A numerical study of interactions between surface forcing and sea breeze circulations and their effects on stagnation in the greater Houston area

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High-resolution simulations from the Advanced Research Weather Research and Forecasting (ARW-WRF) model, coupled to an urban canopy model (UCM), are used to investigate impacts of soil moisture, sea surface temperature (SST), and city of Houston itself on the development of stagnant wind events in the Houston-Galveston (HG) area on 30 August 2000. Surface and wind profiler observations are used to evaluate the performance of WRF-UCM. The model captures the observed nocturnal urban-heat-island intensity, diurnal rotation of surface winds, and the timing and vertical extent of sea breeze and its reversal in the boundary layer remarkably well. Using hourly SST slightly improves the WRF simulation of offshore wind and temperature. Model sensitivity tests demonstrate a delicate balance between the strength of sea breeze and prevailing offshore weak flow in determining the duration of the afternoon-evening stagnation in HG. When the morning offshore flow is weak (3–5 m s⁻¹), variations (1°–3°C) in surface temperature caused by environmental conditions substantially modify the wind fields over HG. The existence of the city itself seems to favor stagnation. Extremely dry soils increase daytime surface temperature by about 2°C, produced more vigorous boundary layer and faster moving sea breeze, favoring stagnation during late afternoon. The simulation with dry soils produces a 3 h shorter duration stagnation in the afternoon and 4 h longer duration in the evening, which may lead to more severe nighttime air pollution. Hourly variations of SST in shallow water in the Galveston Bay substantially affect the low-level wind speed in HG.


1. Introduction

The objective of this paper is twofold: (1) to evaluate the performance of the Advanced Research Weather Research and Forecasting (ARW-WRF) [Skamarock et al., 2005] model coupled to a single-layer urban canopy model (UCM) to simulate urban heat island (UHI) intensity over the Houston metropolitan area, and (2) to understand the contributions of local land-surface and urban forcing to the evolution of land-sea breeze circulations, especially regarding their effects on the development of stagnant wind in the Houston-Galveston (hereafter HG) area. High air pollution events in the HG area are frequently attributed to strong surface emission [Wert et al., 2003; Ryerson et al., 2003] and meteorological conditions. Summertime near-surface winds in this region are determined by interactions between large-scale (background) geostrophic flows and sea breeze circulations. The latter is driven by differential heating between daytime warm land and the relatively cooler water. When the background wind is light to moderate and offshore, the inland penetration of the sea breeze can temporarily counteract the prevailing wind to produce a few hours of calm winds (stagnation) in the afternoon, which results in the buildup of high ozone concentrations in HG [Banta et al., 2005].

A typical summer diurnal cycle of surface winds leading to high air pollution episodes in the HG area is illustrated in Figure 1. The synoptic-scale wind (not shown) was northwesterly with increasing speed during the morning hours. In Figure 1, average surface winds were mostly southwesterly at midnight, and then gradually shifted to westerly around sunrise. In the early afternoon, southerly flow first developed near the shoreline as a result of sea/bay breeze development and then propagated inland. At 1500 CST (Central Standard Time), the southerly flow propagated inland against the northerly flow, resulting in afternoon-evening weak wind over the urban areas. Climatologically, this wind rotation...
pattern is highly correlated to the buildups of high-ozone days in HG [Banta et al., 2005].

Because numerical weather prediction (NWP) model output such as boundary layer depth and wind fields are used in air quality and chemistry models to characterize advection, dispersion, temperatures, and other critical parameters in the boundary layer, the accuracy of air quality forecasts are fundamentally limited by the accuracy of NWP models. The sea breeze has been extensively studied with theoretical analysis and was one of the first meteorological phenomena to be simulated with numerical models. In particular, the HG area is located near the coast and at 30° latitude, which, for given land-sea thermal contrast, maximizes the amplitude of the land–sea breeze circulation [Rotunno, 1983; Yan and Anthes, 1988]. Nevertheless, it is still difficult for current NWP models to accurately forecast the onset and inland propagation of the sea breeze front, the accompanying stagnation, and the development of nighttime return flow (land breeze) [Dabberdt et al., 2004; Bao et al., 2005]. Hence, understanding and correctly representing factors affecting sea breeze circulations in NWP models for complex urban environments is critical to improving air quality forecasting, as described below.

Besides the influence of large-scale flow, the formation and evolution of inland mesoscale circulations (including sea breeze) can be affected, for given synoptic environments, by regional and local land surface processes. For instance, mesoscale (10^2 km) soil moisture heterogeneity can significantly modulate the strength and extent of inland circulations and associated convergence zones [e.g., Chen and Avissar, 1994; LeMone et al., 2010]. On local and small scales, urban-induced atmospheric circulations, through modifying surface temperature gradients with urban heat islands, can significantly impact mesoscale dynamics and wind fields [Loose and Bornstein, 1977; Bornstein and Thompson, 1981; Holt and Pullen, 2007; Miao and Chen, 2008; Miao et al., 2009]. Urban heating also appears to play a role in distorting near-surface temperatures as sea breeze fronts pass [Novak and Colle, 2006] and affect the sea breeze recirculation pattern [Lo et al., 2007]. However, the complex interactions between large-scale and local-scale surface/urban heterogeneity and their collective effects on the evolution of sea breeze and boundary layer structures in HG have not been investigated.

Today’s NWP models are often executed with a grid spacing of 1–10 km for local and regional weather forecasts, and provide input for air dispersion and pollution models. At such fine scales, the role of cities in local and regional scales needs to be realistically represented in these NWP models to capture effects of the urban heat island on boundary layer wind, temperature, humidity, and depth. There has been some success in utilizing very simple urban treatment in NWP models to reproduce observed effects of urban heat islands [Taha, 1999; Best, 2005; Lo et al., 2007]. For instance, Liu et al. [2006] demonstrated that a simple bulk parameterization of cities in the Noah land surface model (LSM) coupled to the MM5 model can capture important features of near-surface weather variables in Oklahoma City and the surrounding rural areas. Nevertheless, a detailed investigation may require accurate description of urban land use and explicit UCMs that parameterize ensemble characteristics of the urban morphology [Brown, 2000; Masson, 2000; Kusaka et al., 2001; Martilli et al., 2002; Dupont et al., 2004; Otte et al., 2004; Chen et al., 2011].

