Modeling Anthropogenic Influences on Urban Meteorology and Air Quality: Insights from Coastal Urban Environments in the Houston metropolitan region

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ABSTRACT

The Houston, TX metropolitan area is impacted by a range of complex factors that influence air quality. This includes local emissions, unique meteorological conditions, and the transport of pollutants. Houston also lies within a humid subtropical climate regime, where sea-breeze dynamics often interacts with local urban and industrial emissions to degrade air quality. In this work, we evaluate how urban morphology affects boundary layer development over Houston, and in turn, how it affects summertime ozone formation using an urban modeling framework. While urban canopy modeling has advanced leaps and bounds in the last decade, it still lags when it comes to representing atmospheric chemistry. Herein we have incorporated an urban land surface model which includes building energy use and a non-local planetary boundary layer scheme to the widely used WRF-Chem model. In addition to improving air quality forecasts the model can also better represent aerosol-cloud processes. This study presents a sensitivity analysis to assess the impacts of different Urban Canopy Parameters (UCP) (based on local climate zones) on boundary layer heights and ozone formation. Model evaluation leverages data collected during the 2021 Tracking Aerosol Convection ExpeRiment – Air Quality (TRACER-AQ) campaign and the 2022 Convective-cloud Urban Boundary-layer Experiment (CUBE), which included 2 ozone lidars, various sonde launches, and aircraft measurements which collect spatial distribution data of NO2, HCHO, and O3. A specific case study used in this investigation occurred between 06 September 2021 and 11 September 2021, where ozone levels ranged from 30 ppb along the coast to more than 100 ppb inland and in urban regions. The model results showed greater NO2 and ozone levels as a function of urban percentage. This was due to coastal-urban flow slowdown and diminished sea breeze effects. The urbanized met-air quality model exceeded the non-urban scenario in terms of both air quality and surface meteorology.

