their effects, this research provides deeper insights into the  
548 relationship between the city and shallow cumulus clouds. These insights contribute to our  
549 understanding of the processes modulating excessive heat indicators over urban environments.

550 Through comprehensive model evaluation using 150 surface station sites, an upper-air  
551 wind profiler and a cloud climatology, our analyses reveal that the model simulations perform  
552 adequately, but common and well-documented biases remained. In agreement with Ngan et al.  
553 (2013), the model overestimates southerly winds by overemphasizing the nighttime low-level jet.  
554 Although it is out of the scope of this study, an energy and momentum budget can help elucidate  
555 and shed more light on the origin of the existing stronger southerly low-level wind biases.  
556 However, the model also simulates a stronger sea breeze, which is somehow consistent with the  
557 urban warm surface temperature bias (Fig. 2), and in turn can favor a more intense temperature  
558 gradient during the late evening and early morning and maintaining the onshore sea-breeze flow  
559 much longer. Likewise, the warm nighttime temperature bias could be partly related to the  
560 outlined biased low-level southerly winds by favoring more temperature advection from the  
561 offshore waters into land and the urban areas. All results and conclusions relying on advection  
562 of environmental parameters, including air pollution constituents (Ngan et al. 2013), into or  
563 downstream the city need to be assessed with caution. For example, the downstream extend of  
564 the UHI impact to the north and northeast of the city may be overemphasized in this model  
565 results due to the strong wind bias. Over rural areas, the warm and dry bias could be related to  
566 over advection of the UHI and urban dry island effects (Qian et al. 2022; Fig. 4). The bias

567 differences between the urbanized and the No City simulations show that the city is modulating  
568 the surface temperature errors, even over the rural areas (UHI advection and UHI dome and  
569 related circulations). On the other hand, Fig. 3d shows that the model simulates a weaker sea-  
570 breeze at La Porte when compared to the No City scenario. According to Cheng et al. (2011) and  
571 Salamanca et al. (2011), the enhanced drag imposed by the city decelerates the flow, which we  
572 show reduces the impact of the enhanced thermal driven land-sea circulation due to the warmer  
573 city (Fig. 10 and Fig. 15).

574         It has been suggested that the UHI is more pronounced during the nighttime (Oke 1982),  
575 but recent studies have found asymmetries in the time of the maximum diurnal UHI effect,  
576 arguing that vegetation type, urban and rural activities (Peng et al. 2012), or clouds (Vo et al.  
577 2023) can affect the time of its maximum. Surface station estimates suggest that during the  
578 period of study the UHI was more intense during the afternoon than during the morning, whereas  
579 the model suggested the opposite when evaluated at the same surface station locations. This UHI  
580 intensity disagreement is common when comparing surface station observations with urban  
581 canopy model output (Hu et al. 2019; Venter et al. 2021; Qian et al. 2022). However, estimating  
582 the magnitude of the UHI based on surface station observations is a challenging task, including  
583 observational uncertainty issues related to limitations of urban stations in following footprint  
584 standards (WMO 2008). Moreover, we noted that the magnitude of the UHI is more pronounced  
585 farther from the coast, but also varies according to the location of the rural stations relative to the  
586 predominant low-level flow, due to outlined advection of UHI downstream from the city. Our  
587 results show the typical ground heat flux driving the nighttime UHI, but other meteorological  
588 factors became apparent when considering the interaction with mesoscale circulations and  
589 clouds. During the afternoon, we speculate that the smaller simulated diurnal UHI can be partly

590 related to overdoing of the urban clouds, limiting temperature highs in the afternoon. During the  
591 nighttime, urbanization enhanced uplift water vapor and clouds that slow down nighttime  
592 longwave radiation cooling.