Holt and Pullen [2007] used the numerical simulations of New York City as an example to demonstrate the importance of properly modeling the urban morphology to improve the model’s predictive capability. A recent study by Carrió et al. [2010] showed that urban growth can intensify sea breeze circulations and increase total precipitation over the HG area based on numerical simulations using different urban land use data sets. Despite previous studies on the role of cities in sea breeze circulations in coastal cities [Novak and Colle, 2006; Lo et al., 2007; Carrió et al., 2010; Leroyer

Figure 1. Diurnal evolution of surface 10 m winds (m s⁻¹) at 25 observation sites in the greater HG area on 30 August 2000. All times are Central Standard Time (CST): (a) 0000–0900 CST and (b) 1200–2100 CST. For UTC time, add 6 h. The thick black outline represents the approximate extent of the Houston metropolitan area.
et al., 2010], the impacts of land-atmospheric interactions at local city scale ($\sim 10^1$ km) and mesoscale ($\sim 10^2$ km) on the sea breeze circulations in major urban metropolitan areas are not fully explored. Therefore, this study investigates the role of surface and urban forcing in the evolution of wind stagnation associated with the 30 August high-ozone pollution event that occurred over the HG area during the Texas Air Quality Study 2000 (TexAQS2000) field program [Banta et al., 2005]. It uses observations and high-resolution mesoscale ARW-WRF model simulations. The HG metropolitan region was chosen as our focus area for several reasons: (1) frequent summer high-pollution events, (2) complex interactions among coastal zone, land sea breeze, and urban heat island, and (3) availability of rich surface and upper air data collected during the TexAQS2000 field experiment.

The two main questions addressed in this paper are: (1) How do regional and local land surface features and land-atmospheric interactions influence the evolution of sea breeze in HG necessary for high air pollution episodes? (2) To what degree can the new-generation NWP model (i.e., the WRF model) capture these physical mechanisms? The second question has practical implications because the WRF Atmospheric Chemistry (WRF-Chem) model has been used by the National Weather Service to issue air quality forecasts for major metropolitan regions since 2005. The remainder of this paper is organized as follows: Section 2 gives a general description of meteorological conditions and boundary layer evolution in the HG area for the selected 30 August 2000 case; a brief description of the coupled WRF/Noah/UCM modeling system is given in section 3; discussion of WRF model simulations and their evaluation against observations are found in section 4; factors influencing the evolution of the sea breeze are discussed in section 5, followed by a summary and conclusions.

2. General Meteorological Conditions for 30 August 2000

The 30 August 2000 event is chosen for this case study because it was part of a nine day pollution episode associated with weak synoptic-scale forcing from a ridge over Texas combined with a subtropical high at 500 hPa slowly moving east (not shown). During the entire pollution episode, the low-level winds over Texas remained weak ($5\sim10$ m s$^{-1}$ at 850 hPa) and the overall conditions were conducive to the persistence of a heat wave. In fact, the maximum surface temperature exceeded 40°C on several days, and an all-time high temperature of 43°C was recorded on 4 September in Houston downtown. Through the analysis of surface weather and chemistry mesonet data, the evolution of the sea breeze having a dominant effect on local O$_3$ concentrations in the HG area has been well established [e.g., Banta et al., 2005]. In this particular case, the surface mesonet data show three distinct phases of the daytime surface winds characterized by (see Figure 1): (1) the offshore flow persisting for most of the morning and early afternoon hours in the HG area; (2) flow along the shore of Galveston Bay indicating the initial influence of the bay breeze until 1400 CST; and (3) the gulf sea breeze in late afternoon. Vertical profiles of the horizontal winds measured at LaPorte, Texas, show that these wind patterns occupied a deep layer within the atmospheric boundary layer. The offshore flow prior to 1400 CST and the transition to light winds at 1400 CST occurred through a layer more than 400 m deep. The onshore flow began before 1500 CST in a layer less than 100 m deep and grew deeper after 1530 CST.

3. Description of the Coupled WRF-Noah-UCM Modeling System and Urban Land Use Data

The ARW-WRF model is a nonhydrostatic, compressible model with mass coordinate system [Skamarock et al., 2005]. We integrate the Advanced Research WRF (ARW version 2.2) over the four nested domains shown in Figure 2a. The model contains $70 \times 70$, $121 \times 121$, $172 \times 172$, and $190 \times 190$ grid points for the domains with a grid spacing of 27, 9, 3, and 1 km, respectively. The vertical grid contains 38 layers levels, and is stretched to allow spacing of $\sim 100$ m near the lowest model grid point (at 25–30 m above the ground level) with $\sim 1$ km spacing at the model top near 50 hPa. In this study, the WRF model is used to conduct 36 h simulations from 0000 UTC 30 August to 1200 UTC 31 August 2000. The initial condition and 3 h lateral boundary conditions are obtained from National Centers for Environmental Prediction (NCEP) Environmental 40-km Data Assimilation System (EDAS) analyses. This case represents a fair weather day without precipitation in the modeling domain D4, and the WRF simulated 24 h rainfall accumulation for D3 is merely 0.8 mm, so the simulated results in D4 are not affected by convective precipitation.

