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OBSERVATIONS AND SIMULATIONS OF THE INTERACTIONS BETWEEN  
COASTAL BREEZES AND THE ATMOSPHERIC BOUNDARY LAYER IN THE  
COASTAL HOUSTON ENVIRONMENT

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COASTAL BREEZES AND THE ATMOSPHERIC BOUNDARY LAYER IN THE  
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## Abstract

The atmospheric boundary layer (ABL) in the coastal environment is constantly evolving due to gradients in temperature, moisture, and surface roughness. The ABL influences regional air quality and weather forecasts through low-level stability and thermodynamic fluxes. Even though the ABL is intrinsic to daily life, it is historically under-sampled and poorly simulated in numerical models, because it evolves on a high spatiotemporal scale. The sea breeze (SB) is a contributor to the rapid coastal ABL evolution and develops because of the land-sea thermal gradient and advects the marine airmass onshore during the day. As a result, the SB can contribute to convection initiation and alter air quality in coastal areas. The TRacking Aerosol Convection interactions ExpeRiment (TRACER) field campaign gathered observations in the coastal-urban environment of Houston, Texas. With the goal of understanding the convective cloud lifecycle, a dense network of ABL measurements was gathered to understand how coastal breezes influence cloud evolution. Ground-based remote sensors and small uncrewed aerial systems (UAS) were deployed throughout the campaign and gathered a high temporal and vertically resolved dataset throughout numerous SB events, some of which triggered convection initiation.

Vertical profiles of temperature, humidity, and winds were collected by the OU CopterSonde UAS from June to September in the coastal region of Houston, Texas. These profiles offer 5 m vertical resolution, on average, every 30 min through diurnal transitions, SB events, and nearby deep convection. During the campaign, CopterSonde observations were gathered through 17 SB events, 6 of which led to convection initiation. The UAS data can resolve the thermodynamic evolution and interactions between the SB and the pre-existing convective boundary layer. Using the UAS observations, SB impacts and interactions with the ABL are investigated. The range of SB thermodynamic impacts is found to be broad and depends on the time of SB passage and influence from additional water bodies, like Galveston Bay. The SB is

also found to convectively destabilize the ABL by advecting an air mass with enhanced equivalent potential temperature ( $\theta_e$ ). The rate at which  $\theta_e$  increases in response to the SB provides insight into how conducive the environment is to convection initiation.

The resolution of UAS observations also provides a unique opportunity to evaluate numerical weather prediction on temporal scales consistent with the PBL evolution during coastal breeze passages, and beyond the surface layer. A case study is evaluated using observations during a bay breeze to sea breeze transition to understand how model parameterizations influence the forecast. The Warn-on-Forecast System (WoFS) is a convection-allowing ensemble designed to predict high-impact weather by combining rapidly updating data assimilation cycles with varying PBL and radiation parameterizations. While the model is not geared toward PBL studies, it provides a benchmark to evaluate commonly used parameterizations for NWP to offer insight into best-performing combinations and potential improvements. The biases of state variables calculated from the UAS observations show distinct differences from biases calculated using surface meteorological station observations, suggesting that traditional ABL evaluation practices may underestimate errors in the mixed layer. Additionally, the SB is variably represented in terms of the depth, arrival time, and intensity with different parameterization configurations. Only a subset of members simulate the preceding Galveston Bay breeze, and none do so accurately. The bay breeze is very sensitive to initial conditions, especially for members with local mixing schemes. As a result, initial cloud cover induced by the radiation scheme affects the ability to simulate a bay breeze, as well as the SB onset time. The mixing scheme for ABL parameterization lends differences in SB depth, intensity, and evolution.

This variability across simulated SBs motivated analyzing how these differences impact simulated convection. Two events are analyzed to understand how simulated convection initiation differs with the ABL parameterization. Forecast performance is evaluated using storm object identification and matching with gridded reflectivity observations. One case's performance is consistent across all members, but the other is greatly dependent on the ABL parameterization. Local mixing scheme members tend to have more moisture across the region and disperse rising motion ahead of the SB front, which leads to an overestimation of storm objects inland. Nonlocal mixing members have more isolated lifting and unstable air close to the SB front that causes an underestimation of convective storms. These differences are less impactful

when the environment is very unstable upon initialization. Then, all EMs result in an overestimation of convective storm objects ahead of the SB. These results suggest that the simulation of the convective boundary layer is more critical to accurately depicting convection initiation than the sea breeze characteristics.

# Chapter 1

## Introduction

### 1.1 Atmospheric boundary layer

The atmospheric boundary layer (ABL) is the interface between the free atmosphere and Earth’s surface, regulating the transport of heat, momentum, and moisture by convection and shear-driven turbulence (Stull 2012). It is a highly dynamic and ever-changing layer in which the world’s populace resides. The ABL depth fluctuates diurnally with surface heating and can extend up to several kilometers. Atmospheric stability and fluxes in the ABL are important to public health, agriculture, energy forecasting, and high-impact weather, yet observations of ABL properties are sparse. Current operational observations in the ABL include surface weather stations, which do not provide vertically resolved information, and radiosondes, which are released too infrequently and ascend through the ABL too quickly to provide a complete depiction of the ABL structure. Additionally, there is no operational network to routinely observe turbulent fluxes in the ABL. This results in an ABL data gap because current observations are insufficient to adequately characterize the ABL for data assimilation and improving our understanding of ABL processes (Bell et al. 2020). This is in part due to the high spatiotemporal resolution needed to fully observe the ABL.

The land surface drives the contribution of turbulent heat and moisture fluxes across a range of spatial and temporal scales. The daytime convective boundary layer

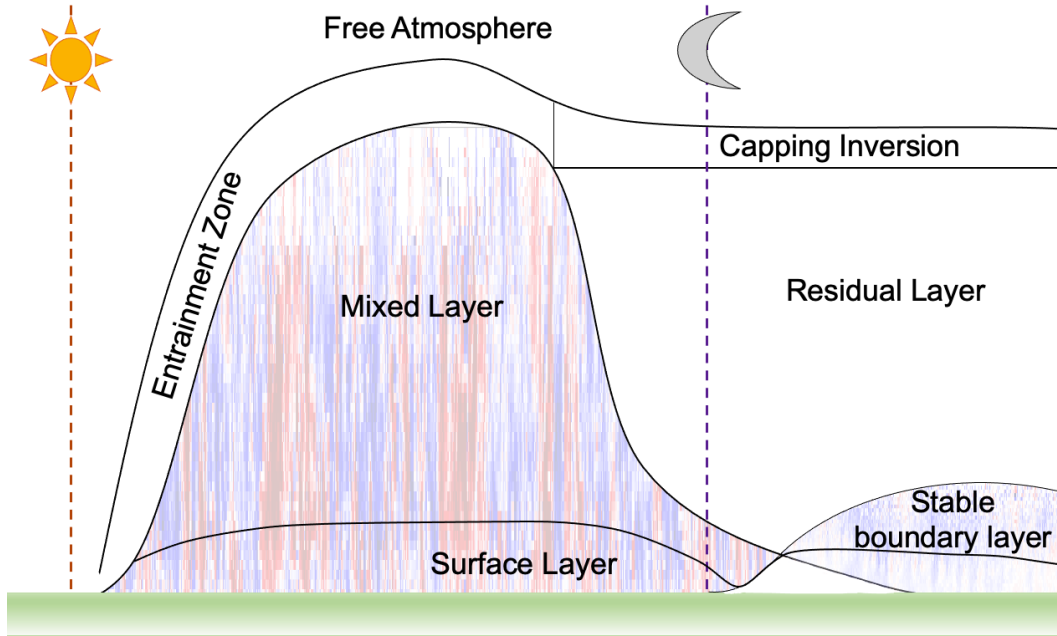


Figure 1.1: Conceptual model of the ABL diurnal cycle with shaded lidar observations of vertical velocity (reds (blues) are positive (negative) vertical motion) based on Stull (2012)

(CBL) is composed of a shallow constant flux surface layer, a deep mixed layer, and an entrainment zone that connects the top of the ABL to the free atmosphere. Without insolation, the nocturnal boundary layer contains a stable layer due to a radiational cooling-induced temperature inversion which the residual CBL resides above. Over flat, homogeneous land, the ABL evolves canonically as in Fig. 1.1, but features like complex terrain, heterogeneous land cover, and large-scale weather patterns can alter the ABL's daily pattern (Angevine 2008; Pinto et al. 2006; Fernando et al. 2019). Over water surfaces, the fluxes, depth, and turbulence within the ABL are different from their continental counterparts and have the added complication of a fluid surface (LeMone et al. 2019). While horizontal homogeneity is a common assumption for ABL theories and estimations, it is rarely observed.

Within the coastal environment, the ABL is influenced by the land and marine surface causing an inhomogeneous ABL that is rarely stationary (Council 1992). From

local climate to mesoscale wind patterns, the coastal ABL is subject to a combination of nonlinear processes (Grisogono et al. 1998; Kristovich et al. 2019). The ocean and land juxtaposition leads to gradients in moisture, temperature, and surface roughness, driving differences in ABL structure (Arya 2001). When an air mass is transported across these gradients, an internal boundary layer forms as the source characteristics adjust to the existing ABL (Garratt and Physick 1985). Land and sea breezes often initiate momentum and thermal internal boundary layers (Raynor et al. 1979; Melas and Kambezidis 1992). As a result, vertical temperature and moisture gradients can evolve on a very short timescale. This compounds with heterogeneous land surfaces and creates a dynamic environment that is operationally undersampled. Coastal urban areas are especially complicated because each local boundary layer structure evolves differently throughout the day (Calmet and Mestayer 2016; Melecio-Vázquez et al. 2018; Rahman et al. 2024).

## 1.2 Coastal breezes

The sea breeze (SB) circulation is driven by the temperature gradient between land and water that happens commonly in the spring and summer months. The sea breeze front (SBF) pushes inland bringing a marine air mass that is traditionally cooler, moister, and more stable than the continental air mass (Simpson et al. 1977). Mesoscale details of the SB circulation have been extensively quantified using radar, surface observations, and numerical models (Wakimoto and Atkins 1994; Baker et al. 2001; Fovell 2005; Park et al. 2020). Crosman and Horel (2010) synthesized the literature relating the scaling relationships between geophysical variables and SB size and intensity using numerical models. Many of the reviewed studies focused on the impact of geostrophic flow as purely shore-perpendicular, which ignores shore-parallel or weak flow influences. More



recently, Allouche et al. (2023) performed an analysis on the influence of thermal and synoptic forcing using large eddy simulations (LES) to categorize land-SB circulations into 4 regimes based on synoptic wind direction: canonical (no synoptic flow), land-driven (offshore flow), sea-driven (weak onshore flow), and advected (strong onshore flow). Crosman and Horel (2010) and Bou-Zeid et al. (2020) remarked that while research on the SB has been prolific, there is still a gap in understanding non-linear interactions with the ABL on a higher temporal scale. This is due to the limited model representativeness of the ABL and observations for verification.

Many studies have aimed to understand SB-driven convection initiation (CI) due to its regularity and lack of strong synoptic forcing. A majority of research on interactions between CI and the SB come from numerical studies but are inherently limited by idealized wind and temperature profiles (Nicholls et al. 1991; Azorin-Molina et al. 2015; Hartigan et al. 2021). There are conflicting theories on preferential CI regions with respect to the SBF. Low-level convergence at the SBF can provide lift to initiate convection, but convection can also be triggered ahead and behind the SBF (Dailey and Fovell 1999; Rao and Fuelberg 2000). Fovell (2005) diagnosed SBs to convectively prime the atmosphere ahead of the SBF by elevating moisture, and collisions with horizontal convective rolls supply adequate lifting. Soderholm et al. (2017) determined that the SB conditions the environment for CI in two parts; first, the advection of low-level moisture increases moist static instability expressed with equivalent potential temperature ( $\theta_e$ ), while upper-level, return flow advects drier, warmer air over the SB inflow layer (lower component of the SB circulation that advects marine air onshore), steepening the thermal lapse rate. Similarly, in all idealized simulations from Boyer et al. (2025), the lake breeze advected an air mass with higher values of  $\theta_e$  with most CI occurring within 10 km of the lake breeze front. The authors also found the lake breeze lowered the level of free convection (LFC), which allows surface-based parcels

to initiate deep CI more readily. However, observations do not show the SB causing a significant difference in the LFC (Sharma et al. 2024). Since CI is highly sensitive to small changes in low-level moisture fluctuations (Crook 1996; McCaul and Cohen 2002), radiosonde, and aircraft data are too coarse to provide a clear evolution of bulk stability metrics and moisture leading up to CI (Wakimoto and Atkins 1994; Dailey and Fovell 1999). To understand convective timing, location, and intensity, more analysis is needed to understand how the SB interacts with the ABL before and after the SBF.

Transportation of moisture, momentum, heat, and aerosols depends on the structure of the ABL and its relationship with the SB. The complex interaction between this advection and mechanical lifting primes the pre-convective environment, but access to positively buoyant air is required to stimulate convection (Fovell 2005; Hartigan et al. 2021; Fu et al. 2022). Although the SB is often treated as steady state and homogeneous along the coastline, Puygrenier et al. (2005) found that the SBF pulsates due to convectively redistributing heat and weakening the pressure gradient force. Within the SBF, regions of enhanced convergence form due to the collision with horizontal convective rolls and increased vertical motion (Atkins et al. 1995; Iwai et al. 2008). Heterogeneities in the SBF are compounded by the addition of other water bodies and urban land use (Baker et al. 2001; Miller et al. 2003; Chen et al. 2019).