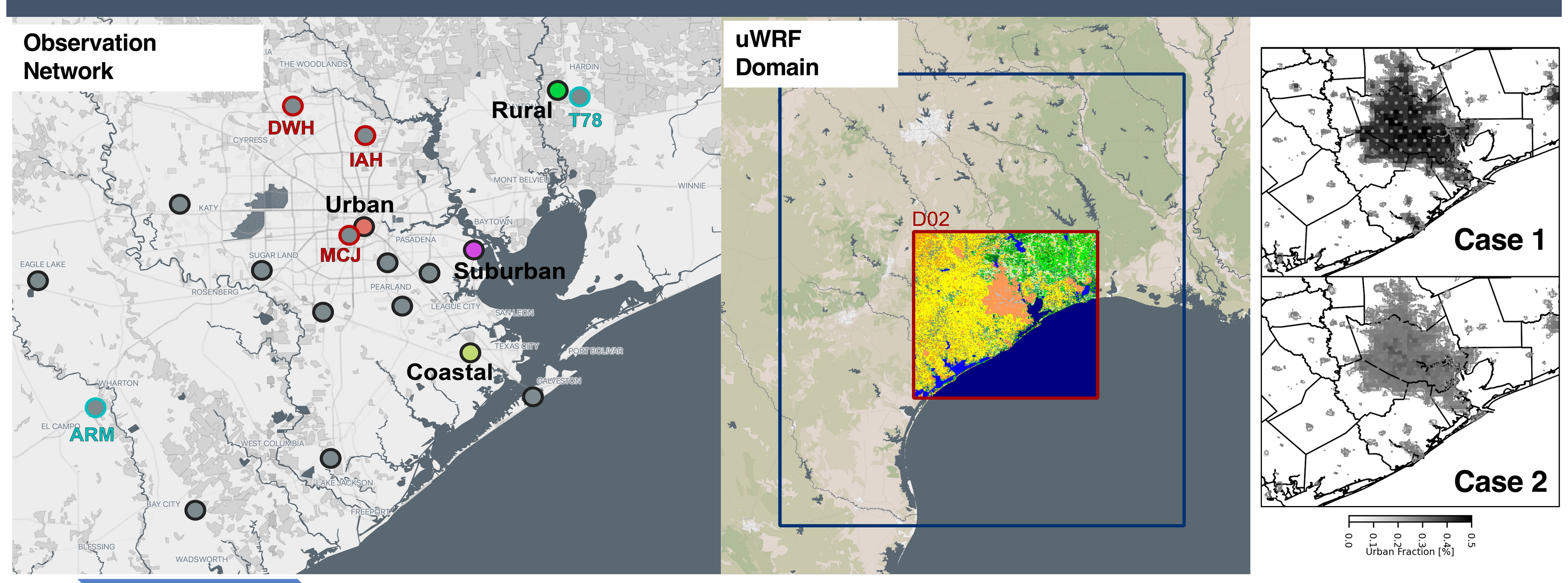
INTRODUCTION

- (Chen et al., 2011) – **Houston Sea Breeze Front (SBF) stagnation** by surface roughness & initiation due to UHI
- (Banta et al., 2005),(Han et al., 2022) – **Urban SBF** modification significant impacts on **air quality (AQ) circulation**
- (Dacic et al., 2020) (Kotsakis et al., 2022) – Differential urban heating create localized breeze patterns, **leading to wind stagnation and reversal confining urban emissions**, resulting in the accumulation of pollutants and exacerbating ozone non-attainment in densely populated coastal areas

Scientific Questions:

1. How does Houston's modification of sea breeze fronts (SBF's) alter local meteorology?
2. What are the specific impacts of modeled urban canopy structures on SBF dynamics, UHI effects, and air quality?
3. How effectively can current modelling techniques simulate these complex interactions, including sea-breeze front (SBF) dynamics, urban heat island (UHI) effects, and air quality