Regardless of the complexity of urban models, the first challenge in NWP urban modeling is to accurately characterize the extent of urban areas, as pointed out by Holt and Pullen [2007] and Chen et al. [2011]. Using remote-sensing data helps specify the underlying surface characteristics in large urban areas. As shown in Figure 2, the urban area categories for the HG area are adjusted by using the USGS 2001 National Land Cover Data set (NLCD, http://landcover.usgs.gov/classes.php) based on the 30 m Landsat satellite data (Figure 2d), which, compared to the 1994 USGS land use map (Figure 2c), show slightly larger urban areas, consistent with the urban expansion from 1994 to 2001. Note that the NLCD data set divides the developed urban land use into four categories: (1) industrial/commercial, (2) low-density residential, (3) high-density residential with distinctive impervious covers, and (4) open space (mixture of some

Figure 2. WRF modeling domain and location of observation sites: (a) model nested meshes with the horizontal grid spacing of 27, 9, 3, and 1 km for domains D1, D2, D3, and D4, respectively; (b) the terrain height (m) for D4, (c) the extent of urban area (in purple) depicted by the 1994 USGS data set for D4, and (d) the urban extent depicted by the 2001 NLCD data set, with: “industrial/commercial” in red, “high-density residential” in yellow, and “low-density residential” in green. The transect A-B indicates the location of the spatially filtered cross section of horizontal wind and humidity (Figure 7) discussed in section 5. Also shown in Figure 2d are observations sites: solid circles indicate surface stations, and solid squares are locations of wind profilers.
Figure 2
constructed materials, but mostly vegetation in the form of lawn grasses). This type of detailed urban classification is critical for defining urban geometry, hydrologic characteristics, and subgrid-scale natural land cover fraction required by more sophisticated urban canopy models such as the one used in this study and described below.

[12] The PBL scheme used (MYJ scheme [Janjic, 1996, 2001]) predicts turbulent kinetic energy and allows vertical mixing between individual layers within the PBL. Other physical parameterizations used here include the single-moment 6-class microphysics scheme (WSM6), the shortwave radiation scheme [Dudhia, 1989], the RRTM longwave radiation scheme, and the Noah land surface model (LSM) [Chen et al., 1996; Chen and Dudhia, 2001; Ek et al., 2003]. The Noah LSM provides surface sensible and latent heat fluxes, and surface skin temperature as lower boundary conditions to drive the atmospheric boundary layer in WRF.

[13] A single-layer UCM developed by Kusaka et al. [2001] and Kusaka and Kimura [2004] was coupled to Noah in WRF to represent the thermal and dynamic effects of cities [Chen et al., 2011]. The basic function of this UCM is to take the urban geometry into account in its surface energy budgets and wind calculations, which includes: (1) 2D street canyons parameterized to represent the effects of urban geometry on urban canyon heat distribution, (2) shadowing from buildings and reflection of radiation in the urban canopy layer; (3) diurnal cycle of solar azimuth angle, (4) man-made surface consisting of eight canyons with different orientation; (5) Inoue’s model for canopy flows [Inoue, 1963]; (6) the multilayer heat equation for the roof, wall, and road interior temperatures; and (7) a very thin bucket model for evaporation and runoff from road surface.

[14] Further, we have made two modifications to the original UCM: (1) adding the calculation of wind speed within the urban canopy, and (2) adding the diurnal cycle of anthropogenic heating (AH) related to energy consumption by human activities (heating/cooling of buildings, industry, traffic, etc.). In the modified UCM, half of the AH from buildings and from vehicles is added to the air of the first vertical level above ground and the other half to the surface energy equations of the roof, wall, and road respectively. Maximum AH values of 90, 50, and 20 W m⁻² are used in WRF-UCM for commercial/industrial, high-density residential, and low-density residential urban land use types, respectively, which are based on the AH data by Ching et al. [2009] for the HG area. Details about these modifications are documented by Miao et al. [2009].

[15] This UCM uses a multilayer heat transport model (five layers in this study) to calculate the surface temperature at the top of roof, wall, and roads and then uses these results to calculate sensible heat fluxes transferred from roof, wall, and road. Finally, these heat fluxes are aggregated into total heat fluxes between the urban canyon and the atmosphere. Those heat fluxes can be estimated with the Monin-Obukhov similarity theory or with the Jurges formula commonly used in the architectural field. The specification of UCM various parameters is described in Table 1.

[16] It is also necessary to estimate heat transfer from the natural surface (parks, recreation areas, etc.) when a modeling grid cell is not fully covered by urban man-made surface. Hence, this UCM is coupled to Noah through a parameter “urban fraction” (U_f) to represent urban subgrid-scale heterogeneity, which can be estimated by fine-scale satellite images. Hence, the aggregated grid-scale sensible heat flux can be estimated as follows:

\[
H = (1 - U_f)H_{LSM} + U_f H_{URBAN}
\]

Here, H is the total sensible heat flux from an “urban” grid cell to the atmospheric surface layer, U_f is the area ratio of a man-made urban surface, and (1 - U_f) represents natural surface such as grassland, farmland, and trees. H_{LSM} is the sensible heat flux from the Noah LSM for natural surfaces, while H_{URBAN} is the sensible heat flux calculated by UCM for “artificial” surfaces. Latent heat flux and upward longwave radiation flux are treated similarly. The effective surface skin temperature at the grid point is calculated as the averaged value of the 4th power of the temperature on the artificial and natural surfaces weighted by their area.

### 4. Evaluation of the WRF-Noah-UCM Simulation

[17] The surface observation data used for the model evaluation are taken from the Texas Commission on ...
Environmental Quality (TCEQ) (http://www.tceq.state.tx.us/cgi-bin/compliance/monops/site_photo.pl) collected during the TexAQS2000 field program. For this particular case (30 August 2000), there were 29 surface met stations (shown in Figure 2d with solid circles), of which 20 stations were located in urban areas. The observed variables used in this study include surface wind speed and direction, air temperature and relative humidity, and hourly data from six wind profilers (solid squares in Figure 2d). Note that the above surface meteorological variables were measure at variety of heights above the ground level at the TCEQ stations, and we use 10 m wind speed and direction, 2 m air and relative humidity diagnosed in WRF for model evaluations.