Additionally, the SB can impact air quality in multiple ways; aerosols can be trapped near the surface or fumigated aloft depending on ABL stability (Verma et al. 2006; Iwai et al. 2008; Finardi et al. 2018). Ozone concentration exceeding 70 parts per billion for 8 h has been linked to the SB circulation due to recirculation with minimal destruction of ozone precursors and reduction of cloud coverage (Banta et al. 2005; Darby 2005; Chen et al. 2019; Li et al. 2020; Stanier et al. 2021). Additionally, the SB can trigger thunderstorm development which can lead to ozone production (nitrogen fixation from lightning) and destruction (decreased insolation and ozone precursor

scavenging) (Cuchiara et al. 2023). The complicated influence the SB circulation has on ozone makes it a critical component for air quality forecasts.

### 1.3 TRACER Field Campaign

Houston, Texas is prone to many of the societal impacts from the SB circulation listed above, motivating researchers to propose enhanced observations in the area. The TRacking Aerosol Convection interactions ExpeRiment (TRACER) took place across the Houston-Galveston area with an intensive observation period (IOP) from May to October 2022. This region is a coastal metropolis where urbanization and industrialization have redefined the landscape and atmospheric composition. To accommodate the demand for space and energy, natural landscapes have been replaced by sprawling urban dwellings and industrial areas. These changes in land use affect surface roughness and fluxes, thereby impacting the structure and stability of the ABL. All along the Gulf Coast, SB CI can lead to potentially heavy rains, which are exacerbated when natural drainage plains have been built over and trigger flash flooding events. Moreover, petrochemical plants dot the coastline, emitting aerosols and gaseous pollutants into the ABL, leading to high ozone and particulate matter events that are closely linked with the SB circulation (Caicedo et al. 2019; Li et al. 2020; Park et al. 2020). The influence of aerosol loading on convection is still disputed in the literature, with some suggesting it enhances convection (Fan et al. 2020; Zhang et al. 2021) and others finding it inhibits convection (Grant and van den Heever 2014; Varble 2018; Park et al. 2020). The combination of urbanization effects makes the Houston area vulnerable to hazardous air quality and heavy rain events, thus driving a need for enhanced observations to understand the processes accompanying a changing climate and landscape (Hagos et al. 2016). The coastal Houston region has a unique urban-coastal boundary

layer with impacts from the urban heat island as well as the SB circulation, making it a perfect laboratory to understand how these processes interact.

The main goal of TRACER is to further understand the convective cloud life cycle and its interplay with aerosols (Jensen et al. 2022). This spans from shallow cloud development, which represents one of the great uncertainties in climate projections (Bony et al. 2015; Zhao et al. 2016), to deep convection and the intertwining of microphysical and dynamic processes that dictate storm intensity (Khain et al. 2005). To investigate these processes, the Department of Energy (DOE) Atmospheric Radiation Measurements (ARM) employed a suite of radars, air quality instruments, and surface flux stations to validate models and improve the physical parameterizations. While clouds form near the top of the ABL, their life cycle begins within the ABL and depends on low-level moisture, composition, and momentum.

A major hindrance to understanding the dynamics of complex PBL environments is the density of observations required to represent the multiscale processes. Operational observations within the PBL include radiosondes, flux towers, and surface weather observing systems, but these have insufficient temporal, spatial, and vertical resolution to capture the necessary details to resolve processes leading up to CI. Thus, to meet the goals of TRACER, dense observations of the ABL across the region are necessary. To develop an ABL dataset, ground-based remote sensors, radar wind profilers, and small uncrewed aerial systems (UAS) were deployed. The parent TRACER campaign encompassed several subprojects, including the Coastal Urban Boundary-layer Interactions with Convection (CUBIC) and Uncrewed Aerial System (UAS) projects that took place during the IOP, both of which include PBL processes as a key focus. TRACER-CUBIC and TRACER-UAS offer a unique opportunity to explore SBC impacts and PBL characterization via collaboratively deployed observation platforms.

## 1.4 Uncrewed aerial systems

Over the past decade, the use of UAS in weather research has expanded due to its proven utility across a range of meteorological conditions (Elston et al. 2011; Cassano 2014; Elston et al. 2015; Båserud et al. 2016; Cione et al. 2016). Reineman et al. (2013, 2016) used a fixed-wing platform to gather turbulence measurements within the marine boundary layer. Flagg et al. (2018) found that assimilating data from the same platform improved the model’s representation of the marine boundary layer and reduced bias. With careful consideration of sensor placement, UAS-collected wind and thermodynamic data are of comparable quality to data collected with meteorological towers, radiosondes, and ground-based remote sensors (Barbieri et al. 2019; Bell et al. 2020; de Boer et al. 2024). Observations from fixed-wing UAS deliver horizontal transects of the environmental state, capturing heterogeneities in the ABL during turbulent times, such as during the passage of the SBF or CI. Rotary-wing UAS, which collect repeated vertical profiles, resolve the structural evolution of the ABL in transitional and pre-convection conditions (de Boer et al. 2020; Lappin et al. 2022). The TRACER-UAS campaign deployed the University of Colorado Integrated Remote and In Situ Sensing (IRISS) Robust Autonomous Aerial Vehicle – Endurant Nimble (RAAVEN) and the University of Oklahoma CopterSonde UAS (Segales et al. 2022). Utilizing both platforms allows for a complex four-dimensional dataset of the ABL in complex terrain.

## 1.5 Parameterization verification studies

In addition to observations gathered during TRACER, the campaign motivated numerous numerical simulations across the domain. In modeling studies, the ABL is commonly referred to as the planetary boundary layer (PBL) and both will be used interchangeably, herein. Numerical weather prediction (NWP) models have improved

computational efficiency over the years, thus decreasing the grid resolution and increasing resolved processes in the atmosphere. Nevertheless, subgrid processes in the PBL still rely on parameterizations of surface fluxes, mixing length, turbulent exchanges, and stability (Stensrud 2007). Large-eddy simulations (LES) reduce numerical assumptions by resolving the largest energy-containing eddies of the turbulent kinetic energy spectrum, thus representing the PBL stability and mixing length more accurately (Stoll et al. 2020). Due to the computational expense of LES, they are not yet feasible for operational NWP. There are numerous PBL parameterization schemes available in NWP models that vary the turbulence closure and how they transfer heat and momentum across model levels. Turbulence closure refers to how unknown turbulent moments, which emerge from Reynolds averaging, are modeled in terms of known quantities in a simulation of turbulent flow. Local mixing schemes can only interact with the adjacent model level, leading to slower vertical transport of heat, moisture, and momentum. Nonlocal mixing schemes allow vertical transport across the mixing length which is more computationally expensive, but a more accurate depiction of the PBL.

There have been many studies to evaluate the performance of PBL parameterization during severe weather (Coniglio et al. 2013; Cohen et al. 2015; Potvin et al. 2020), air quality (Hu et al. 2010; Xie et al. 2012), and coastal processes (Challa et al. 2009; Zhong et al. 2007; Miao et al. 2009; Gómez et al. 2016). To summarize these: nonlocal schemes overmix the PBL and are often too warm and dry at the surface while local schemes create too cool and moist ABLs with overestimated wind speeds. The timing and location of locally-driven CI are especially sensitive to moisture and heat fluxes, which can be highly dependent on parameterization choice. Chen et al. (2020) and Madaus and Hakim (2016) found locations that simulated successful CI had positive anomalies of sensible heat flux helping to sustain the updrafts. Chen et al. (2020) found these updrafts were colocated with regions with enhanced values of  $\theta_e$ . The most

accurate PBL scheme is difficult to determine since biases can differ across variables and parameterization performance can depend on weather phenomena.

Coastal areas are particularly difficult to simulate accurately with NWP models due to the various land-air interactions and regional circulations. The PBL in these areas is more dynamic and does not comply with the horizontal homogeneity assumed in the development of the associated parameterizations. Coastal clouds also play a strong role in radiative feedback, meanwhile, cloud coverage and depth are poorly modeled, historically (Huang et al. 2013). NWP models succeed in simulating SB occurrences, but accurate timing and intensity are not always well captured. Numerous studies have noted that the WRF model frequently delays SB onset (Miao et al. 2009; Salvador et al. 2016; Caicedo et al. 2019). The time of SB passage with respect to the boundary layer regime (stable, convective, or transitioning) influences the strength of SB impacts on turbulent intensity and PBL state variables (Arrillaga et al. 2016). Arrillaga et al. (2020) further determined that WRF model performance simulating temperature, moisture, and PBL depth varies with the PBL regime; the simulated SB alterations to wind speed, mixing-layer height, and specific humidity agree best with observations during the CBL and worse during the afternoon-evening transition. Additional water bodies can induce their own breeze circulations (i.e. bay, lake, river) that alter the evolution of the SB (Baker et al. 2001). In a WRF model evaluation of the SB impacts on ozone around Houston, Caicedo et al. (2019) found the model failed to simulate the Galveston Bay breeze (BB), leading to an underestimation of ozone levels around Galveston Bay.

There have been a few studies regarding parameterization’s influence on SB characteristics. Zhong et al. (2007) analyzed the performance of various parameterizations in the coastal environment, evaluating the daily transitions, low-level jets, and the SB.

They found that errors in simulated mixed layer depth and daytime surface temperatures are sensitive to the PBL parameterization. While the authors looked at the diurnal wind oscillation with the SB circulation, they did not evaluate the accuracy of SB characteristics (Zhong et al. 2007). Miao et al. (2009) and Gómez et al. (2016) compared PBL scheme combinations with land surface variations to surface observations throughout the SB circulation. Miao et al. (2009) found that the SB onset time and strength are highly sensitive to the PBL parameterization due to differences in sensible heat flux. Gómez et al. (2016) used radiosondes to gauge the representation of the thermodynamic structure and found there are strong differences in PBL moisture, temperature, and lapse rate between the local and nonlocal mixing schemes. A major drawback to these studies is the resolution of observations to compare against the model. They used surface observations and radiosondes data to represent the ABL, which undersamples the surface layer and rapid changes to the stability profile.

## 1.6 Research questions

The SB has been studied thoroughly over the past century, but, because of sparse observations within the ABL across the SB lifetime, there are still numerous processes that would benefit from a microscale approach. There have been numerous advancements in the way the ABL is observed, including UAS and thermodynamic retrievals from ground-based remote sensors. TRACER is a recent campaign that utilized these advancements by gathering an ABL dataset to study the role the ABL plays within the cloud life cycle. Furthermore, it motivated the generation of regional simulations that can be coupled with observations to evaluate operational parameterizations. With these assets, models and observations can be used synergistically to learn the dynamics



behind ABL processes in a coastal environment. Thus, we aim to answer the following questions:

- How large and persistent are the observed SB impacts on the ABL, and what drives the intensity of these impacts?
- How well are coastal breezes and their ABL interactions simulated? Is performance dependent on PBL or radiation parameterization?
- How does the SB drive CI and what characteristics precede successful CI? Does SB-driven CI vary with different PBL parameterizations?

## Chapter 2

### Overview of TRACER

The TRACER campaign combined observations and simulations in a concerted effort to understand the convective cloud lifecycle from the ABL to microphysical processes within deep convection. Multiple datasets were used to gather a complete depiction of ABL processes in response to additional factors like coastal breezes or convection. Observations from UAS platforms, ground-based remote sensors, radiosondes, and surface meteorological stations compose the observations utilized herein. Each platform and data processing techniques will be described in the following section. First, the ground-based remote sensors included in TRACER-CUBIC are introduced. Then, the flight strategies and data intercomparison from TRACER-UAS are described, which has been previously published Lappin et al. (2024). Lastly, an ensemble mesoscale weather model was included to understand processes across a four-dimensional space, and its specifications will also be cataloged. Methods specific to a results chapter will be included in said chapter for convenience.

## 2.1 Observations

### 2.1.1 Ground-based remote sensing platforms

The TRACER subproject Coastal Urban Boundary layer Interactions with Convection (CUBIC, Klein et al. (2023)) deployed ground-based remote sensors across the

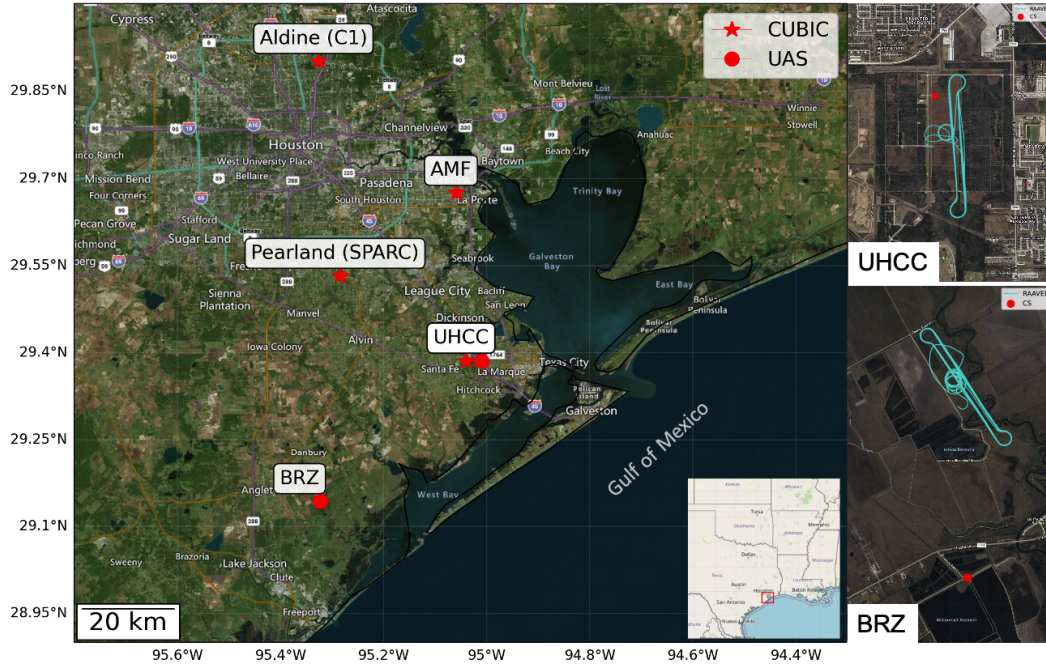


Figure 2.1: Map of the Houston-Galveston region with TRACER-UAS flight sites (circles) and TRACER-CUBIC remote sensing sites (stars). On the right, TRACER-UAS flight locations are zoomed-in with flight paths by the RAAVEN (blue line) and CopterSonde profiling site (red dot). More information about the TRACER sites is given in sections 2.1.1 and 2.1.2. Maps are satellite imagery courtesy of ©Google Maps, 2022.