METHODS

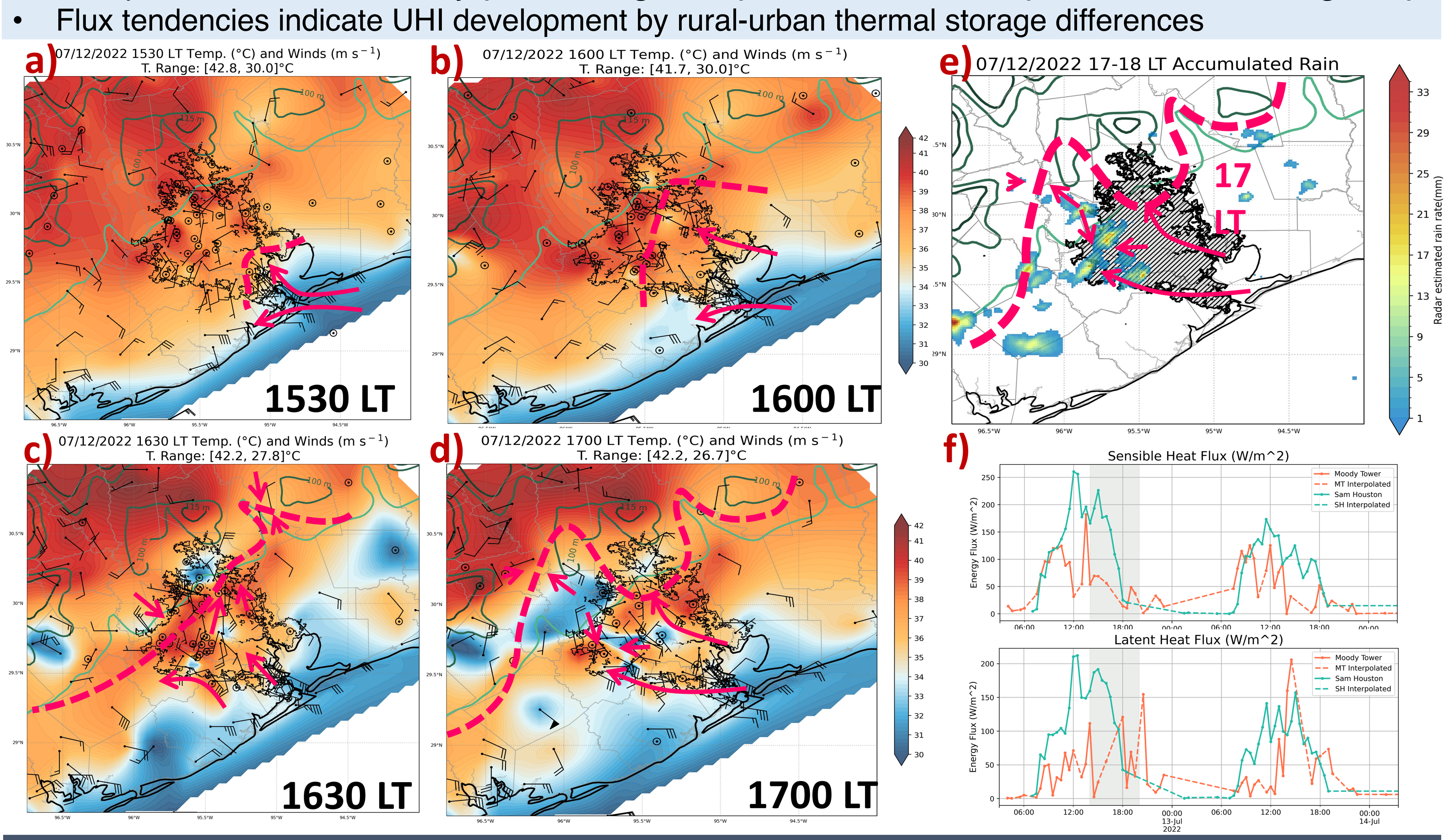


- **Surface Station Data (Temperature):** Timestamp w/ 10 min window → Spatial interpolation w/ nearest neighbor algorithm
- **Flux Data:** Coarsen data to 30 min avg → Linearly interpolate missing data
- **1 & 4km uWRF Model with Chem:** ICBC: HRRR → MYNN PBL → UCP: WUDAPT → BEP+BEM

Note Urban fraction in case 2 is scaled down by 20% of case 1

OBSERVATION RESULTS 07/12/22 CASE

- **Weak SBF initiated** by **UHI** enhanced land-sea gradient deepens storm convection
- Front stalling North of city by topography
- Strongest **convergence** in **urban domain** throughout episode
- Precipitation stifled East of city **(urban roughness)**, enhanced to West **(downwind reconvergence)**
- Flux tendencies indicate UHI development by rural-urban thermal storage differences