4.1. Diurnal Wind Rotation

[18] Although sea breeze circulations are one of the first meteorological phenomena simulated by mesoscale models, today’s mesoscale models still have difficulty capturing the timing and location of wind reversal in coastal cities such as those occurring in the HG Bay area [Dabberdt et al., 2004]. Therefore, it is imperative to verify how well WRF simulates the evolution of observed surface wind in the HG area as shown in Figure 1. Average simulated surface winds are mostly southwesterly across the domain at midnight, and then gradually shifted to westerly with reduced speed before sunrise (0300 CST), as shown in Figure 3. They are northwesterly with increasing speed (∼3–4 m s⁻¹) during morning hours (0900 CST). While the WRF model captures the nighttime land breeze wind rotation very well, it underestimates the strength of the land breeze at 0900 CST.

[19] By 1200 CST, weak southeasterly flow (∼1 m s⁻¹) developed in WRF in two stations close to the bay shoreline, slightly earlier than observations. In the early afternoon (1500 CST), onshore southerly flow was apparent in the simulation, as well as in observations, as a result of sea breeze development and its subsequent inland propagation. The combination of the synoptic and sea breeze forcing resulted in weak winds (<2 m s⁻¹) over the urban areas from 1500 CST to 1800 CST. By 2100 CST, the dominant WRF surface winds in the domain, except north of the urban areas, were southwesterly. Bao et al. [2005] found that the MM5 forecast had a systematic easterly bias in low-level winds for HG, but that problem is not apparent in the WRF simulation. Overall, WRF is able to reproduce the observed diurnal wind rotation and stagnant wind over most of urban regions in early afternoon to late evening, but slightly underestimates both morning and afternoon wind speeds.

4.2. Near-Surface Variables Verification

[20] Simulated surface weather variables are compared to observations obtained from urban and rural sites in Figure 4. Note that for urban sites, the diagnostic urban canyon temperature (TC) and wind speed (UC), documented by Miao et al. [2009], are also included for this verification in addition to the 2 m temperature and 10 m wind speed, which are derived from the traditional Monin-Obukhov similarity theory. The model captures well the observed diurnal cycle of 2 m air temperature, particularly the nocturnal urban heat island (UHI) (i.e., 1°–2°C higher temperature in urban regions), while it slightly underestimates the amplitude of the diurnal cycle of rural temperature. The daytime cold bias in rural air temperature was also identified in the MM5 model simulations for HG [Bao et al., 2005]. However, our WRF simulation does not have the same nighttime cold bias in 2 m air temperature noted by Holt and Pullen [2007], which used the same single-layer UCM in the coupled Ocean-Atmosphere Mesoscale Prediction System (COAMPS) for simulating the month of August 2005 for the New York City metropolitan area, although the diagnosed urban canyon
air temperature has substantial cold bias for the first night, which somewhat improved later in the simulation. Moreover, the WRF simulation with UCM, used with a detailed urban classification map, was able to produce the often-observed heterogeneous distribution of air temperature within an urban heat island, namely higher temperature in high-intensity residential and commercial/industrial areas.

Figure 4. Comparison of observed and modeled (a, b) air temperature (°C), (c, d) wind speed (m s⁻¹), and (e, f) relative humidity (%) from 1800 CST 29 August 2000 to 0600 CST 31 August 2000 averaged for all urban sites (Figures 4a, 4c, and 4e) and for rural sites (Figures 4b, 4d, and 4f) in modeling domain 4. T2, WRF 2 m temperature; TC, WRF urban canyon temperature; WS10, observed and modeled 10 m wind speed; UC, WRF urban canyon wind speed.

[22] Use of the UCM represents a significant improvement. A WRF test simulation (not shown here) using the Noah LSM without the UCM, produced the nighttime 2 m air temperature averaged for the urban area, about 5 degrees lower than that simulated by WRF, with UCM.

[23] WRF-simulated 10 m wind speed also traces reasonably well the observed diurnal cycle of surface wind, but underestimates the early morning increase in wind speed for both urban and rural areas (the same problem as seen in Figure 3). In general, the model underestimates the relative humidity for both urban and rural sites, presumably due to a
high bias in simulated 2 m air temperature. Table 2 shows the verification statistics for urban and rural observations sites, calculated for 2 m temperature and relative humidity, 10 m wind speed, and canyon-level temperature and wind speed from the 1 km domain averaged for the period of 1800 CST August 29 to 0600 CST 31 August 2000. These statistics include the index of agreement (IOA) \[Pielke and Pearce, 1994\], and hit rate (HR) \[Schlüenzen and Katzfey, 2003\]. Both the 2 m and canyon-level temperature have a mean bias less than 1°C, and their averaged RMSE is less than 2°C. The WRF 10 m wind speed is slightly higher than observations and its canyon-level wind speed is lower, but the mean bias and averaged RMSE are less than 2 m s\(^{-1}\). In general, the traditionally diagnosed variables perform slightly better than the corresponding canyon-level variables, and the IOA and HR statistics are fairly close to those for the Beijing city from a similar WRF model configuration \[Miao and Chen, 2008; Miao et al., 2009\]. The model underestimates the relative humidity, which, as mentioned above, is apparently attributed to low humidity in initial conditions.