Houston domain (Fig. 2.1). These systems gathered thermodynamic and kinematic profiles within the ABL nearly continuously throughout the campaign. Observations came from two similar systems, the Collaborative Lower-Atmospheric Mobile Profiling System (CLAMPS) and Space Science and Engineering Center Portable Atmospheric Research Center (SPARC; Wagner et al. (2019)). Each is comprised of a scanning Doppler lidar, microwave radiometer (MWR), and Atmospheric Emitted Radiance Interferometer (AERI). The Doppler lidar operated a planned position indicator scan at  $60^\circ$  every 15 minutes, providing a vertical wind profile derived from the velocity azimuth display (Päschke et al. 2015), otherwise the lidar was in a fixed-point vertical stare. The MWR and AERI data were processed with the Tropospheric Remotely Observed

Profiling via optimal estimation, (TROPoe; Turner and Blumberg (2019)) to retrieve vertical temperature and moisture profiles every 10 min. The data processing procedures are uniform across the CLAMPS and SPARC observations. TRACER-CUBIC had three profiling locations with two CLAMPS units and one SPARC. CLAMPS1 was located in Aldine, TX, north of downtown Houston. CLAMPS2 was located at the University of Houston Coastal Center (UHCC), colocated with the CopterSonde for portions of the campaign. SPARC was located south of Houston in Pearland, TX. In this work, observations from CLAMPS2 and SPARC will be utilized since they are closer to the UAS flight sites. Additionally, radiosondes were released every 6 h at 00, 06, 12, and 18 UTC at the Atmospheric Radiation Measurement (ARM) Mobile Facility (AMF) in La Porte, TX. Radiosonde observations were used to calculate surface-based CAPE (SBCAPE) and mixed-layer CAPE (MLCAPE).

### **2.1.2 Uncrewed aerial systems**

Two UAS platforms were utilized throughout TRACER-UAS to sample the ABL: the University of Oklahoma CopterSonde (Segales et al. 2022) and the University of Colorado IRISS RAAVEN (de Boer et al. 2022). Flights were conducted either at the UHCC or near the Brazoria Wildlife Refuge (BRZ). A full list of flight conditions and locations can be found in Appendix A.1. Figure 2.1 marks the location of each site and shows the differences between proximity to the Gulf of Mexico, Galveston Bay, urban areas, and overall development. The UHCC flight site was colocated with the National Severe Storm Laboratory (NSSL) CLAMPS2. During the campaign, data were collected during sea breeze events, prior to or near convection, and during quiescent periods. In total, the CopterSonde and the RAAVEN collected over 200 flight hours worth of data at two flight sites. The two flight sites have differences in

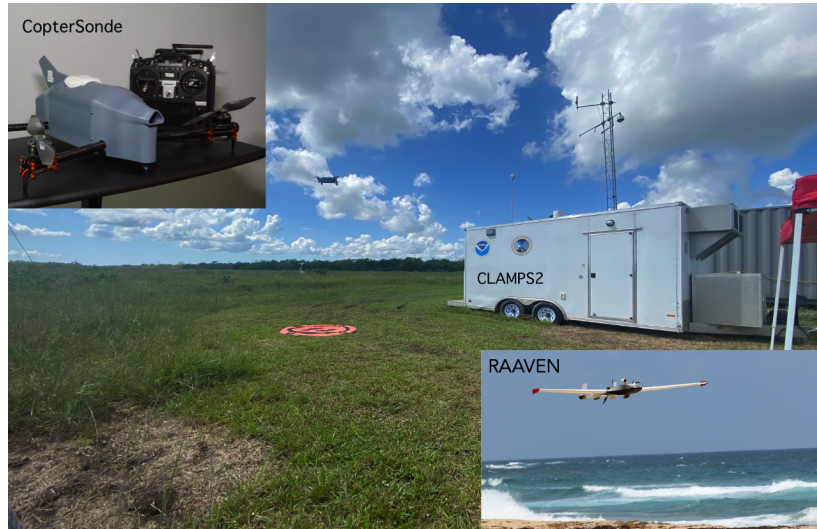


Figure 2.2: Pictures of the CopterSonde, RAAVEN, and CLAMPS2 at the UHCC site roughness length, air quality, and forcings which illustrate ABL heterogeneity in the region.

The RAAVEN and CopterSonde have been used extensively to collect atmospheric measurements in connection with several different field campaigns (de Boer et al. 2020; Cleary et al. 2022). As part of the preparations for TRACER, significant time was spent comparing measurements from the two platforms to radiosonde and tower-based measurements collected at the US Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) Southern Great Plains (SGP) facility. These efforts revealed that both platforms captured the state of the atmosphere with significant accuracy and were comparable to each other and to the ARM instrumentation. Additional details on this intercomparison can be found in de Boer et al. (2024). Below we provide an overview of each platform, along with additional references that provide detailed information on the sensor and system specifications.

### 2.1.2.1 The University of Oklahoma CopterSonde

The CopterSonde is a rotary-wing quadcopter used to collect frequent vertical profiles of the ABL (Fig. 2.2). It was developed at the University of Oklahoma (OU) and is maintained by the Cooperative Institute for Severe and High-Impact Weather Research and Operations. The platform is 0.5 m in diameter and weighs 2.3 kg, making it easily transportable. The CopterSonde uses a combination of direct sensors, autopilot software, and algorithms to gather a profile of atmospheric data. Pressure, temperature, and humidity are observed using an MS5611 barometric pressure sensor, iMet-XF bead thermistor, and HYT-271 humidity capacitor, respectively. The pressure sensor is integrated into the Pixhawk CubeOrange autopilot board to improve the altimeter estimation. To remove temperature fluctuations from the pressure observations, the Pixhawk is heated to a constant temperature within the first two minutes of start-up. The thermistors and humidity capacitors are housed in the intake scoop of the CopterSonde, where they are sheltered from insolation and heat from the motors or Pixhawk Cube. The positioning of temperature sensors was selected based on findings in Greene et al. (2018). Within the intake scoop, there is a small fan to aspirate the sensors, although it does not turn on until the CopterSonde reaches an elevation of 3 m above ground level (AGL) to avoid ingesting dust into the scoop. In addition to the fan aspiration, the autopilot implements the wind vane mode explained in Segales et al. (2020) to direct the scoop into the prevailing flow. As such, the air is not altered by the UAS before it passes over the sensors. Additionally, the wind vane mode improves wind speed and direction estimation by increasing axis symmetry and reducing vibrations. Wind speed and direction are determined by a linear algorithm estimator using aircraft attitude described more in Section 4.2. Sensor accuracy response times, and further specifics on the system specifications can also be found in Segales et al. (2022).

#### 2.1.2.2 CopterSonde data processing and quality control

Raw data from the CopterSonde are stored on an SD card as binary files and then converted to NetCDF. Subsequently, data go through a process of averaging, filtering, and objective quality analysis to optimize the quality of observations. Since data from the Pixhawk are logged at a faster rate of 20 Hz than the temperature and humidity sampling rate of 10 Hz, the position and rotation data gathered by the Pixhawk are downsampled to 10 Hz to ensure a standard timeline of observations. After achieving a common time coordinate, offsets determined in the Oklahoma Climatological Survey calibration chamber are applied to each sensor. Every CopterSonde is calibrated prior to deployment, so each one has unique offsets due to minor differences in sensors. To eliminate spurious, high-frequency signals in data, the attitude data (roll, pitch, and yaw), temperature, and relative humidity data have a low-pass finite impulse response (FIR) filter applied, described in Greene et al. (2022). Sets of three identical temperature and humidity sensors were used to ensure agreement between observations. Acceptable thresholds for sensor bias and standard deviation were experimentally determined during sensor calibration and characterization studies; if an individual sensor exceeds those thresholds, the sensor’s observations are removed. Then, all remaining thermistors and humidity capacitors are averaged, and the data are binned to 5 m. This combination of sampling rate and vertical resolution ensures at least 16 observations per sensor in each bin.

Wind direction is estimated during the flight by altering the yaw angle to minimize the roll to optimize stability and promote flow into the sensor scoop. A wind speed estimate comes from the pitch angle, and in cases of high wind, the UAS will automatically return home to avoid battery fatigue or failure. In post-processing, a more accurate horizontal wind vector is derived using a more robust linear model on the roll, pitch, and yaw while accounting for the aircraft geometry. In cases of very

low wind speeds, the autopilot struggles to calculate the true wind direction, and for wind speeds less than  $2 \text{ m s}^{-1}$  the wind direction values are considered questionable. In data comparison calculations, the wind speed and direction were removed when the wind speed was less than  $2 \text{ m s}^{-1}$  (Table 2.3).

### **2.1.2.3 RAAVEN**

The University of Colorado’s IRISS RAAVEN fixed-wing UAS is equipped with a suite of sensors to capture the thermodynamic and kinematic state of the atmosphere with duplicate observations and high frequency (Fig. 2.2). In addition to the variables collected by the CopterSonde, the RAAVEN carried a printed optical particle spectrometer (POPS) and an infrared thermometer to observe the aerosol size distribution and sky brightness temperature. Horizontal and vertical winds were obtained using data from a multihole pressure probe which provides information on aircraft’s angle of attack and sideslip, in combination with information on aircraft velocity and attitude from an onboard inertial measurement unit. As a fixed-wing aircraft, the RAAVEN is designed to fly longer, coupling horizontal transects used for collecting statistics required for evaluating fluxes and spatial variability at a given level with helical, vertical profiles. The RAAVEN collected coastal ABL observations from previous experiments in the Barbados (de Boer et al. 2022) and along Lake Michigan (Cleary et al. 2022), and more details on sensor performance and data acquisition can be found in these articles.



### **2.1.3 Description of TRACER-UAS measurement locations, deployment strategies, and sampling**

TRACER-UAS flights were completed at two locations south and southeast of Houston, TX, approximately 20 km from the Gulf of Mexico, as seen in Fig. 2.1. The UHCC site is a restored coastal prairie surrounded by low-grade urban sprawl in La Marque, TX. This location lies 15 km due west of the Galveston Bay shoreline, and as a result, frequently feels the effects of the Galveston Bay breeze prior to the sea breeze. The BB at UHCC is detected by an acceleration of easterly flow, while the SB flow comes from the southeast direction. During TRACER, there was additional instrumentation at UHCC, including a sonic anemometer and gas analyzer, ground-based remote sensors, and a sun photometer. The other site near the Brazoria Wildlife Refuge (BRZ) is surrounded by wetlands and bayous southeast of Angleton, TX. At BRZ, the RAAVEN launch site is 2.7 km north of the CopterSonde for logistical reasons, while at UHCC, the flight tracks are much closer (Fig. 2.1).

A total of 4 IOPs, lasting two weeks in each month from June-September, were completed by both teams. Table 2.1 outlines the data availability throughout the campaign. The CopterSonde team arrived one week before the RAAVEN team, such that there was one week of overlap to collect co-located observations each month. From June-August, the RAAVEN collected data only at the BRZ site. The CopterSonde collected data only at BRZ in July but used either site in June and August, depending on the research objectives and weather conditions. In September, both teams only flew at UHCC due to landowner agreements. Table 2.2 documents the flight numbers for the campaign. In total, there are 13 days of co-located observations from both platforms.