593         Houston-Galveston urbanization favors more shallow cumulus clouds. Our modeling and  
594 satellite results support Vo et al. (2023) by showing apparent cloud enhancement due to  
595 urbanization. The simulation period for this study coincides with the time of the year when the  
596 urbanization cloud patterns are the largest for Gulf Coast coastal cities (Vo et al. 2023). Our  
597 results agree with Loughner et al. (2011) and Theeuwes et al. (2019) hypothesis stating that even  
598 over urban areas with relatively drier environments, the surface-driven turbulence can sustain  
599 longer-lasting clouds compared to the surrounding rural areas. Despite the model uncertainties  
600 and biases shown and discussed above, and without considering the role of aerosols, which play  
601 a crucial role in the cloud and precipitation invigoration (Fan et al. 2020) in urban environments,  
602 our results help understand the mechanistic processes involved in the urban cloud enhancement.  
603 Particularly, our simulations confirm the control of the UHI in the clouds by enhanced vertical  
604 mixing due to aerodynamical drag and an enhanced sensible heat compared to the surrounding  
605 rural areas. In addition, our results also offer a deeper insight on the dynamical and  
606 thermodynamical factors interplaying in the cloud enhancement. The city sustains more clouds,  
607 with higher cloud heights and deeper shallow cumulus owing to enhanced moist static energy,  
608 partly due to enhanced enthalpy by the surface sensible heat and partly due to the enhanced latent  
609 heating favored by the enhancement of low-level horizontal moisture flux convergence  
610 (Loughner et al. 2011; Fan et al. 2017; Theeuwes et al. 2022; Chiu et al. 2022). We showed that  
611 more clouds, in turn, are related to a cooler surface temperature high, when compared to the No  
612 City environment and the rural areas surrounding the city. This cooling can further reduce

613 afternoon urban-rural heating contrasts and suppress vertical mixing. However, our mixing line  
614 analysis also shows that part of this cooling can also be attributed to evaporative cooling  
615 downdraft fluxes. Notwithstanding, enhanced MSE is predominantly maintained by the surface  
616 heat fluxes, with a minor role from the warm air entrainment fluxes. All these mechanisms also  
617 help understand the precipitation enhancement associated with urbanization (SFig. 4; Ryu et al.  
618 2016; Zhu et al., 2016; Lorenz et al. 2019; Madeline et al. 2021; Fan et al. 2020, Chiu et al.  
619 2022; Wang et al. 2023) and aerosol-cloud interaction and air pollution impacts (Loughner et al.  
620 2011; Seigel 2014; Fan et al. 2020; Zhong et al. 2015, 2017; Caicedo et al. 2019), which are  
621 ongoing observational and modeling research foci in the area (Jensen et al. 2022).

622 For the first time, our results suggest that the enhanced drag, sensible heat, and vertical  
623 mixing related to urbanization act as an obstacle to the prevailing flow, favoring urban  
624 circulation dome patterns with a horizontal scale of influence as large as the urban area (Fan et  
625 al. 2017). Previous studies have suggested that the UHI circulation can strengthen the sea breeze  
626 circulation, which favors moisture flux convergence and cooler airflow into the urban  
627 environment (Ryu et al. 2016; Zhong et al. 2017; Shen et al. 2018; Fan et al. 2020). However,  
628 our results show that dynamical fictional drag due to urbanization slows down the low-level flow  
629 with a scale of influence that appears to weaken the thermal-driven bay- and sea-breezes  
630 influencing the city. It is possible that deceleration owing the urban-dynamical drag effect  
631 becomes less prominent, and the urban land effect on the sea breeze circulation can become more  
632 evident, during weaker or different south-southwesterly background flow regimes (Chen et al.  
633 2011; Ngan et al. 2013; Wang et al. 2022).

634 Urbanization increases the mean HI, but at the time of high HI, urbanization shows less  
635 intense HI, due to the cloud pathway as a cooling mechanism. Additionally, the model

636 sensitivities to SSTs revealed that the coastal environment can modulate the UHI intensity, with  
637 warmer SSTs producing cooler urban surface temperature highs due to a similar enhanced  
638 shallow cumulus cloud pathway, despite the weaker but warmer and moist sea-breeze. Near the  
639 coast, the effect of the warmer and more humid environment advected by the sea-breeze due to  
640 the warmer SSTs appears to have a net intensification of the urban HI, whereas the high HI does  
641 not show significant sensitivity, likely due to the competing factors between the surface  
642 temperature and relative humidity. These results offer new insight and complements other  
643 studies focusing on urbanization and related modulation of the sea breeze as driving mechanisms  
644 of the urban heat stress and transport problems in cities near large surface water bodies (Shen et  
645 al. 2018; Caicedo et al. 2019; Wang et al. 2023).