### Table 2. Verification Statistics Averaged for 1800 CST 29 2000 to 0600 CST 31 August 2000 and Averaged for Stations Located in Urban Areas

<table>
<thead>
<tr>
<th>Variable</th>
<th>Number of Stations [Urban Stations]</th>
<th>Mean</th>
<th>Standard Deviation</th>
<th>Mean Bias</th>
<th>RMSE</th>
<th>IOA</th>
<th>HR</th>
</tr>
</thead>
<tbody>
<tr>
<td>T</td>
<td>25 [18]</td>
<td>29.84</td>
<td>30.66</td>
<td>4.06</td>
<td>4.03</td>
<td>0.81</td>
<td>0.6</td>
</tr>
<tr>
<td>WS</td>
<td>25 [16]</td>
<td>2.21</td>
<td>2.36</td>
<td>0.76</td>
<td>0.56</td>
<td>0.15</td>
<td>1.09</td>
</tr>
<tr>
<td>RH</td>
<td>5 [4]</td>
<td>74.53</td>
<td>64.06</td>
<td>21.48</td>
<td>17.36</td>
<td>-10.5</td>
<td>-11.37</td>
</tr>
</tbody>
</table>

The criteria for hit rate calculation for temperature, wind speed, and relative humidity are 2°C, 1 m s\(^{-1}\), and 15%, respectively. Due to disparity in data quality, the number of stations used for verification is different for temperature, wind, and humidity. T, temperature (°C); WS, wind speed (m s\(^{-1}\)); RH, relative humidity (%); Obs, observation; V_Tr, traditional near-surface diagnosed variables; V_UC, variables in urban canopy; Mean, mean value; RMSE, root-mean-square error; IOA, index of agreement; HR, hit rate.

4.3. Verification With Wind Profiler Data

[24] Observed horizontal winds obtained from five wind profilers in the HG area are used to verify the model simulation. The differences between model results and observation at these five sites are quite small and illustrated by using the comparison with the data from the profiler located at the LaMarque site (southeast of Houston), as shown in Figure 5. The daytime convective boundary layer is defined as the center height just below the maximum signal-to-noise ratio (SNR) drop-off rate with the height \[Coulter and Holdridge, 1998\].

[25] Wind profiler observations (Figure 5a) reveals a four-stage evolution of PBL wind: (1) from 0600 to 1200 CST, the southerly flow in the boundary layer below 0.5 km starts to turn westerly and northwesterly; (2) stagnant winds emerge in the early afternoon and extend throughout the entire mixing layer, indicating the inland penetration of the easterly/southeasterly sea breeze, which counteracts the northwesterly flow; (3) a dominant southerly flow with speed increasing between 1800 and 0000 CST; and (4) nocturnal westerlies (land breeze) development, superimposed on the prevailing

![Figure 5](image-url)
flow, which starts near the surface 0200 CST and extends to 0.9 km by 0600 CST. The maximum convective layer depth is about 1.6 km over this urban site.

Compared to the above observations, the WRF results show a few deficiencies, namely: (1) overestimation of the low-level (<1 km) wind speed by 2–3 m s\(^{-1}\) from 1800 CST 29 August to 0600 CST 30 August, (2) underestimation (by 3–4 m s\(^{-1}\)) of the nocturnal wind speed (0000–0600 CST 31 August) above 1.6 km; and (3) slight overestimation of maximum boundary layer depth (by about 100 m). However, the model captures the following features remarkably well: (1) timing and vertical extent of afternoon low-level stagnant wind, (2) timing of sea breeze inland penetration (1500 CST) and its reversal (about 0200 CST), and (3) evolution of daytime convective boundary layer depth. Note that the wind profiler data have uncertainties and quality control issues (e.g., removal of migrating passerine birds contamination), so the model comparison with these data shown in Figure 5 may not be conclusive.

5. Impacts of Land–Atmospheric Interactions on Development of Land–Sea Breeze Circulations

In the foregoing, we have seen that the WRF-Noah-UCM model is able to reasonably capture both the daytime and nocturnal UHI and the diurnal cycle of wind fields at the surface and in the lower boundary layer. In the following, we investigate the effects of mesoscale surface features on the surface wind fields. As the strength of differential heating between the land and the water determines the evolution of land–sea breeze for given large-scale environmental conditions, four WRF numerical experiments are conducted for assessing the role of land and water surface characteristics in modulating the modeled land–sea breeze circulations: (1) replace daily 40 km sea surface temperature (SST) from NCEP EDAS by 6 km hourly SST (referred to as Exp. SST simulation hereafter); (2) replace the urban land use in HG by cropland (Exp. U2C); (3) set the root zone soil moisture at each grid point in the modeling domain 3 (3 km domain) to its soil-texture-dependent wilting point, which effectively eliminates the evaporation (Exp. DRY); and (4) like in Exp. DRY but set the root zone soil moisture at each grid point in the modeling domain 3 to its soil-texture-dependent field capacity so as to maximize surface evaporation (Exp. WET). The WRF simulation discussed in Section 4 is referred to as Exp. CTL.

5.1. Impact of Using Hourly Sea Surface Temperature

Previous studies indicated that high temporal resolution of SST is able to influence meteorological conditions along the coastline of the HG area [Byun, 2007]. Similar to the approach used by Ching et al. [2004] and Byun [2007], we use hourly SST derived from the Geostationary Operational Environmental Satellites (GOES), which has been routinely available and used in previous studies [Legeckis and Zhu, 1997] (also E. Maturi, Geostationary Operational Environmental Satellites (GOES)-derived sea surface temperature data sets, 2007, ftp://podaac.jpl.nasa.gov/pub/sea_surface_temperature/goes/goes10-12/doc/goes_guide_doc.html). Compared to the time-fixed SST Exp. CTL, the hourly SST (Exp. SST) are lower (2–3\(^\circ\) C) in the early morning in the Galveston Bay presumably due to radiative cooling in the shallow water in the bay (Figure 6a), higher during daytime (up to 3–4\(^\circ\) C) in the bay due to solar heating of shallow waters close to the coastline (Figure 6b). In the WRF simulation incorporating the diurnally varying SST, the 2 m air temperature over the Galveston Bay in the afternoon is about 1.5–2\(^\circ\) C warmer than Exp. CTL (Figure 7b). This result is similar to the study of Byun [2007] where he applied hourly SST in the MM5 model to simulate the meteorological conditions for the 26–27 September 2006 case over the Houston area.