Table 2.1: Data availability for each platform throughout TRACER-UAS in 2022. Numbers in each grid represent the number of flights completed. Bold numbers indicate flights at UHCC and italic at BRZ.

|             |          |          |    |           |           |           |           |           |           |           |           |           |           |           |           |           |           |          |          |           |           |           |           |          |           |          |
|-------------|----------|----------|----|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|----------|----------|-----------|-----------|-----------|-----------|----------|-----------|----------|
| June        | 1        | 2        | 11 | 12        | 13        | 14        | 15        | 16        | 17        | 18        | 19        | 20        | 21        | 22        | 23        | 24        | 25        | 26       | 27       | 28        | 29        | 30        |           |          |           |          |
| CopterSonde |          |          |    |           | <b>17</b> | <b>16</b> |           |           | <b>18</b> | <b>18</b> | <b>10</b> |           | <b>19</b> | <i>18</i> | <i>18</i> | <i>18</i> |           |          |          |           |           |           |           |          |           |          |
| RAAVEN      |          |          |    |           |           |           |           |           | <i>1</i>  | <i>3</i>  |           | <i>2</i>  | <i>3</i>  | <i>1</i>  | <i>3</i>  | <i>3</i>  |           | <i>3</i> | <i>3</i> | <i>3</i>  | <i>3</i>  |           |           |          |           |          |
| July        | 1        | 2        | 11 | 12        | 13        | 14        | 15        | 16        | 17        | 18        | 19        | 20        | 21        | 22        | 23        | 24        | 25        | 26       | 27       | 28        | 29        | 30        | 31        |          |           |          |
| CopterSonde |          |          |    | <i>16</i> | <i>14</i> | <i>17</i> | <i>18</i> |           |           | <i>20</i> | <i>16</i> | <i>20</i> |           |           |           |           |           |          |          |           |           |           |           |          |           |          |
| RAAVEN      |          |          |    |           |           |           |           |           |           |           |           | <i>3</i>  | <i>2</i>  | <i>2</i>  | <i>3</i>  | <i>2</i>  | <i>2</i>  | <i>4</i> | <i>3</i> | <i>3</i>  | <i>2</i>  | <i>3</i>  | <i>3</i>  | <i>2</i> |           |          |
| August      | 1        | 2        | 11 | 12        | 13        | 14        | 15        | 16        | 17        | 18        | 19        | 20        | 21        | 22        | 23        | 24        | 25        | 26       | 27       | 28        | 29        | 30        | 31        |          |           |          |
| CopterSonde |          |          |    |           |           |           |           |           |           |           |           |           |           |           | <b>15</b> | <b>12</b> | <i>16</i> |          |          | <i>16</i> | <i>15</i> | <i>17</i> | <b>17</b> |          | <b>12</b> |          |
| RAAVEN      |          |          |    |           |           |           |           |           |           |           |           |           |           |           | <i>3</i>  |           |           | <i>3</i> |          |           | <i>3</i>  | <i>4</i>  | <i>3</i>  | <i>1</i> | <i>3</i>  | <i>3</i> |
| September   | 1        | 2        | 11 | 12        | 13        | 14        | 15        | 16        | 17        | 18        | 19        | 20        | 21        | 22        | 23        | 24        | 25        | 26       | 27       | 28        | 29        | 30        |           |          |           |          |
| CopterSonde |          |          |    |           | <b>19</b> | <b>16</b> | <b>15</b> | <b>20</b> |           |           | <b>12</b> | <b>16</b> | <b>20</b> | <b>22</b> | <b>13</b> |           |           |          |          |           |           |           |           |          |           |          |
| RAAVEN      | <i>3</i> | <i>3</i> |    |           |           |           |           |           |           |           |           |           | <b>2</b>  | <b>3</b>  | <b>3</b>  | <b>1</b>  | <b>3</b>  | <b>2</b> | <b>2</b> | <b>3</b>  | <b>3</b>  | <b>3</b>  | <b>3</b>  |          |           |          |

Flights were conducted during daylight hours in the altitude range spanning from the surface to 609 m AGL. These flights were supported by Certificates of Authorization (COAs) from the US Federal Aviation Administration (FAA). When equipped with the POPS sensor, the RAAVEN can fly up to 1.5 h, so the primary flight pattern combined helical profiles with long horizontal transects at multiple height levels to gather observations over a wider spatial region. During TRACER-UAS, the RAAVEN team would generally conduct three flights daily, with each flight starting with a profile

Table 2.2: Flight statistics from the CU RAAVEN and OU CopterSonde across the entire TRACER-UAS campaign

| Aircraft                | CU RAAVEN | OU CopterSonde |
|-------------------------|-----------|----------------|
| Flight days at UHCC     | 12        | 19             |
| Flight days at BRZ      | 35        | 14             |
| Total number of flights | 131       | 549            |
| Number of profiles      | 251       | 547            |
| Flight hours            | 187       | 56             |

up to 600 m AGL and would then proceed to complete a series of stepped-level legs, where the aircraft would maintain an altitude for approximately 9 minutes per leg. The altitudes sampled by these level legs during TRACER were nominally 600, 400, 250, 150, 100, 50, and 20 m AGL, though sometimes adjustments were needed due to weather conditions or air traffic conflicts. After the completion of these level legs, the aircraft would conduct another profile or two to 600 m AGL before landing to end the flight.

The CopterSonde has a shorter battery life, but batteries can be quickly replaced to conduct vertical profiles with high temporal resolution. Each flight up to 609 m takes about 6 min to complete, which is how on 22-23 September, there were 4 flights completed at a 7-min cadence during a late-onset sea breeze. Typically, the flight cadence was 30 min until there was evidence of a sea breeze moving onshore or interesting features in the temperature profile that would motivate increasing the flight cadence to 15 min. Most days had at least 1 h of flights at a 15-min cadence, which was decided in real-time using satellite and CopterSonde data. Given the flexibility of the flight strategy, the start and end times were chosen two days in advance to meet certain objectives. The FAA only allowed 8 h of flight time per pilot per day, so operations usually started between 0800-1000 LST and ended at 1600-1800 LST. Team members used numerical weather models to estimate the sea breeze timing and convection initiation to decide operation hours. Throughout the dataset, there are some breaks in the flight pattern due to lightning or rain delays, technical errors, or airspace deconfliction. Low clouds were an occasional problem that limited the flight ceiling, but 75% of CopterSonde flights reached the 609 m flight ceiling.

### 2.1.4 UAS observation intercomparison

The operational dates for each platform were intentionally staggered by a week to expand the amount of data collected by the two platforms over the course of the four-month campaign. Nevertheless, on 13 days, both teams were co-located and conducting simultaneous flight operations offering a limited amount of data for platform intercomparison. Such intercomparison was viewed to be important to ensure that there was no significant sensor drift over the four-month field campaign window, and to ensure that data from the two platforms was able to be used confidently together to develop statistics. This intercomparison included the calculation of mean vertical profiles from both platforms during time periods when both aircraft captured profiles within 15 minutes of one another. Such tight time alignment was required to minimize the impacts of a rapidly evolving atmospheric boundary layer. A total of 44 profiles from each platform were matched and used in the data comparison. Moreover, the RAAVEN data were interpolated to a 5-m vertical grid to match the vertical resolution of the CopterSonde, and both were set to an equal profile depth.

Table 2.3 provides the statistical comparison of direct observations from each platform. Temperature, relative humidity, and wind direction are all in strong agreement with Pearson correlations above 0.9. The wind speed correlation is lower due in part that the CopterSonde wind speed calculation is less accurate at very low wind speeds, and the relatively high amount of variability in wind speed and direction within the eddy-driven structure of a convective boundary layer with low mean wind speeds. Because near-zero wind speeds are challenging to compare, the wind data were filtered if the wind speed was less than  $2 \text{ m s}^{-1}$ . As an extra assurance of data quality, the CopterSonde wind speed and direction were compared against a Doppler lidar located within 6 m of the profile site at the UH Coastal Center (Fig. 2.3). The lidar completed 60° plan-position indicator scans every 15 min in order to calculate velocity azimuthal

displays of wind speed and direction. The correlation between the lidar winds and the CopterSonde is 0.866, which is slightly better than the correlation between the two UAS platforms, but the mean difference shows a  $0.326 \text{ m s}^{-1}$  underestimation of wind speed by the CopterSonde.

It is important to note that this intercomparison is not meant to be a detailed evaluation of the measurement quality provided by both platforms. Such an evaluation was previously conducted in the pre-campaign preparations for the TRACER project, and the results of that evaluation can be reviewed in de Boer et al. (2022). Overall, differences in observations in the TRACER-UAS dataset fall in line with findings from that manuscript. While the data are not perfectly correlated due to inherent spatial heterogeneity in the ABL and differences in sensors, the data are in strong agreement with each other and ground-based observations, offering confidence that the datasets can be used together to develop statistical analyses of atmospheric phenomena as part of this deployment.

### 2.1.5 Categorizing TRACER Conditions

Table 2.4 summarizes OU’s contribution to the TRACER-UAS campaign by number of days with an SB, BB, and/or convection at each flight site. These events were determined using a multi-data approach analyzing CopterSonde, radar, and satellite observations. The KHGX radar was located 9 km north of UHCC and 45 km northeast of BRZ. Days with convection were identified by KHGX base reflectivity greater than 30 dBZ within a 35 km radius of the observation site at any point during flight hours. The UHCC site was uniquely positioned west of Galveston Bay, such that the wind direction from any BB was distinct from observed SBs. At UHCC, the BB is recognized

Table 2.3: Data comparison statistics from 4425 data points of co-located vertical profiles from the RAAVEN and CopterSonde (CS). Mean difference is (CopterSonde - RAAVEN). Uncertainty is given as CopterSonde/RAAVEN. Values with an asterisk are sensor uncertainties provided by the manufacturer. Values with an <sup>†</sup> are mean biases based on comparisons to radiosondes reproduced from de Boer et al. (2024).

| Base Variables                  | $r^2$ | Mean Difference | $\sigma$ | Uncertainty             |
|---------------------------------|-------|-----------------|----------|-------------------------|
| Temp. [K]                       | 0.985 | -0.287          | 0.327    | 0.3/0.2*                |
| RH [%]                          | 0.945 | -3.763          | 3.934    | 3/3*                    |
| Wind Dir. [°]                   | 0.967 | 0.067           | 13.256   | 1.15/-3.76 <sup>†</sup> |
| Wind Speed [m s <sup>-1</sup> ] | 0.829 | -0.409          | 1.227    | -0.70/0.58 <sup>†</sup> |

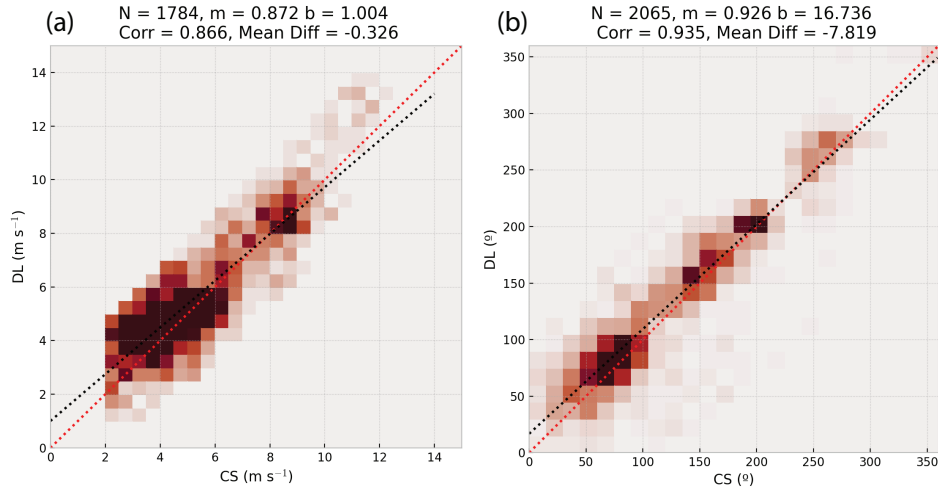


Figure 2.3: (a) Wind speed (m s<sup>-1</sup>) and (b) direction (°) comparison between CopterSonde (CS) and Doppler wind lidar (DL) observations collected within 15 min of each other at UHCC

Table 2.4: Overview of conditions by number of days at each location

| <b>Location</b> | <b>SB<br/>Days</b> | <b>BB<br/>Days</b> | <b>SB +<br/>Convec-<br/>tion</b> | <b>Non-SB<br/>Convec-<br/>tion</b> | <b>No SB or<br/>Convec-<br/>tion</b> | <b>Total</b> |
|-----------------|--------------------|--------------------|----------------------------------|------------------------------------|--------------------------------------|--------------|
| BRZ             | 10                 | 0                  | 5                                | 2                                  | 2                                    | 14           |
| UHCC            | 7                  | 4                  | 1                                | 3                                  | 9                                    | 19           |

by an increase in easterly flow; then, throughout the day, flow rotates to the south-southeasterly, indicative of the SB (Banta et al. 2005). Suspected SB days were initially identified using CopterSonde time-height fields. It was common that morning flights had light and variable winds, allowing the SB to be identified by an abrupt increase in wind speed and reduction of wind direction variance. To verify the SB occurrence, the timing of wind speed acceleration was compared against air mass boundaries observed by radar and satellite. On most SB days, enhanced cloud cover along the coastline would push inland at the time of flow acceleration, visible on satellite and sometimes the lowest radar scan. Radar was also used to ensure the wind shift was not due to outflow boundaries from nearby convection.

## 2.2 Simulations

The Warn-on-Forecast System (WoFS, Stensrud et al. (2009); Heinselman et al. (2023)) is a convection-allowing model with rapidly updating data assimilation cycles designed for high-impact weather events. The WoFS is initialized from the 36-member HRRR Data Assimilation System (HRRR-DAS; Dowell et al. (2022)). The WoFS configuration is on 750 km X 750 km domain with 3 km horizontal grid spacing. There are 51 vertical levels on a hybrid sigma-terrain following coordinate system, where vertical spacing is less than 100 m near the surface and expands up to 1 km at the 10 hPa

Table 2.5: WoFS ensemble member (EM) parameterization configuration

| <b>EM</b> | <b>PBL</b> | <b>SW<br/>Radiation</b> | <b>Longwave<br/>Radiation</b> | <b>Microphysics<br/>and Land<br/>Surface</b> | <b>GEFS<br/>Member<br/>for BC</b> |
|-----------|------------|-------------------------|-------------------------------|----------------------------------------------|-----------------------------------|
| 1         | YSU        | Dudhia                  | RRTM                          | NSSL 2-Moment<br>and RUC                     | 1                                 |
| 2         | YSU        | RRTMG                   | RRTMG                         |                                              | 2                                 |
| 3         | MYJ        | Dudhia                  | RRTM                          |                                              | 3                                 |
| 4         | MYJ        | RRTMG                   | RRTMG                         |                                              | 4                                 |
| 5         | MYNN       | Dudhia                  | RRTM                          |                                              | 5                                 |
| 6         | MYNN       | RRTMG                   | RRTMG                         |                                              | 6                                 |
| 7         | YSU        | Dudhia                  | RRTM                          |                                              | 7                                 |
| 8         | YSU        | RRTMG                   | RRTMG                         |                                              | 8                                 |
| 9         | MYJ        | Dudhia                  | RRTM                          |                                              | 9                                 |
| 10        | MYJ        | RRTMG                   | RRTMG                         |                                              | 10                                |
| 11        | MYNN       | Dudhia                  | RRTM                          |                                              | 11                                |
| 12        | MYNN       | RRTMG                   | RRTMG                         |                                              | 12                                |
| 13        | YSU        | Dudhia                  | RRTM                          |                                              | 13                                |
| 14        | YSU        | RRTMG                   | RRTMG                         |                                              | 14                                |
| 15        | MYJ        | Dudhia                  | RRTM                          |                                              | 15                                |
| 16        | MYJ        | RRTMG                   | RRTMG                         |                                              | 16                                |
| 17        | MYNN       | Dudhia                  | RRTM                          |                                              | 17                                |
| 18        | MYNN       | RRTMG                   | RRTMG                         |                                              | 18                                |



model top. Lateral boundary conditions (BCs) are supplied by the operational HRRR forecast combined with large-scale perturbations from the GEFS (Zhou et al. 2022). Satellite, radar, and surface observations are assimilated every 15 min, with free forecasts generated every 30 min. For this study, the full forecast from 1700–2300 UTC is used with output every 10 min. There are 18 ensemble members (EMs) varying in PBL and radiation parameterizations, described in Table 2.5. Across all members, the microphysics and land-surface schemes are fixed, using NSSL 2-moment (Mansell et al. 2010) and the RUC (Smirnova et al. 2016) schemes, respectively. Beyond the initial and boundary conditions, the first six EMs vary only in shortwave (SW) radiation and PBL schemes and are the only members evaluated in Chapter 4. All members are examined in Chapter 5.