646         Modeling work aiming to assess the impact of heat adaptation and mitigation strategies  
647 need to assess the tradeoffs in the UHI circulations and clouds pathways relationships. Most  
648 mesoscale urban heat mitigation modeling studies suggest different cooling strategies influencing  
649 city scale net cooling effects ranging from  $\sim 0.1$  to a few degrees  $^{\circ}\text{C}$ , depending on the intensity  
650 of the implementation (Krayenhoff et al. 2021), but often assume that model biases and other  
651 errors are somehow steady under different model conditions and disregard the effect of model  
652 errors on relevant physical process. Hence, the impact of cooling strategies can be overwhelmed  
653 by uncertainties in SST fields (i.e., those related to observations and data assimilation  
654 uncertainties), or by the accuracy of the simulated clouds and precipitation, which is typically an  
655 important source of uncertainty in the model.

656

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664 *in earlier versions of our model configurations.*

665

## 666 **Open Research**

667 All the observational data needed to develop this study is readily available online. Model  
668 configuration needed to replicate the simulations are described in the text. Readers can reach out  
669 the correspondent author for details and model output availability and postprocessing software  
670 (Python) used in the analyses.

671

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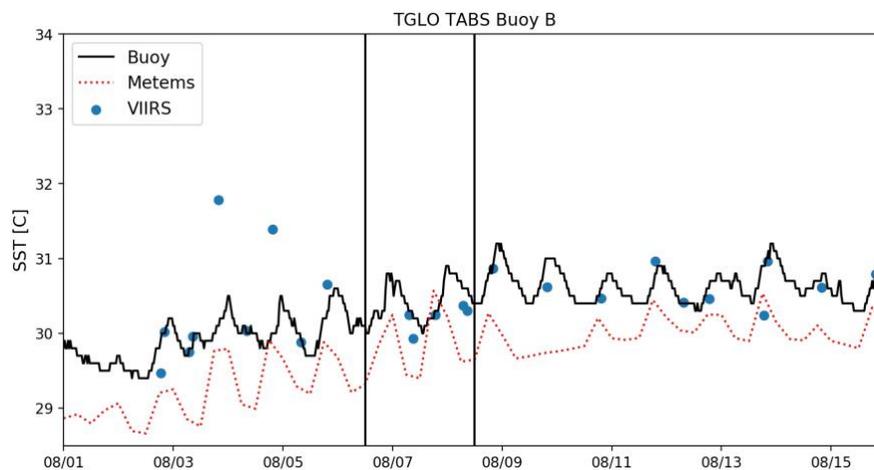
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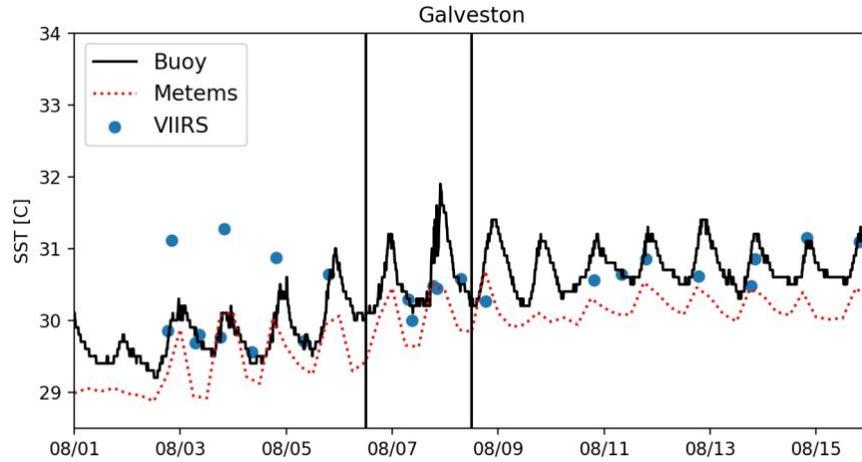
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## 848 5 Supplemental Material