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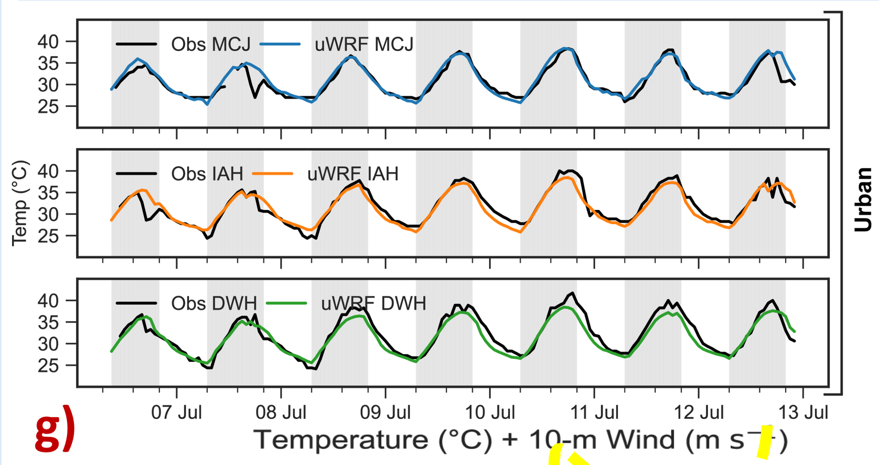
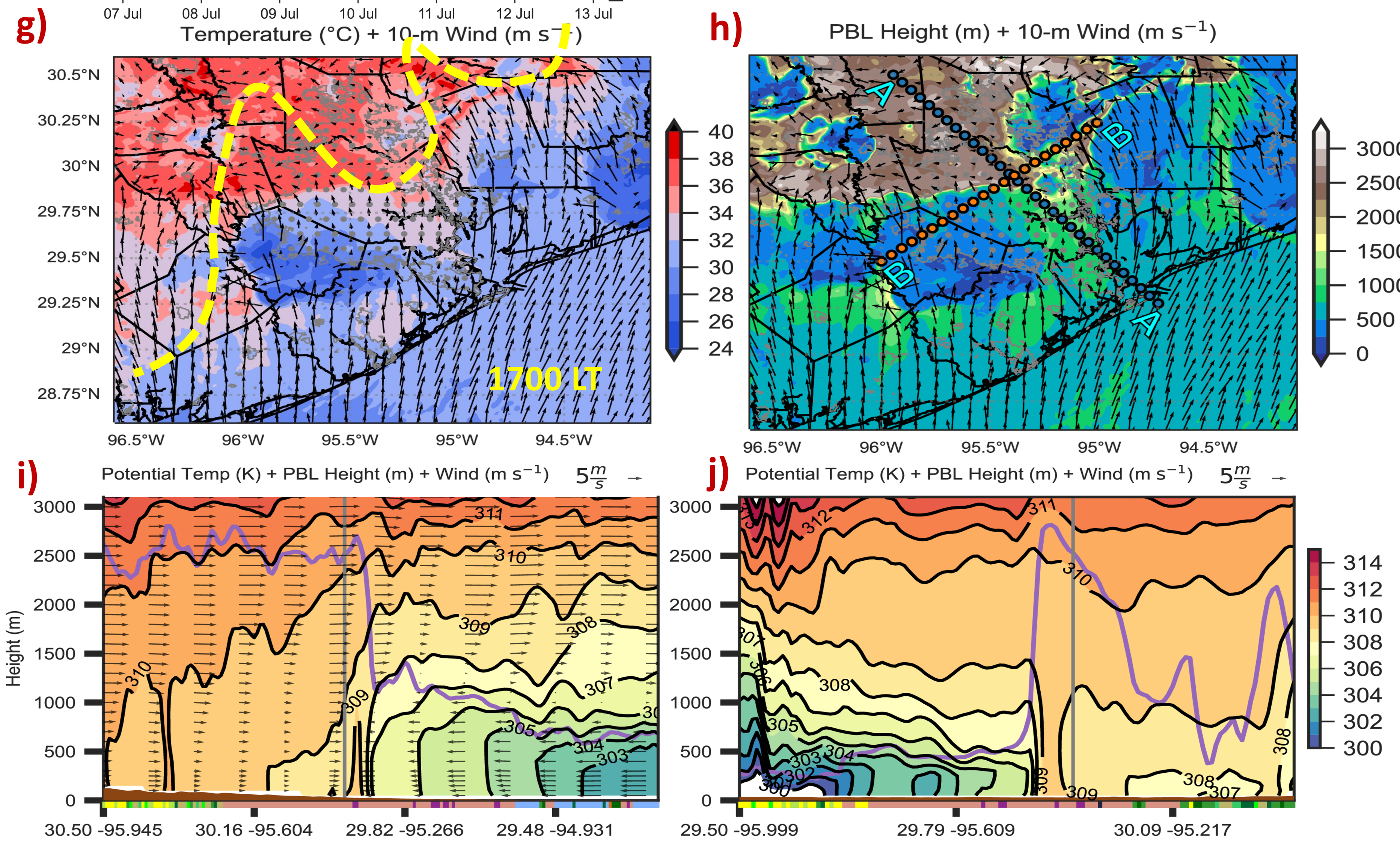
MET MODELING RESULTS 07/12/22 CASE

- uWRF evaluation against surface station showed a strong level of agreement i.e., R2 values across all stations ranging from **0.85 to 0.92**
- Model captures the **convergence in urban domain**
- SBF has similar characteristics as observed front due to **urban roughness effects**
- Cross sections show SBF structure and **rural to urban contrast**