Herein, we will focus on three PBL schemes frequently used in WRF modeling: MYJ (Janjić 1994) and MYNN (Nakanishi and Niino 2006) are both local mixing schemes with 1.5-order turbulence closure, and YSU is a nonlocal, first-order closure scheme (Hong et al. 2006). One main difference between MYJ and MYNN is how scaling relationships are derived; MYJ is based on observations and MYNN is based on LES output, which increases the range of turbulence closure constants that could be calculated under controlled conditions. To improve the inadequate vertical mixing in MYJ, MYNN uses a surface-layer length scale as a function of stability that is blended into the master mixing length. Each scheme varies in how the PBL depth is determined: YSU selects the lowest height at which a critical Richardson number, based on stability, is reached; MYJ is based on a turbulence kinetic energy (TKE) threshold where  $\text{TKE} < 0.1 \text{ m}^2 \text{ s}^{-2}$ ; MYNN is similar to MYJ but requires the level to have a positive potential temperature ( $\theta$ ) gradient. Additionally, the effects of SW radiation schemes will be analyzed as members alternate between the Dudhia or RRTMG SW

scheme. The Dudhia scheme is simpler and more computationally efficient by not explicitly solving the radiative transfer equation, but relies on empirically derived scaling equations and look-up tables, whereas the RRTMG scheme is much more complex and computationally expensive, utilizing radiative transfer models to explicitly solve the radiative transfer equation. The WoFS model is used for verification in Chapter 4 and for understanding the implications of PBL parameterizations on CI in Chapter 5.

## Chapter 3

# Observations of coastal breezes and impacts on the ABL

Quantifying the impacts coastal breezes have on altering the ABL is the first step in improving the understanding of their influence on air quality and weather forecasts. The bay breeze (BB) and sea breeze (SB) can vary in strength, duration, depth, and speed in terms of thermodynamics and kinematics. The driving factors in coastal breeze intensity are often determined numerically, as described in Crosman and Horel (2010). However, the TRACER dataset provides evidence that coastal breezes evolve on smaller spatiotemporal scales than previously documented. The following analysis evaluates the thermodynamic impacts of the BB and SB and what factors control the magnitude. This is used to understand how the pre-convective environment is altered and what conditions precede convection initiation (CI). The results in this chapter have been accepted in Lappin et al. (2025).

### 3.1 Methods

The CopterSonde provided high-resolution Eulerian observations throughout the daily progression. Given these unique observations, previous SB detection algorithms needed to be altered to best utilize the UAS dataset. Additionally, the thermodynamic evolution did not always behave like the classical model of the SB (cooling and moistening),

and the most reliable SB identifier was a shift in wind direction along with an increase in wind speed. To test the impacts of the BB and SB, estimating the time of the frontal passage is crucial. While subjective estimates of the BB and SB could be made using the CopterSonde time-height fields, an objective algorithm was applied to detect the timing of distinct wind regime shifts for added confidence. A change-point detection algorithm from Arlot et al. (2019) and Truong et al. (2020) was applied to the profile averaged wind direction. Each case study figure (Fig. 3.1-3.4g, h) shows the time series of the profile-averaged state variables and the algorithm-determined BB and SB passage times. This algorithm was not used to determine if there was a BB or SB, but rather the closest estimation of SBF passage time based on the observations available. A description of how BB and SB occurrences are determined can be found in Chapter 2.

The change point algorithm implements a linearly penalized segmentation search method and a kernelized mean change cost function. The selected search method and cost function were motivated by methods in Wang et al. (2024), which used 10 m wind direction observations averaged over 1 min. The UAS observations are averaged over the entire 609 m profile to get a representative sample beyond the surface layer. The UAS did not fly through the top of the BB or SB, such that return flow was not observed within the profile. The minimum segment length was set to 1 h to allow enough time separation to capture the BB and SB. The algorithm was allowed to detect as many change points in wind direction as possible, but each case only detected the expected number of breezes. In cases with a BB and SB, two change points were detected and the BB was identified by the first breakpoint when the wind direction shifted to easterly flow. The SB is found at the second breakpoint where the wind direction ranges from southeast to south. All observations of the BB come from UHCC, and every BB was

followed by an SB, on average, 2.15 h later. The SB passage times range from 1730-0007 UTC (1230-1907 LST), with the SB (on average) arriving slightly later in the day each month. Identifying the frontal passage times allowed for calculations to be centered on the BB or SB for compositing.

The rate of change for temperature and moisture was chosen to quantify the ABL response to the BB/SB, both immediately at the frontal passage and well into the SB inflow layer. To investigate the differences with height, the profile was divided into 3, 200 m deep layers and averaged. For each layer, the difference is calculated  $(X_t - X_{t-1})$ , where  $X_t$  and  $X_{t-1}$  are the variables temperature ( $T$ ) and water vapor mixing ratio ( $w$ ) measured from consecutive profiles. The rate of change was standardized to a 30 min time grid and converted to hourly rates. If the sampling cadence was 15 min, the rate of change was averaged over the 2 flights to maintain a 30 min grid.

## 3.2 Sea breeze cases

Out of the 33 days observations were gathered, 17 experienced an SB (Table 2.4). Only 4 BBs were observed, all at UHCC, since BRZ is not close enough to Galveston Bay. Not all SB days at UHCC observed a BB because sometimes the thermal gradient across Galveston Bay was not strong enough to generate a BB circulation. The range of conditions during SB events is introduced by showing 4 different SB passage cases using CopterSonde observations (Figs. 3.1-3.4). These cases are distinct from each other, but each event has at least two other days that are similar. The broad range of these SBF characteristics motivated the remaining analysis to quantify the thermodynamic changes and isolate the differences among them. For the case description, maps of synoptic conditions were analyzed from the archived TRACER forecast discussions.

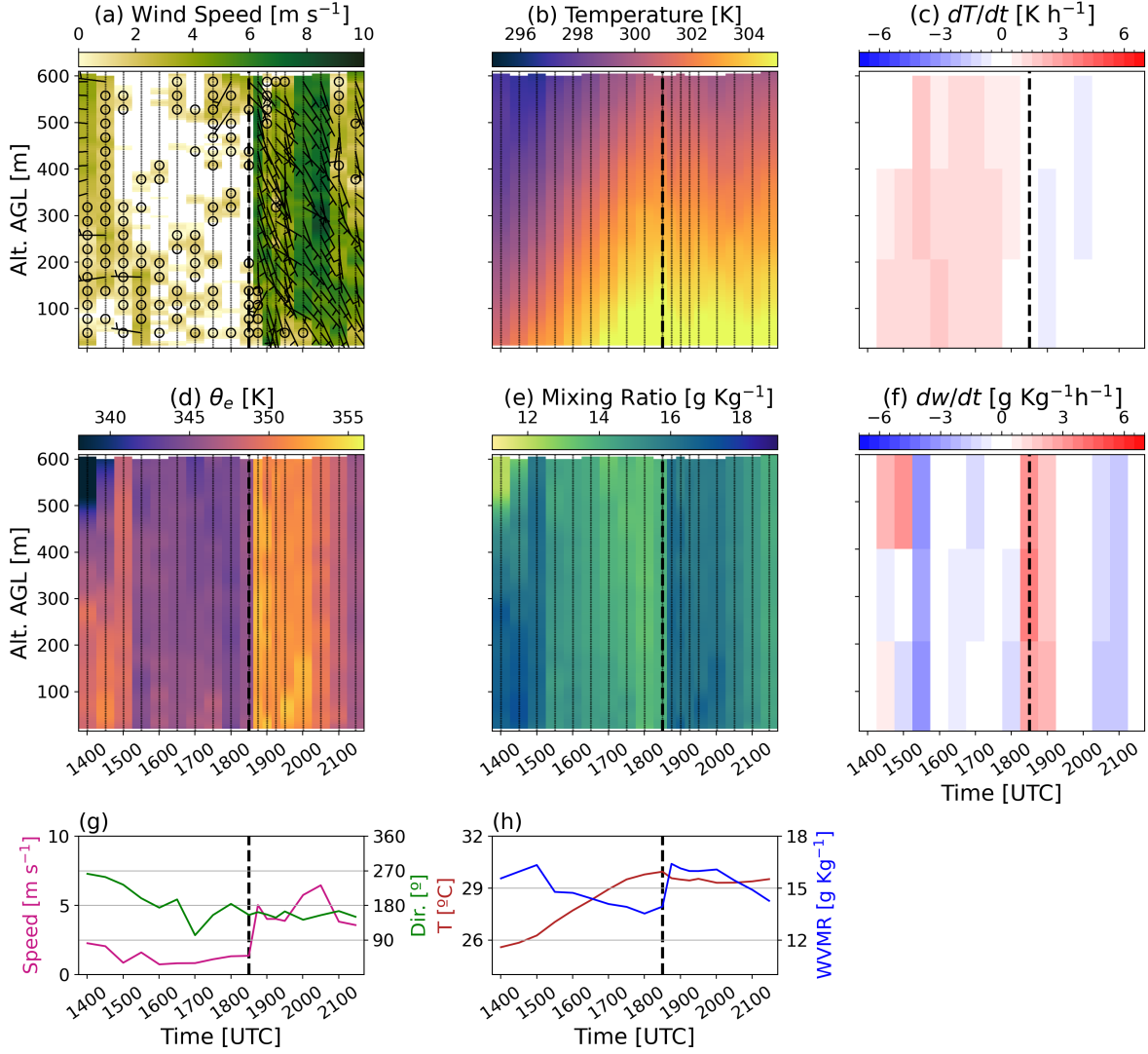


Figure 3.1: CopterSonde observations from 23 June 2022 at BRZ. (a) wind speed ( $\text{m s}^{-1}$ ) with wind barbs overlaid (K), (b) temperature (K), (c) temperature rate of change ( $dT/dt$ ,  $\text{K h}^{-1}$ ), (d) equivalent potential temperature (K), (e) water vapor mixing ratio ( $\text{g kg}^{-1}$ ), (f) water vapor mixing ratio rate of change ( $dw/dt$ ,  $\text{g kg}^{-1} \text{h}^{-1}$ ), (g) profile averaged wind speed (pink) and direction (green) time series, (h) profile averaged temperature ( $^{\circ}\text{C}$ ) and  $w$  ( $\text{g kg}^{-1}$ ) time series. Dashed lines indicate the SB. LST = UTC - 5

*Typical SB (23 June):* Mid-June 2022 featured a developing mid-level omega block pattern over the Great Plains, leading to high temperatures and weak synoptic flow. Mid-level moisture was lacking which caused any precipitation to be short-lived and scattered, leading to intensifying drought conditions. A local high centered over the

greater Houston area brought regional flow to near zero. This allowed a CBL to develop by 1530 UTC marked by well-mixed  $\theta_e$  and near-surface drying (Fig. 3.1b, c). Winds were below  $2 \text{ m s}^{-1}$  until 1830 UTC when southeasterly flow first increased above 200 m, then extended through the entire layer after 30 min (Fig. 3.1d). Simultaneously, moisture increased, contributing to a rise in  $\theta_e$ . The diurnal warming was consistent throughout the morning, then was interrupted by the SB and temperature remained steady through the afternoon (Fig. 3.1e). While the SB flow speeds were weak and variable with height, the influence on the thermodynamic state was evident and strong relative to other events. However, the elevated moisture was temporary and subsided 2 h after the SB (Fig. 3.1f).