Warmer onshore air in the afternoon reduces the temperature gradient between the bay and the land leading to a weaker bay breeze, which modifies the afternoon wind fields in Houston, roughly 50 km northwest of the Galveston Bay. Figures 7c and 7d compare the early morning and early afternoon 10 m wind speed obtained from Exp. SST and Exp. CTL. At 0500 CST (i.e., 11 h into the WRF model integration), differences are only discernable over the bay and gulf.
Figure 7. WRF simulation results: (a) difference of 2 m temperature between Exp. SST and Exp. CTL valid at 0500 CST 30 August 2000; (b) same as Figure 7a but valid at 1700 CST 30 August 2000; (c) 10 m wind vector at 0500 CST 30 August 2000; and (d) same as Figure 7c but valid at 1700 CST 30 August 2000. Black lines represent results from the simulation without hourly GOES SST and red lines represent results from Exp. SST (with hourly SST).

Table 3. Verification Statistics for the WRF Simulation With Hourly GOES SST: Exp. SST

| Variable | Number of Stations | Mean Obs | Mean V_Tr | Mean V_UC | Standard Deviation Obs | Standard Deviation V_Tr | Standard Deviation V_UC | Mean Bias V_Tr | Mean Bias V_UC | RMSE V_Tr | RMSE V_UC | IOA V_Tr | IOA V_UC | HR V_Tr | HR V_UC | HR V_Tr | HR V_UC |
|----------|-------------------|----------|-----------|-----------|------------------------|------------------------|------------------------|----------------|----------------|-----------|-----------|-----------|-----------|---------|---------|---------|---------|---------|---------|
| T        | 25 [18]           | 29.84    | 30.26     | 30.5      | 4.06                   | 3.62                   | 3.46                   | 0.41           | 0.29           | 1.69      | 1.61      | 0.95      | 0.95      | 0.76    | 0.79    | 0.76    | 0.79    |
| WS       | 25 [16]           | 2.21     | 2.24      | 0.71      | 0.98                   | 1.08                   | 0.56                   | 0.02           | -1.43          | 1.11      | 1.66      | 0.66      | 0.53      | 0.64    | 0.32    | 0.64    | 0.32    |
| RH       | 5 [4]             | 74.53    | 64.36     | 62.71     | 21.48                  | 16.37                  | 17.74                  | -10.17         | -8.96          | 17.04     | 16.88     | 0.81      | 0.84      | 0.61    | 0.64    | 0.61    | 0.64    |

*These statistics are averaged for 1800 CST 29 August 2000 to 0600 CST 31 Aug 2000 and averaged for stations located in urban areas. The criteria for hit rate calculation for temperature, wind speed, and relative humidity are 2° C, 1 m s⁻¹, and 15%, respectively. Due to disparity in data quality, the number of stations used for verification is different for temperature, wind, and humidity. T, temperature (°C); WS, wind speed (m s⁻¹); RH, relative humidity (%); Obs, observation; V_Tr, traditional near-surface diagnosed variables; V_UC, variables in urban canopy; Mean, mean value; RMSE, root-mean-square error; IOA, index of agreement; HR, hit rate.
where the Exp. CTL produces slightly higher wind speed, but
that differences propagates inland in the afternoon with a
much lower wind speed from Exp. SST, especially in urban
area. The wind speed in Exp. SST along the seashore is
about 2 m s\(^{-1}\) (i.e., half of that in Exp. CTL). Note that the
average (westerly or northwesterly) background wind speed
(Figure 3b) at 1200 CST (before the development of sea
breeze) over Houston is roughly 2–3 m s\(^{-1}\). Therefore, this
bay breeze with reduced strength properly counteracts the
background wind and results in a stagnant wind over the HG
urban areas in the afternoon.

Table 3 shows the evaluation of surface weather
variables obtained from Exp. SST. Compared to Exp. CTL
(Table 2), the Exp. SST reduces the bias for mean 2 m tem-
perature by 0.4 °C, 10 m wind speed by 0.13 m s\(^{-1}\), and
canyon-level temperature by 0.4°C. The bias improvement
seems to outgain the slightly worse RMSE. Ching et al.
[2004] also pointed out a similar improvement and found
that using hourly SST in MM5 improved the prediction of
sea breeze circulation simulations at 4 km grid resolution.

5.2. Impact of City

To better illustrate the inland penetration of sea breeze,
we examine the vertical cross section of simulated wind
vector and mixing ratio along the AB line shown in Figure 2d.
When the HG urban areas are replaced by crops (Exp. U2C),
the sea breeze starts earlier with a more vigorously developed

Figure 8. WRF-simulated wind vector (m s\(^{-1}\)) and mixing ratio of water vapor (×1000 kg kg\(^{-1}\)) in the
lowest 1200 m above the ground level. (a) Valid at 1600, 1800, and 2000 CST 30 August 2000, and (b) valid
at 0200, 0400, and 0600 CST 31 August 2000. (left) Results from Exp. CTL; (right) results from Exp. U2C
(without cities). The mixing ratio values are only shown for 0.016, 0.017, and 0.018 kg kg\(^{-1}\) to illustrate the
breeze front.
boundary layer at 1600 CST and 1800 CST, penetrates further inland at 1800 CST, and extends to the northern part of the city by 2000 CST (Figure 8a). There are two opposing effects involved in determining the strength of the daytime sea breeze. On one hand, the Exp. U2C slightly reduces the daytime temperature in HG urban areas, decreases the water-land temperature gradient, and hence reduces the strength of the sea breeze. This result is consistent with the study of Carrió et al. [2010] in that urban growth and associated larger UHI would increase sea breeze strength. On the other hand, due to lower roughness length for crops, after the bay breeze reaches the land in the afternoon (e.g., at 1600 CST), it propagates faster because of lower surface friction. The latter effect (dynamical effect) seems dominant and results in further inland penetration of the bay breeze and high wind speeds in the lower boundary layer. Comparing results of Exp. CTL and Exp. U2C at 1800 CST and 2000 CST reveals that the Exp. U2C, despite its early afternoon deeper boundary layer depth, has the same boundary layer depth as Exp. CTL once the sea breeze reaches the city, because the city generates more vigorous boundary layer development in Exp. CTL.