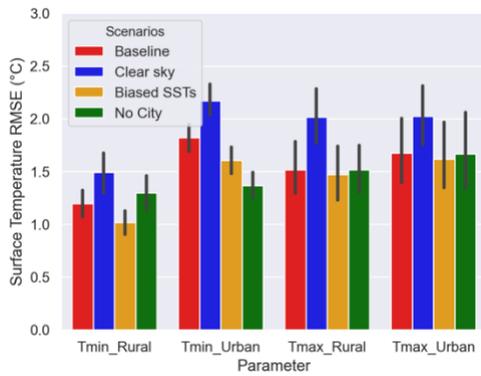




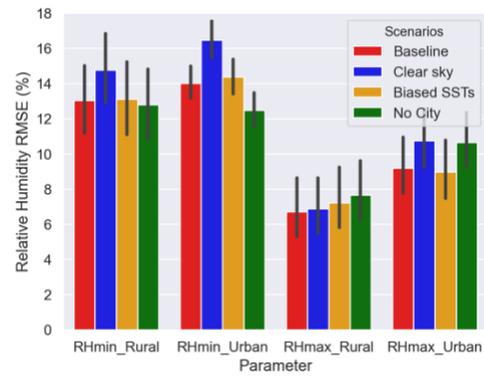
850

851 **Figure 1.** (Top panel) TGLO TABS Buoy B and (bottom panel) Galveston hourly buoy SST, twice a day remotely  
 852 sensed data (NOAA-SNPP VIIRS SST) and untreated-biased SST (after preprocessed by WRF). Date (MM/DD)  
 853 range for the first half of August 2020.

a) Surface temperature RMSE



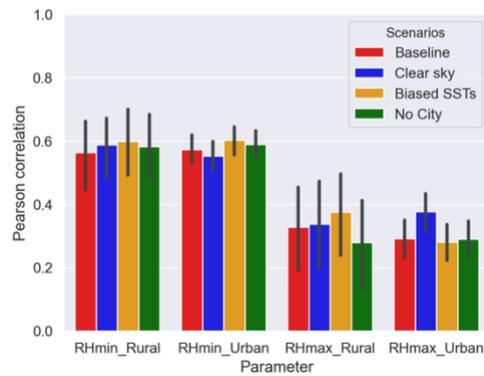
b) Relative humidity RMSE



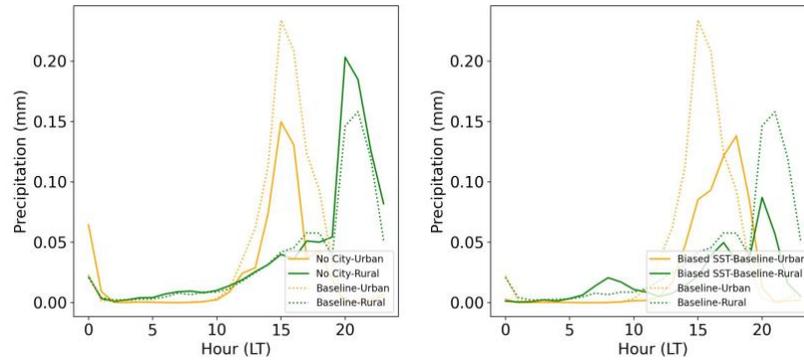
c) Surface temperature Pearson correlation



d) Relative humidity Pearson correlation



854 **Figure 2.** Simulated RMSE and Pearson correlation for evaluated at surface station sites for different scenarios  
 855 (Table 2) for (a, c) daily for surface temperature low and high (Tmin, Tmax), (b, d) relative humidity maximum and  
 856 minimum (RHmax, RHmin), and corresponding bias distribution for all examined surface station sites as  
 857 categorized as Urban or Rural according to MODIS/WUDAPTv2 land use/land cover types. Evaluation period is 1-  
 858 16 August 2020. Analysis constrained to non-rainy periods as described in the text.



859  
 860 **Figure 4.** Spatially averaged diurnal precipitation in the urban and rural areas for (left panel) Baseline and No City  
 861 and (right panel) Baseline and Biased-SST scenarios.