*Atypical SB case (21 June):* A mid-level ridge sat over the Appalachian mountains, leading to weak southeasterly, onshore winds over the Texas Gulf Coast. Mid-level moisture increased around the Gulf Coast states, increasing convective potential. At 1200 UTC, convection initiated north of Galveston Bay, resulting in anvil shading over the western side of Galveston Bay. However, this did not impede the cumulus field that developed over BRZ after 1400 UTC. On 21 June, the earliest flights had weak onshore flow around  $2\text{--}4 \text{ m s}^{-1}$  (Fig. 3.2d). With this came moisture advection concentrated below 400 m and high  $\theta_e$ . At 1730 UTC, the easterly component of the flow increased, and the onshore winds accelerated to  $5\text{--}7 \text{ m s}^{-1}$  (Fig. 3.2d, g). At this time, moisture decreased variably with height for 1 h and then increased slightly (Fig. 3.2f). The change in temperature was minor and stayed nearly constant for the next 4 h (Fig. 3.2e). After 2100 UTC, the rise in moisture and fall in temperature was more pronounced even though there was little change in the onshore flow. The SB passed through 1 h earlier than the SB on 23 June, but since the CBL was not well developed, the SB seemed to act as a mixing agent to transport moisture vertically,

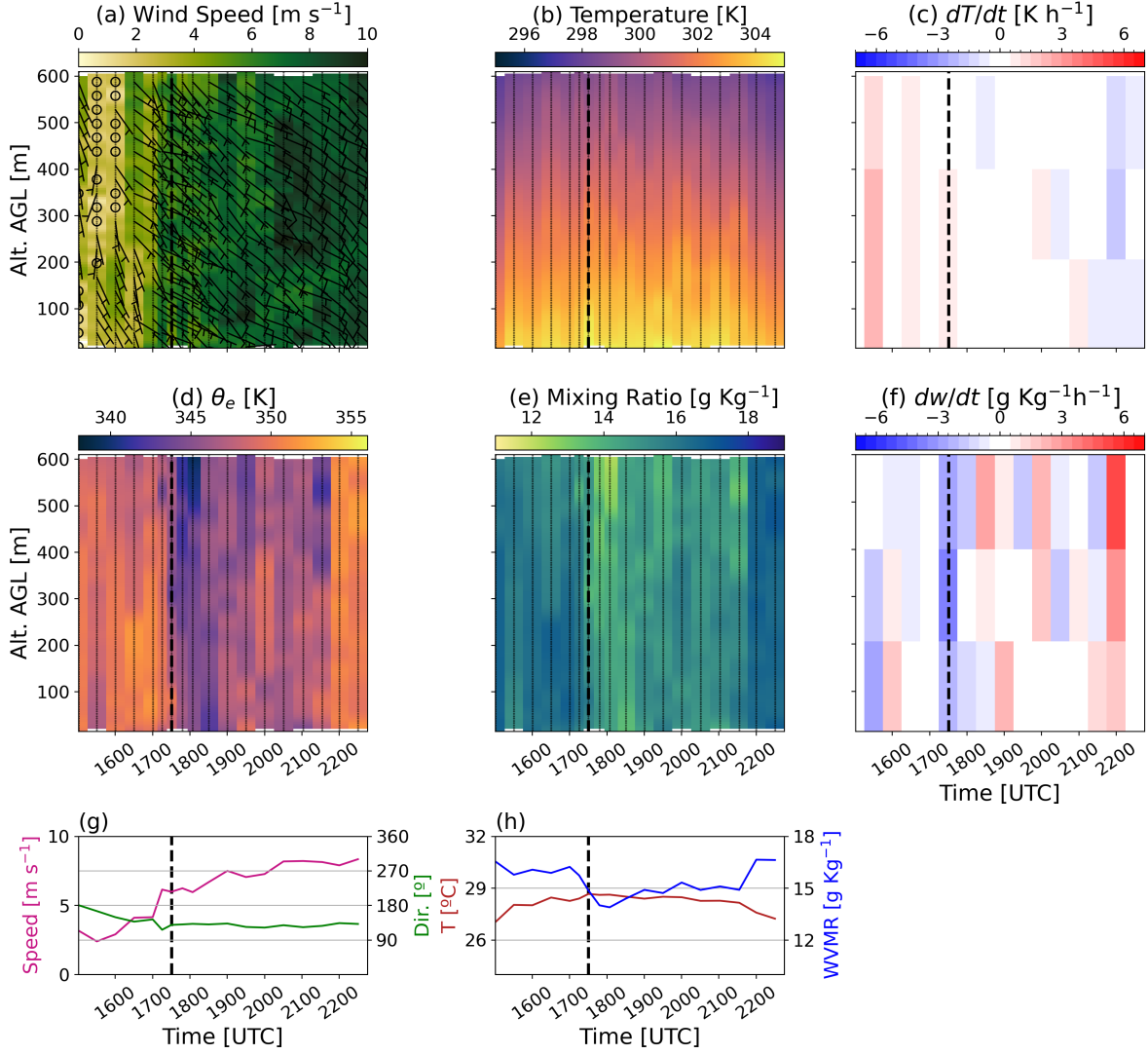


Figure 3.2: Same as Fig. 3.1 but for 21 June 2022 at BRZ

leading to low-level drying. This case represented a deviation from the traditional SB model, with the SB reducing low-level moisture as the coastal environment is already moisture-rich.

*BB to SB Case (16 June):* On 16 June, synoptic conditions were similar to those on 23 June. Figure 3.3a-d shows the day began with weak flow and a quickly developing CBL, seen through increasing surface temperatures and well-mixed water vapor mixing ratio ( $w$ ), similar to Fig. 3.1. At 1730 UTC, there was a sudden increase in easterly flow



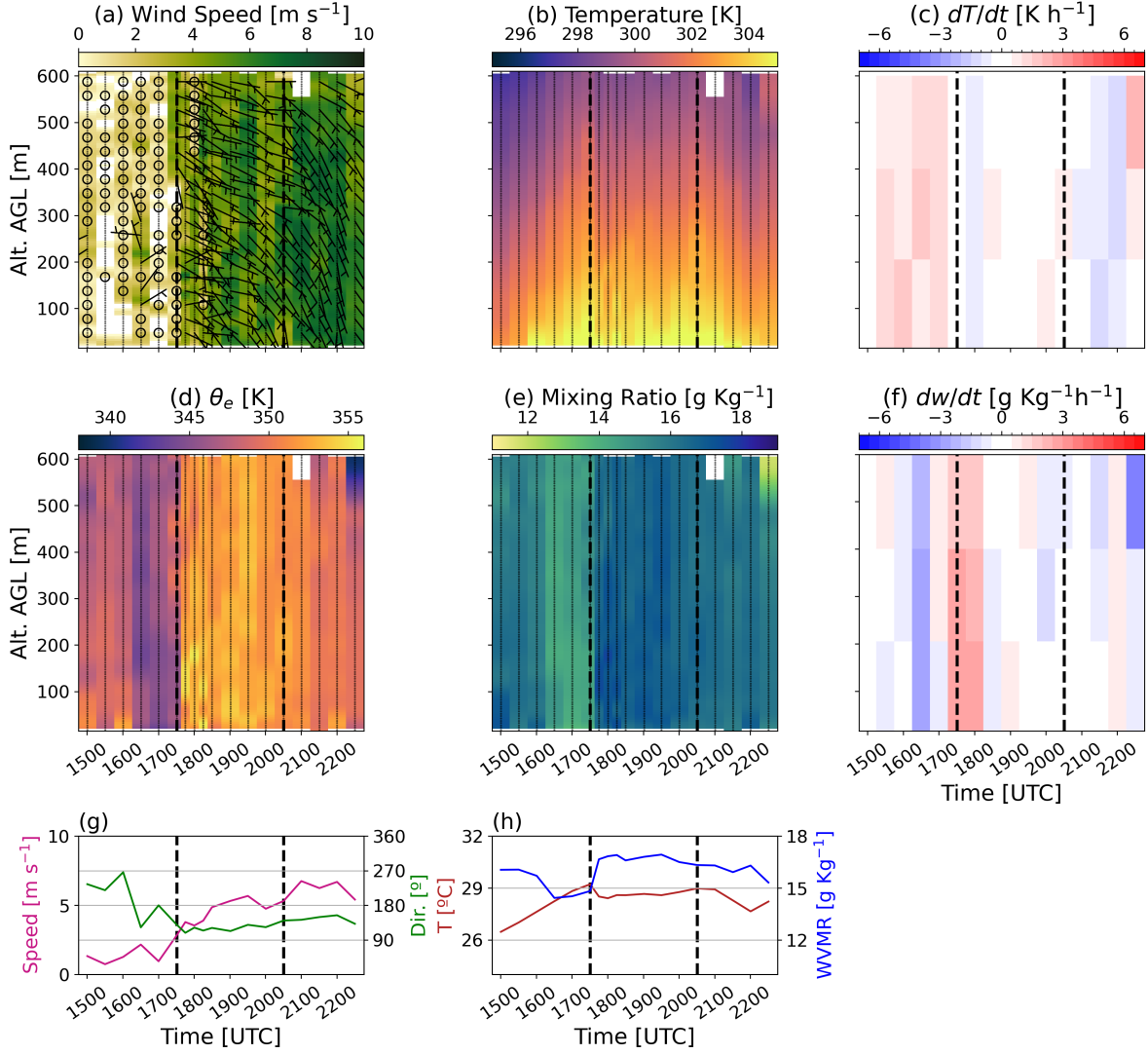


Figure 3.3: Same as Fig. 3.1 but for 16 June 2022 and at UHCC. The dashed lines represent the BB at 1730 UTC and the SB at 2030 UTC

and  $w$  throughout the column (Fig. 3.3g, h). Equivalent potential temperature ( $\theta_e$ ) rose while temperature decreased marginally and then remained steady. Moisture began to decrease 2 h after the BB passage but stayed higher than before the BB (Fig. 3.3f). The winds veered with time and accelerated at 2100 UTC becoming southeasterly, indicating the passage of the SB. Wind speeds remained elevated and the temperature began to decline, as did moisture and  $\theta_e$  (Fig. 3.3b, c). The BB and SB are distinct due

to the air masses being advected; Galveston Bay is warmer than the Gulf of Mexico but holds plenty of moisture, leading to a boost in low-level  $w$ . Once the SB pushed inland, the moisture remained steady, but the cooling rate intensified. Due to dry mid-levels, there was very little potential for CI, which allowed an uninterrupted look at the BB and SB progression into the afternoon.

*SB in stronger flow (17 July):* While many SB detection algorithms use a filter to eliminate days that have existing flow with any onshore component (e.g. Azorin-Molina et al. (2015); Arrillaga et al. (2020)), we observed that some SBs can compound with onshore flow, and are detectable with high-resolution observations. On 17 July, a high-pressure system over the Gulf of Mexico drove weak southerly flow along the Gulf coastline through the late morning. Figure 3.4a shows the morning winds are variable in direction, shifting from south to southwest (shore-parallel), and wind speeds stay around  $4 \text{ m s}^{-1}$ . The flow accelerated at 1930 UTC and became steadily from the south, marking the SB passage. The change point detection algorithm successfully located the SBF passage time due to the reduction in wind direction variability (Fig. 3.4g). While southerly flow is not directly onshore, it caused gradual cooling and a modest increase in  $w$  (Fig. 3.4e, f). Moisture began to decline for 1.5 h after the SB passage, primarily at the top of the profile but rebounds to moister than at SBF passage time. Although it was common for there to be no morning flow prior to an SB, this event shows that onshore advection does not necessarily inhibit the SB.

These four cases do not intend to serve as archetypes, but rather, to present the variability of SB data collected throughout TRACER. While they were selected to highlight the differences in SB propagation, there were also similarities across these events. The events on 16 June and 23 June had virtually no wind before BB/SB onset (Fig. 3.1, Fig. 3.3). They had the most drastic increase in moisture but negligible

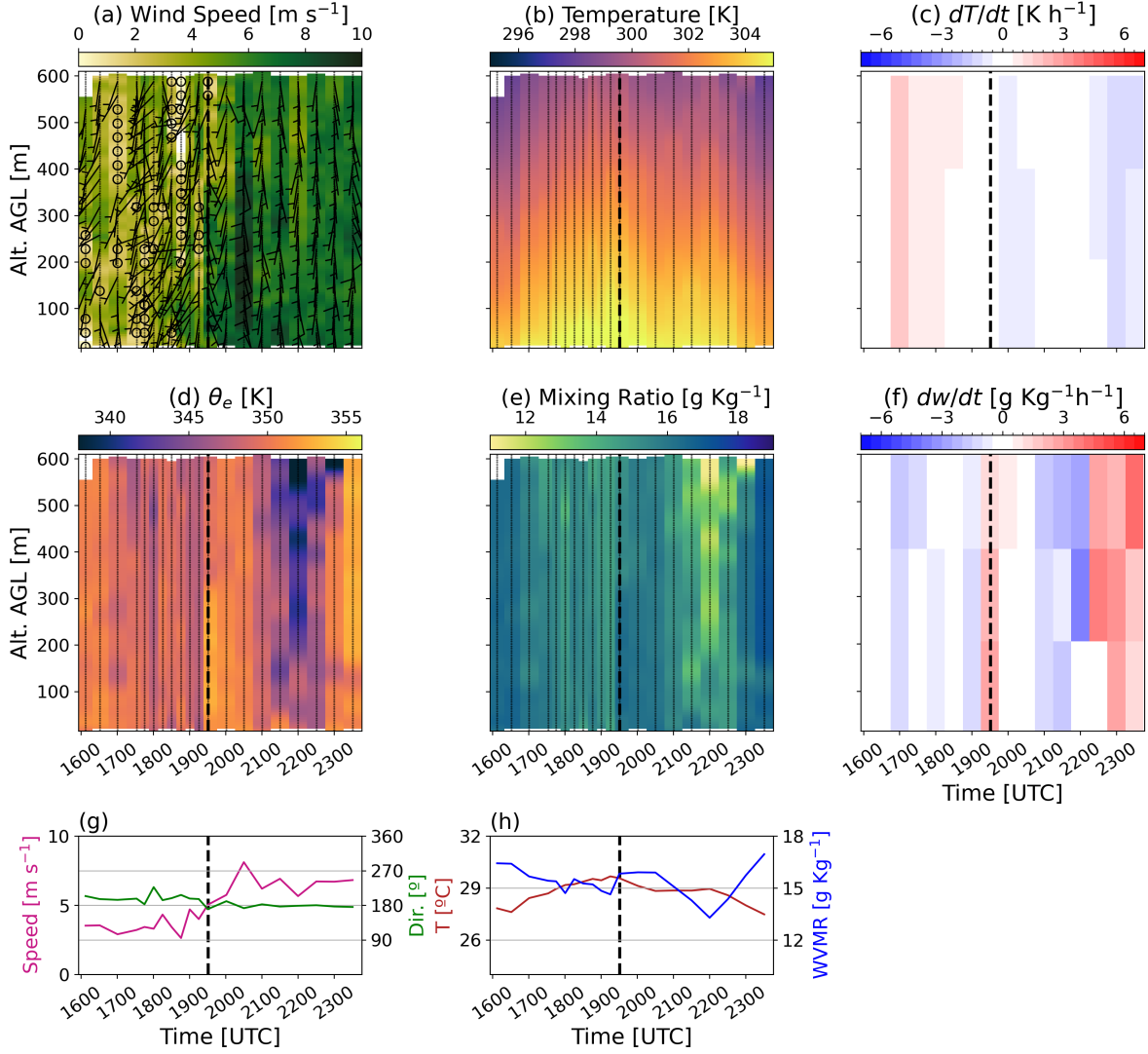


Figure 3.4: Same as Fig. 3.1 but for 17 July 2022 at BRZ

changes to temperature at frontal passage time, and both also saw a general decrease in moisture 2–3 h after the initial increase. The main difference was stronger cooling rates on 16 June after the SB, possibly because the turbulent intensity was reduced by the BB, allowing cooler marine air to stay at low levels. The other two cases had slight onshore flow prior to the SB that delayed the development of a well-mixed CBL. As a result, the changes to the thermodynamic environment at the SBF were small but evolved more rapidly than the 16 June and 23 June. However, for the 21 June and