[32] Similarly, the nocturnal land breeze in Exp. U2C is stronger than that in Exp. CTL over the urban areas and leads to higher wind speed in the lower part of the boundary layer (Figure 8b). Therefore, the actual existence of the city appears to reduce wind speed and generally favors stagnant wind conditions due to higher roughness elements in urban areas.
Figure 9. Differences in (a, b) sensible heat flux (in W m\(^{-2}\)) and (c, d) latent heat flux (in W m\(^{-2}\)) valid at 1400 CST 30 August 2000 between the WRF control simulation and soil moisture sensitivity runs. Exp. WET – Exp. CTL (Figures 9a and 9c) and Exp. DRY – Exp. CTL (Figures 9b and 9d).
Figure 10. Differences in 2 m temperature (°C) valid at (a, b) 1400 CST 30 August 2000 and (c, d) 0200 CST 31 August 2000 between the WRF control simulation and soil moisture sensitivity runs. Exp. WET – Exp. CTL (Figures 10a and 10c) and Exp. DRY – Exp. CTL (Figures 10b and 10d).
5.3. Role of Background Soil Moisture

Figure 9 shows the differences of afternoon surface heat fluxes in the 1 km modeling domain between the WRF control simulation and soil moisture sensitivity tests. As expected, Exp. WET produces less sensible heating and more evaporation. These differences reach 200 W m$^{-2}$ northeast of the Galveston Bay and in the higher terrains west of Houston, and they also cover a large portion of the domain. Note that the distribution of the difference field in Exp. DRY is different from that in Exp. WET, with the large differences confined to west and southwest of the Galveston Bay.

Surface heat fluxes directly modify the lower level atmospheric temperature, particularly for daytime 2 m temperature (Figure 10) due to strong solar radiation heating at the surface. The afternoon 2 m temperature in Exp. DRY (Exp. WET) is roughly 2°C higher (lower) than that in Exp. CTL for the whole domain excluding cities. Despite its higher daytime temperature, the Exp. DRY produces lower nighttime temperature than Exp. CTL, because dry soils have lower thermal conductivity and the higher daytime temperature is not absorbed into soils but rather into the atmosphere through sensible heat fluxes.

With higher evaporation and lower air temperature, Exp. WET produces a moister boundary layer, reduces the land–water temperature gradient, and hence slows down the development of the sea breeze, which barely reaches the coast at 1600 CST (Figure 11a). In contrast, Exp. DRY increases temperature over the land surfaces, enhances boundary layer growth, and produces earlier sea breeze onset. As a result, it generates strong wind speed near the surface in the early afternoon before the bay breeze reaches the city. Compared to Exp. CTL (Figure 8a), although the Exp. WET develops a shallower boundary layer and a slowly progressing sea breeze, its wind speed is quite comparable to that in Exp.

Figure 11. Same as Figure 8 but for simulations results of (left) Exp. WET and (right) Exp. DRY: (a) valid at 1600, 1800, and 2000 CST 30 August 2000 and (b) valid at 0200, 0400, and 0600 CST 31 August 2000.
CTL, once the bay breeze reaches (1800–2000 CST) the city of Houston. Although the stagnation in the lower part of the boundary layer is very similar among Exp. CTL, WET, and DRY from 1600 to 1800, the wind speed in Exp. DRY is lower than the other two simulations at 2000 CST.

For all simulations (Exp. CTL, U2C, WET and DRY), the nocturnal land breeze is well developed by 0200 CST (Figures 8b and 11b). On average, Exp. WET has the highest wind speed in the lower boundary layer and the Exp. DRY produces the most significant stagnant wind, especially over the city.

Key characteristics of sea breeze development simulated by these four simulations are summarized in Table 4. Not surprisingly, the earliest (latest) inland propagation of the sea breeze is found in Exp. DRY (WET) due to their respective strongest (weakest) daytime land-water differential.

Table 4. Characteristics of Sea Breeze and Land Breeze Development Simulated by Exp. CTL, UTC, DRY, and WETa

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Time of Sea Breeze Reaching the Land Along the Line BA (Figure 2c)</th>
<th>Time of Sea Breeze Reaching the City Along the Line BA (Figure 2c)</th>
<th>Time of Sea Breeze Reaching the Northern Part of City Along the Line BA (Figure 2c)</th>
<th>Time for Sea Breeze to Cross the City (hours:min)</th>
<th>Time of Land Breeze Onset</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTL</td>
<td>1040 CST</td>
<td>1835 CST</td>
<td>2050 CST</td>
<td>02:15</td>
<td>0150 CST</td>
</tr>
<tr>
<td>U2C</td>
<td>1040 CST</td>
<td>1820 CST</td>
<td>2010 CST</td>
<td>02:00</td>
<td>0150 CST</td>
</tr>
<tr>
<td>DRY</td>
<td>1020 CST</td>
<td>1720 CST</td>
<td>2010 CST</td>
<td>02:50</td>
<td>0150 CST</td>
</tr>
<tr>
<td>WET</td>
<td>1100 CST</td>
<td>1815 CST</td>
<td>2120 CST</td>
<td>03:05</td>
<td>0135 CST</td>
</tr>
</tbody>
</table>

aThese results are based on 5 min WRF model output.
heating. Having drier soils and replacing urban areas with croplands will result in an earlier arrival of sea breeze in urban areas, at least 30 min sooner than the control simulation that produced the slowest arrival of sea breeze in the city. Because of its weakest strength, the sea breeze in Exp. WET reaches the urban areas the latest among these four simulations and takes the longest time (roughly 1 h longer than Exp. U2C) to reach the northern part of the city. The timing of the appearance of nocturnal land breeze is similar among these simulations except for Exp. WET, which is slightly (about 20 min) earlier due to the generally cool surface because a large portion of daytime incoming energy is used for evaporation rather than for heating the surface.