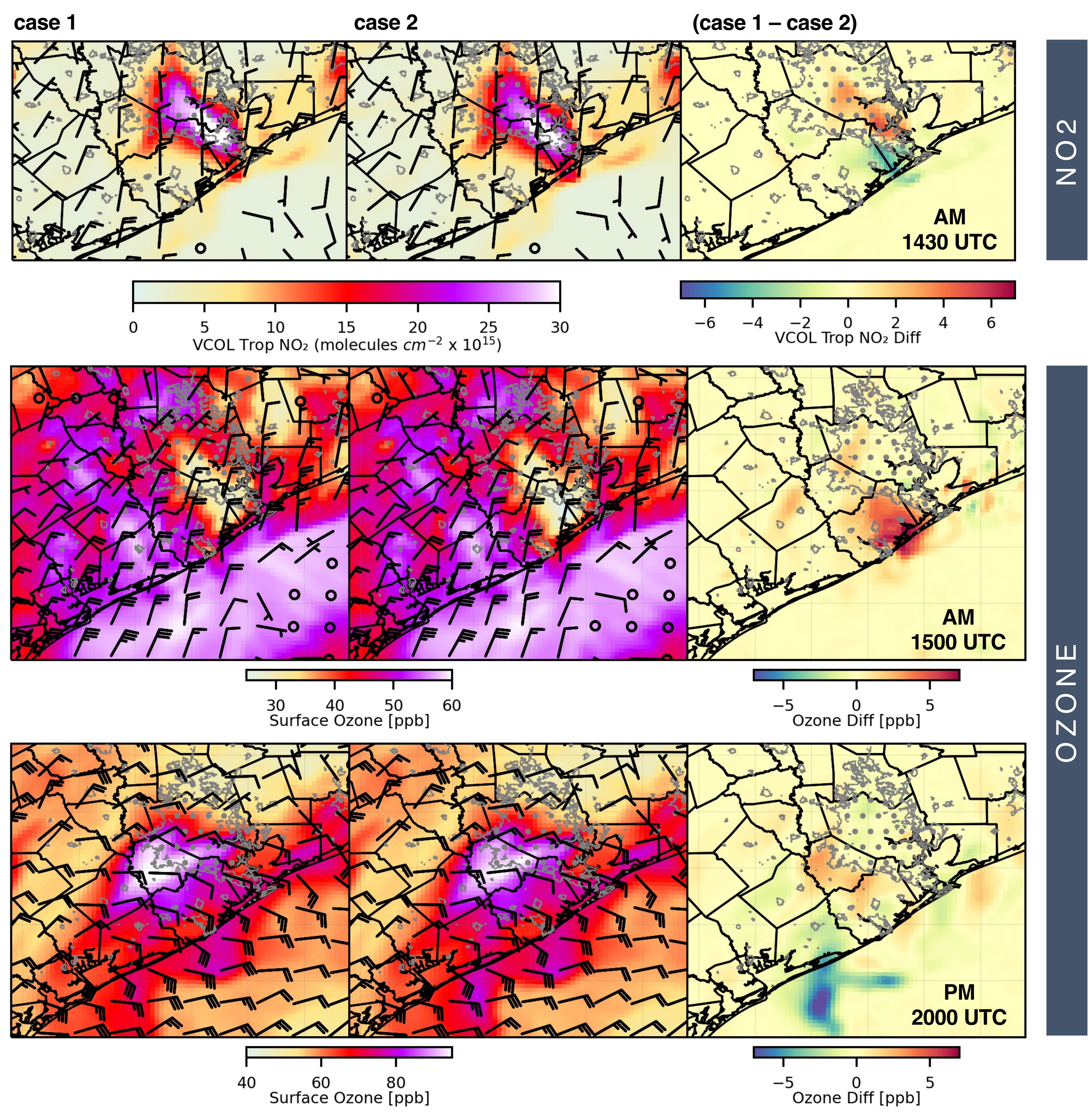


Station	RMSE	Bias	R^2
MCJ	1.31	0.37	0.85
IAH	1.49	-0.29	0.85
DWH	1.56	-0.73	0.87
ARM	1.27	-0.13	0.92
T78	1.34	0.20	0.88



AQ MODELING RESULTS 09/08/21 CASE

- Urban fraction **has significant impact on the distribution of NO2** due to urban effects on momentum
- **Urban deceleration** of winds caused NO2 to lag in case 1 during AM, resulting in more ozone along the shore
- NO2 build up from early morning results in peak > 90 ppb O3 in PM. Case1 had more NO2 build up resulting **in ~ 5 ppb higher O3** vs case 2



FUTURE WORK

- Explore uWRF's ability to capture UHI contrast
- Explore uWRF-Chem's PBLH differences and its impact on chemical mixing
- Compare model output with surface AQ data
- Expand evaluation to leverage TRACERS ozone lidars, various sonde launches, and aircraft measurements which collect spatial distribution data of PBLH, NO2, HCHO, and O3

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