17 July cases moisture increases and temperature drops later in the afternoon, 4–5 h after the SB passage (Fig. 3.2, Fig. 3.4), unlike 16 June and 23 June. Due to this wide range of impacts, we aim to further investigate the drivers behind BB and SB intensity with respect to temperature and moisture. Understanding how the pre-SB air mass influences the SB evolution may lend insight into better forecasting of CI potential.

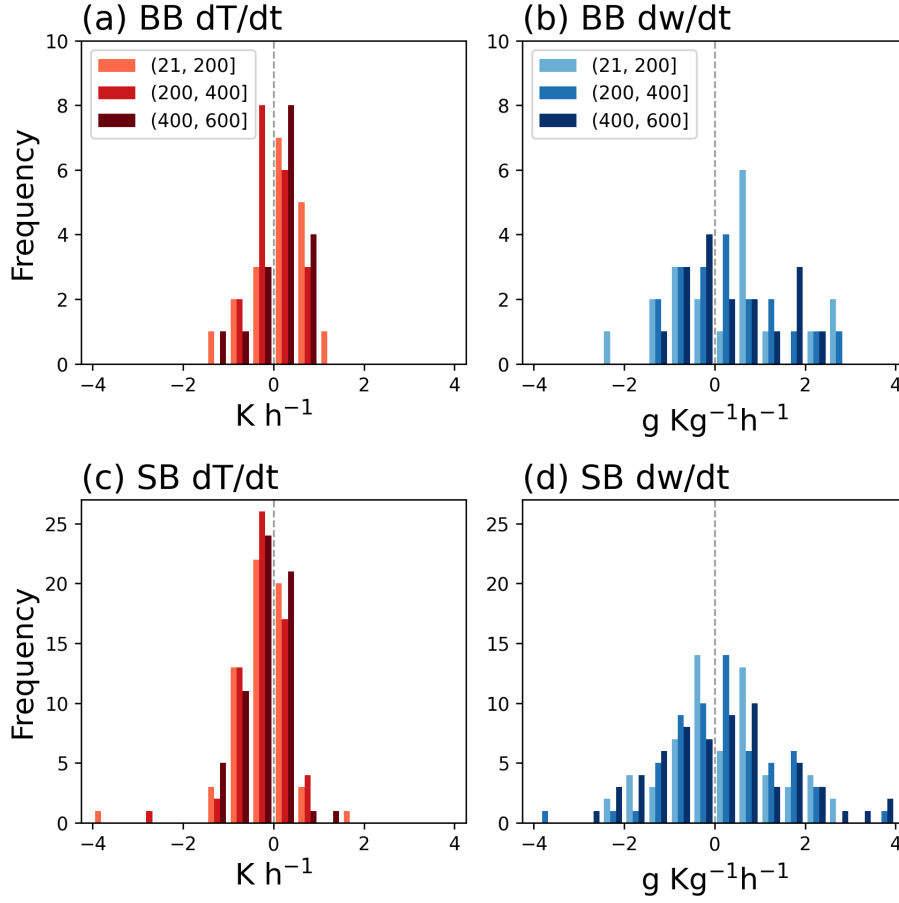


Figure 3.5: Histograms of 30 min rate of change values up to 2 h after the breeze passage for all BB (a, b) and SB (c, d) events. (a, c) temperature rate of change ( $dT/dt$ ,  $K h^{-1}$ ) and (b, d) moisture rate of change ( $dw/dt$ ,  $g kg^{-1} h^{-1}$ ). Colors correspond to the height layer of observations AGL (m)

### 3.3 Range of observed sea breeze impacts

To understand the factors influencing the SB intensity, the scope of SB effects must be evaluated. Previous climatologies of the SB have relied on surface observations and/or radiosonde data, focusing on the broad signals by calculating average values of temperature, relative humidity, and wind speed (Papanastasiou and Melas 2009; Anurose et al. 2018). Given the high-resolution UAS dataset, the deviations and vertical thermodynamic characteristics can be investigated. Temperature and water vapor mixing ratio

rates of change were composited across all SB days and centered by the SBF passage time. Centering variables as a function of the SBF passage time helped reduce signals from other processes like ABL transitions. Analysis of the rate of change was limited to 2 h post-SB or BB to isolate the immediate impacts. Figure 3.5 shows that rate of change for both temperature and moisture follows a normal distribution centered near zero. While the distribution is not perfectly symmetric there are comparable instances of warming and drying trends post-SB, contrary to the expected outcomes. The peak near zero is due to initial BB/SB impacts often being weak and the environment becoming steady with time. Across the height layers, there are no distinct differences in sign or magnitude for temperature or moisture. The vertical consistency of changes suggests the SB inflow layer is at least 600 m deep with no indication of an internal boundary layer developing at the two observation sites.

To better characterize the datasets, Table 3.1 shows the median, skewness, and kurtosis of each rate of change variable. The temperature rate of change distribution is skewed slightly negative (cooling), while the moisture rate of change is skewed positive (moistening), for the BB and SB (Table 3.1). Both statistics align with cooling and moistening, suggesting that the typical BB/SB progression is still dominant. However, warming and drying periods are frequent within 2 h after the breeze often enough to maintain symmetrically distributed variables with low skewness. The SB has higher kurtosis and, therefore, more outliers than the BB in both rate of change variables (Table 3.1). These outliers are primarily in the cooling and moistening direction leading to the slightly larger skewness magnitudes from the SB (Fig. 3.5, Table 3.1). The strong cooling and moistening outlier SB events, based on Fig. 3.5, tended to be more shallow, leading to higher kurtosis at the lowest level. The median BB  $dT/dt$  is positive due to the temperature advection from Galveston Bay being too weak to offset daytime heating during the early afternoon. In terms of moisture, the BB is more consistent

in moistening effects with a larger median rate of change and low kurtosis, but the SB displays more moistening potential with a larger spread in  $dw/dt$  and more frequent positive outliers. While the median values for thermodynamic rate of change are weak and do not show clear differences between the BB and SB, higher moment statistics can highlight variability in the distribution.

Figure 3.6 shows the evolution of rate of change observations from BB/SB passage (0 min) until 90 min after BB (green) or SB (blue) passage in 30 min periods. The 0 min distribution represents the rate of change as the SB passes compared to the undisturbed environment 30 min before a BB/SB. There is no consistent evolution across the variables or breeze type, but the spread amongst all rates of change is the largest immediately after the breeze passage, most prominently in water vapor mixing ratio. The SB  $dT/dt$  distribution is the most consistent with negative skewness and decreasing median values with time, suggesting subtle, sustained cooling rather than an abrupt temperature shift. The BB  $dT/dt$  is more variable, oscillating between weak warming and cooling periods with time, which may be a byproduct of a smaller sample size than the SB. Since the forcing mechanism behind the BB is weaker, the BB can only cause temperatures to remain steady for 30–60 min before returning to the diurnal heating. Moreover, the moisture response after the BB trends down across each time range (Fig. 3.6a), with drying from 60–90 min after the BB, suggesting a return to the pre-BB, CBL state. The BB and SB are most likely to add significant moisture in the first 30 min, but the second highest median increase is 90 min after the SBF (Fig. 3.6b). This moisture fluctuation with time is similar to the pulsating SBs observed in Puygrenier et al. (2005). Moisture and temperature evolve on different timescales during the SB and BB, with moisture changing abruptly upon breeze passage and temperature evolving more gradually.

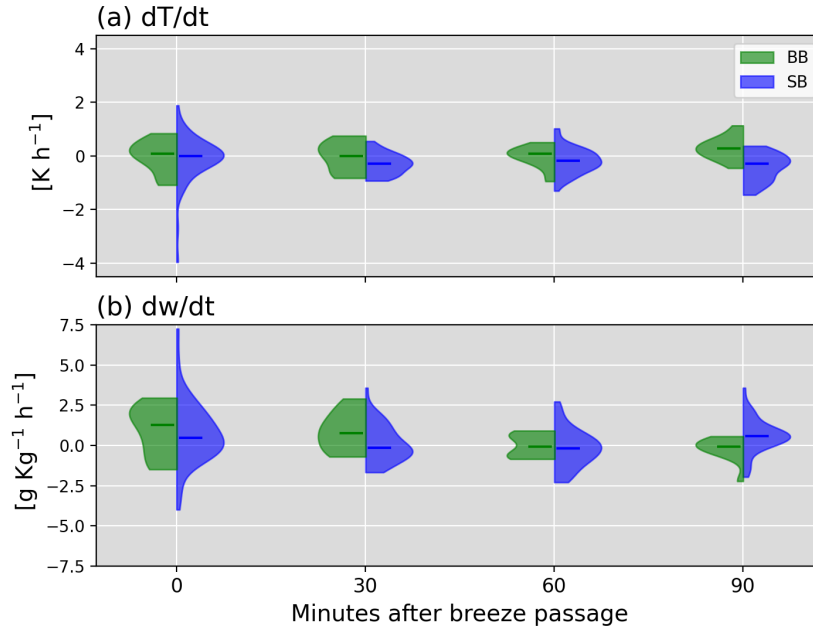


Figure 3.6: Split distribution plots of rate of change for all 3 layers categorized into 30 min periods following SB (blue) or BB (green) passage. (a) rate of change of temperature, (b) rate of change of water vapor mixing ratio. Horizontal lines within distributions indicate the median value. For each variable, N=42 for BB and N=180 for SB

Table 3.1: Rate of change statistics from the CopterSonde data during TRACER-UAS. N=51 for BB and N=189 for SB statistics

| Rate of change | Median | Skewness | Pearson Kurtosis |
|----------------|--------|----------|------------------|
| $dT/dt$ (BB)   | 0.11   | -0.14    | 2.58             |
| $dT/dt$ (SB)   | -0.18  | -0.20    | 7.96             |
| $dw/dt$ (BB)   | 0.30   | 0.04     | 2.30             |
| $dw/dt$ (SB)   | 0.14   | 0.22     | 5.70             |



### 3.4 Factors impacting sea breeze thermodynamic intensity

To dissect the different responses to the BB or SB in relation to location, layer, and timing, a two-sample Z test was performed. These tests use independent variables like location and time of year to understand the spatial and seasonal evolution. Table 3.2 summarizes which samples have statistically different mean rates of change. Differences in the BB and SB are only significant for changes to temperature, with the SB showing stronger median cooling. In terms of the thermodynamic structure, there is no significant difference in changes to temperature or moisture at different levels. This suggests that the SB inflow region is consistent up to 600 m with no discernable internal boundary layer at lower levels. Notably, the timing of the SBF influences how strong thermodynamic changes are to the ABL, such that SBs that occur later than the median SBF passage time are stronger at cooling and moistening across the profile. As follows, September SBs, which arrived closer to sunset, are stronger at cooling and moistening than June SBs. Although the median BB tends to warm UHCC, the median SB cooling is significantly greater at UHCC than BRZ (Tables 3.1, 3.2). This could be an artifact of exclusively flying at UHCC in September and those SBs being stronger at cooling and moistening. When comparing the location difference during June, there was no statistical significance in either variable. Converging statistics show that September SBs are stronger because they arrive later, stemming from the coherence of the evening transition with SB passage. It is possible that decaying convective turbulence allows the marine airmass to retain more of its qualities as it is advected over the observation site.