To further understand the effects of city and soil moisture conditions on producing calm wind situation, 5 min WRF output are averaged for the city area and the stagnation condition is defined when the hourly averaged 10 m wind speed is less than 1.5 m s\(^{-1}\) for a specific hour. The simulated stagnation time and boundary layer depth, also averaged for the city, are plotted in Figure 12 for the four simulations. Without the city, the daytime convective boundary layer in Exp. U2C peaks earlier but also collapses earlier than the other three simulations, indicating that the urban characteristics (rougher surfaces, anthropogenic heating, radiation trapping, etc.) in developed areas are able to sustain mixing in the boundary layer; the maximum PBL depth in Exp. U2C is between the lowest in Exp. Wet and highest in Exp. Dry. The development of stagnant wind over the city does not seem to be highly correlated with boundary layer depth in the city area, but it is obvious that Exp. U2C produces the shortest duration (only 3 h) of calm wind due to its overly smooth surface. Although the other three simulations have nearly identical stagnant wind duration (14–15 h during the 36 h simulation period), Exp. WET produces a 3 h shorter duration in the afternoon and 4 h longer duration in the evening. This, combined with a shallower boundary layer depth in the afternoon, could lead to more severe nighttime air pollution, because a weaker nighttime land breeze would reduce the dispersion of pollutants.

6. Summary and Discussion

In general, the WRF-UCM simulation captures the observed diurnal cycle of 2 m air temperature fairly well, particularly the observed nocturnal urban-heat-island intensity (i.e., 1°–2°C higher temperature in urban regions), although the model slightly underestimates the amplitude of the diurnal cycle of rural temperature. WRF simulations underestimated early morning increase in wind speed, seemingly a common problem associated with PBL parameterization schemes used in MM5 and WRF [Zhang and Zheng, 2004; Liu et al., 2006]. Nevertheless, WRF-UCM simulation results track the observed diurnal rotation of surface winds reasonably well. This demonstrates its ability, together with high-resolution urban land-use data, to accurately capture the development and propagation of sea (land) breezes, which are critical for the onset and subsequent evolution of stagnant wind in HG. Moreover, the model captures the timing and vertical extent of sea breeze and its reversal in the boundary layer remarkably well.

For both rural and urban sites, the averaged WRF model temperature bias errors are less than 1°C, and the averaged RMSE is less than 2°C. Verified against surface observations at the urban sites, the traditionally diagnosed near-surface variables in WRF perform slightly better than the corresponding canyon-level variables. But the WRF
model underestimates the relative humidity for both urban and rural sites. The surface pressure was not measured at the five stations where the relative humidity was measured, so we can only evaluate relative humidity (instead of mixing ratio). Such dry bias in relative humidity may be caused by initial high bias in 2 m temperature (Figure 4). Using hourly SST, compared to the use of daily SST, slightly improved the WRF simulation of offshore wind and temperature by capturing the daytime warming of shallower waters close to the bay coastline.

[41] More importantly, this study highlights a delicate balance between the strength of sea breeze and prevailing flow when the latter is offshore and weak. Such balance determines the duration of the afternoon–evening stagnation in the HG metropolitan area and is affected by environmental conditions. For this selected case in which the morning prevailing flow is offshore and relatively weak (3–5 m s⁻¹), the WRF model sensitivity tests reveal the effects of background soil moisture and city itself on the stagnant wind over urban areas. These effects can be summarized as the following in order of their relative importance:

[42] 1. The very existence of the Houston urban area favors stagnation. The built-up areas are probably the most significant factor, but their thermal effects and dynamical effects on stagnation seem opposing. Without urban areas, the dynamic effect (acceleration due to lower roughness length) dominates its thermal effect (i.e., reducing the water–land thermal contrast), resulting in a fast-moving sea breeze with increased wind speed and a stronger nighttime land breeze. That leads to a reduction of frequency of surface stagnation.

[43] 2. Background soil moisture can change the surface heat fluxes on the order of 50–200 W m⁻² at broader scales. Extremely dry soils increase daytime surface air temperature by about 2°C, develop a more vigorous boundary layer, and produce faster penetration of the sea breeze with high wind speed before reaching the city, which generally results in weaker winds in the urban areas in late afternoon. While the total durations of stagnation are similar between the simulations using wet and dry soil conditions, the simulation with dry soils produces a 3 h shorter duration in the afternoon and 4 h longer duration in the evening, which may lead to more severe nighttime air pollution.

[44] 3. Hourly, localized variations of SST in shallow water in the Galveston Bay have regional implications and influence the low-level wind speed in Houston, roughly 50 km in its northwest. Warmer (1°–2°C) air over the Galveston Bay in the afternoon caused by higher SST of the same magnitude reduces the strength of sea breeze, which rightly compensates the background wind of 2–3 m s⁻¹ and results in an afternoon stagnation in Houston.

[45] Note that although this selected case represents a summer stagnant wind situation typical to the HG area, it is nonetheless a case study and we need to exercise caution when generalizing the results. This study highlights that the land–atmospheric interactions are able to alter sea breeze circulation and the development of stagnant wind and high-pollution episodes. Therefore, a comprehensive field campaign with a network of surface flux towers located at both rural and urban sites with companion surface and upper air observation will help to further understand such complex interactions. The field experiment conducted in Marseille (a coastal city in France) is a good example [Lemonsu et al., 2004]. Moreover, a multilayer UCM developed by Martilli et al. [2002] has been recently incorporated in WRF [Chen et al., 2011], which allows buildings to directly interact with atmospheric boundary layer. Salamanca et al. [2011] compared its performance with single-layer UCM and found that the multilayer UCM generally produces better results when high–resolution city morphology data developed by Ching et al. [2009] are incorporated in WRF. Our future work will utilize this new urban modeling capability and focus on long-term simulations.

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