Table 3.2: Z-test significance testing for temperature and moisture rate of change. M-dash (—) indicates no significant difference in two samples, single star (\*) indicates  $p < 0.1$  value, double star (\*\*) indicates  $p < 0.01$  value.

| 2 sample Z-test     | $dT/dt$ | $dw/dt$ | Outcomes                                                          |
|---------------------|---------|---------|-------------------------------------------------------------------|
| BRZ v UHCC          | **      | —       | SB cooling at UHCC is stronger                                    |
| BB v SB             | **      | —       | SB cooling is stronger than BB                                    |
| 0–200 m v 400–600 m | —       | —       | No difference across height layers                                |
| Early v Late SB     | **      | *       | Later SBs are stronger at cooling and moistening than early SB    |
| June v September SB | *       | *       | September SBs are stronger at cooling and moistening than June SB |

### 3.5 Sea breeze influence on the pre-convective environment

The SB is a frequent forcing mechanism for CI, so the pre-convective ABL evolution is a critical component of understanding the convective lifecycle. Since the changes to temperature and moisture content are self-consistent across varying layers (Table 3.2), the vertical temperature gradient does not change appreciably with the passage of the SB. As a result, traditional stability metrics like lapse rate do not show clear shifts in convective potential with the SB passage (Figs. 3.3-3.4c). However, the CopterSonde captures rapid changes in low-level moisture and temperature that are well-known to alter the potential instability (McCaul and Cohen 2002). Since the CopterSonde is not well suited to calculate bulk convective parameters like CAPE and CIN, due to limited height range, an alternative low-level variable to quantify instability would

be beneficial. Using radiosondes released from the TRACER AMF in La Porte, TX we can evaluate metrics against CAPE.  $\theta_e$  quantifies moist static energy to highlight the total ABL response and has been used by Soderholm et al. (2017) to understand the SB influence on the pre-convective environment.  $\theta_e$  is calculated using the Bolton (1980) formula, where  $\theta_{DL}$  and  $T_L$  are the potential temperature and temperature at the lifting condensation level, and  $r$  is the water vapor mixing ratio.

$$\theta_e = \theta_{DL} \cdot \exp \left[ \left( \frac{3036}{T_L} - 1.78 \right) \cdot r(1 + 0.448r) \right] \quad (3.1)$$

Using radiosonde observations to calculate CAPE and  $\theta_e$ , Fig. 3.7 shows that  $\theta_e$  correlates well with surface-based and mixed-layer CAPE, similar to results in Kalthoff et al. (2011). The surface level  $\theta_e$  has a slightly better correlation with surface-based CAPE, showing even a single value of low-level  $\theta_e$  provides proportional insight into surface-based CAPE (Fig. 3.7). Thus,  $\theta_e$  can be used as a proxy to bulk instability from low-level observations, including from UAS.

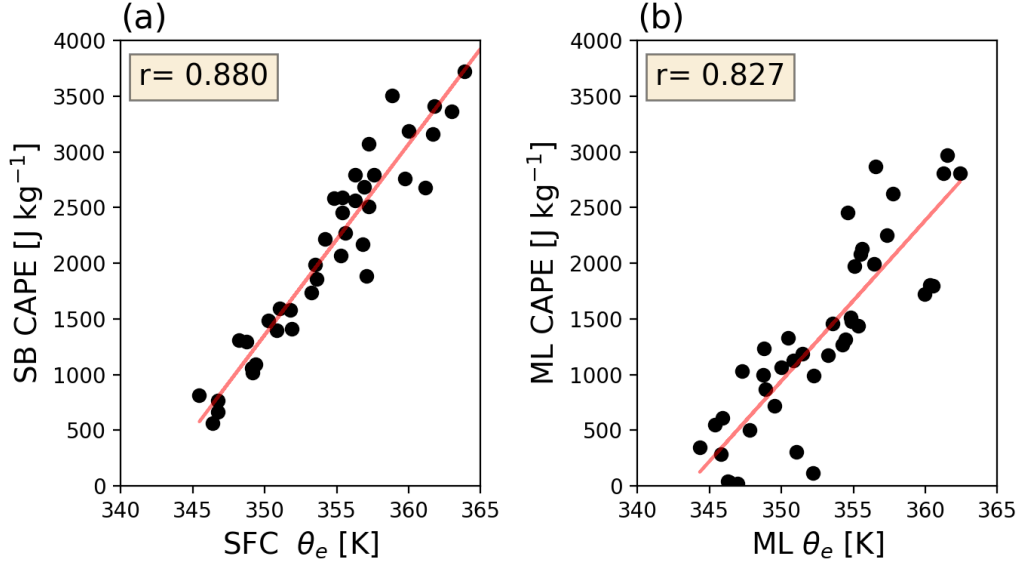


Figure 3.7: (a) Surface-level  $\theta_e$  comparison with SBCAPE and (b) mixed-layer  $\theta_e$  comparison with MLCAPE

Like potential temperature,  $\theta_e$  is a conserved quantity that often becomes well-mixed in the CBL (Fig. 3.1-3.4c). Multiple forcing mechanisms influence the daily evolution of  $\theta_e$ , so to dissect the interactions between the SB, convection, and boundary layer transitions, days will be categorized into modes based on the SB and the presence of convection. Days are considered to have convection based on precipitating cores with  $\text{dBZ} > 30$ , within 35 km of the observation site. The evolution of  $\theta_e$  provides insight into the convective potential before and after the SB passage.

While a correlation of  $\theta_e$  to CAPE is useful, we can also utilize the radiosonde observations to look beyond the CopterSonde flight ceiling to see how the  $d\theta_e/dz$  responds to the SB passage. To compare the CopterSonde and radiosonde observations, the difference in location must be noted; the radiosondes were released at AMF which is closer to downtown Houston and less than 5 km from the Galveston Bay coastline. With more moisture and urban heating at AMF, this leads to larger values of  $\theta_e$  gathered

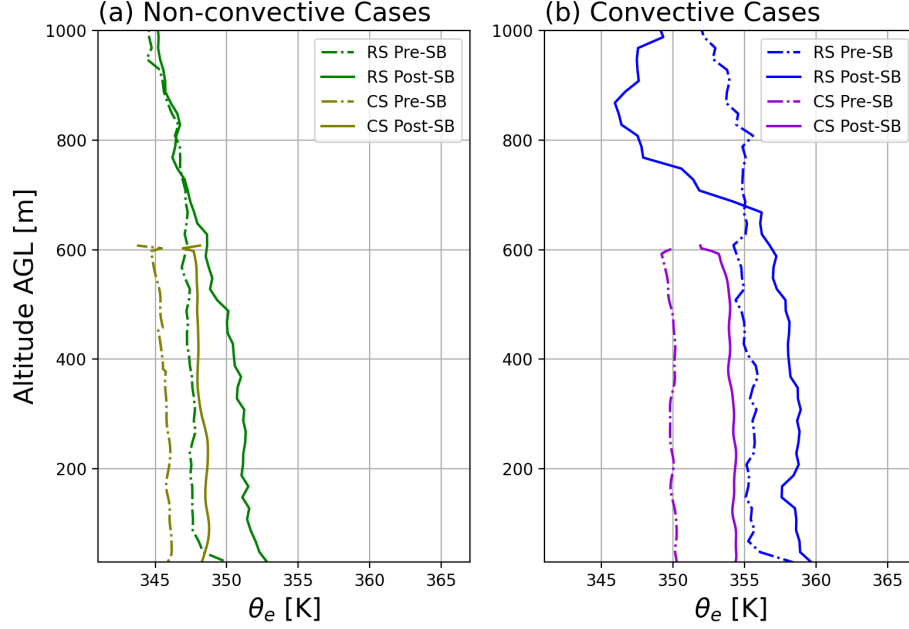


Figure 3.8: Composite average of  $\theta_e$  from radiosondes (RS) and CopterSonde (CS) observations before and after the SB (a) for cases without CI and (b) cases with CI. Pre-SB radiosondes are valid for 1800 UTC and post-SB radiosondes are valid for 0000 UTC. Pre-SB and post-SB CopterSonde observations are averaged profiles of 1 h before and after an SB, respectively

by the radiosondes than the CopterSonde (Fig. 3.8). In all cases,  $\theta_e$  is fairly uniform up to 600 m and in all pre-SB profiles, this well-mixed layer extends to at least 1 km (Fig. 3.8). Following the SB passage,  $\theta_e$  increases below 650 m for both radiosonde and CopterSonde observations. In terms of the magnitude of  $\theta_e$  increase from before and after the SB, the radiosonde data shows the non-convective cases having a larger increase than the convective cases whereas the CopterSonde observations show the opposite. However, in non-convective cases above that height, the profile returns to the pre-SB  $\theta_e$  but in convective cases there is a sharp decline in  $\theta_e$  leading to a strong  $d\theta_e/dz$  gradient. It is important to consider the post-SB radiosonde could be released anywhere from 1-5 h after the SB passage and the CopterSonde post-SB profile is created compositing profiles up to 1 h after the SB. The capability of the CopterSonde to

observe rapid changes in the environment allows a more precise analysis surrounding the SB impacts.

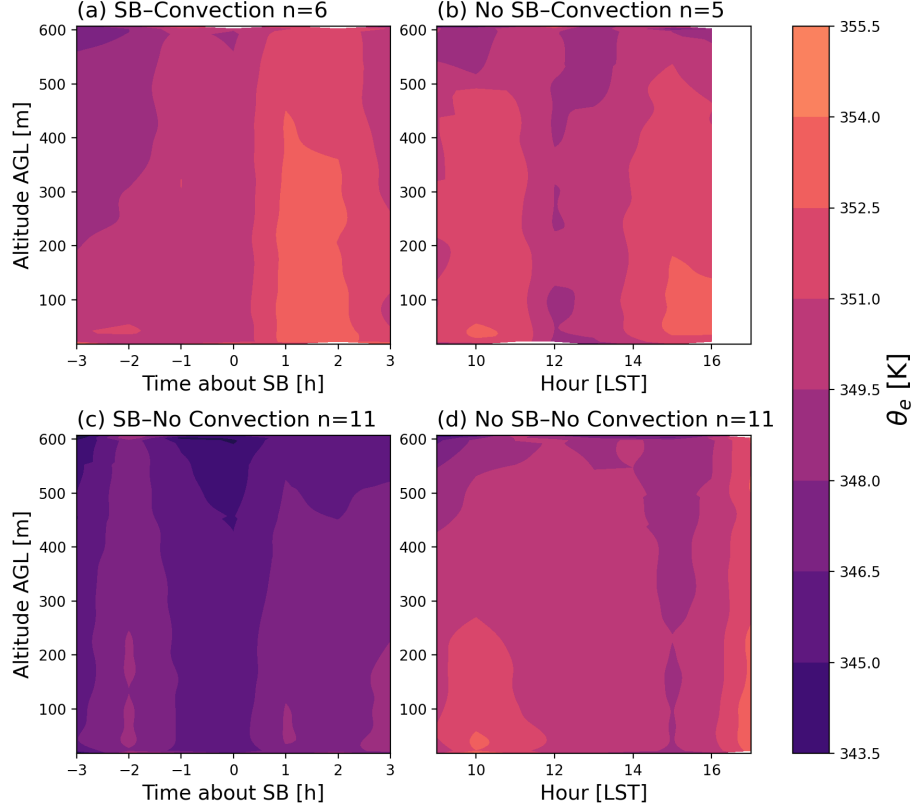


Figure 3.9: Composite average of CopterSonde observed  $\theta_e$  across altitude and hour, for (a, c) hour about the SB passage and (b, d) hour of the day (LST, UTC-5)

UAS observations allow a more temporally resolved depiction of  $\theta_e$ 's evolution compared to radiosondes. While there is synoptic variability in  $\theta_e$  based on air mass source region, compositing across the campaign can show if consistent patterns in daily evolution exist. The time-height  $\theta_e$  evolution is subsetting into categories with or without an SB and with or without CI (Fig. 3.9). Days without an SB are composited by hour in the day which shows the typical diurnal cycle (Fig. 3.9d) and how the presence of convection alters the evolution (Fig. 3.9b). Since the SB arrives at various times throughout the day, compositing the evolution by hour surrounding SB passage time

provides a clearer picture of how  $\theta_e$  is directly influenced by the SB (Fig. 3.9a, c). The subset of cases represents the entire campaign, with at least one SB-Convection case in each month, but half occur in July. All non-SB convective events occur in August or September due to stronger synoptic forcing. The SB-No convection and No SB-No Convection are well spread across all months, see Appendix A.

In the morning hours (9-10 LST, 14-15 UTC), there is a slight negative vertical gradient of  $\theta_e$  while the nocturnal stable ABL is still observed, but  $\theta_e$  quickly becomes well-mixed throughout the afternoon (Fig. 3.9b, d). Without an SB or CI (Fig. 3.9d), the mean progression of  $\theta_e$  is consistent throughout the day and there is a slight decline throughout the day with minimum values around 1500 LST (2000 UTC). With synoptically forced CI (not SB-driven), the minimum occurs earlier and is more pronounced (Fig. 3.9b). With an observed SB, the evolution is marked by the arrival of the SB with a sharp increase in  $\theta_e$  (Fig. 3.9a, c). On days with successful CI,  $\theta_e$  is larger throughout all hours and the post-SB increase is consistent for 2 h unlike the gradual decline on days without CI (Fig. 3.9a, c). Prior to the SB, there is more variability in  $\theta_e$  on days without convection which is likely due to the few BB cases which also increases  $\theta_e$  via moisture advection (Fig. 3.3).

From the profile-averaged evolution of these subsets, it is clear that without an SB the  $\theta_e$  evolution is fairly consistent, regardless of convection (Fig. 3.10a). It is interesting to note the similarities in non-SB days with and without convection, and this is likely due to strong synoptic forcing hindering the establishment of the SB circulation. Most often this was in the form of onshore flow continuously advecting marine air inland, leading to elevated  $\theta_e$  with and without convection (Fig. 3.10a).

However, there is a clear difference in environmental changes on SB days that lends insight into convective potential (Fig. 3.10b). On days with successful CI, the

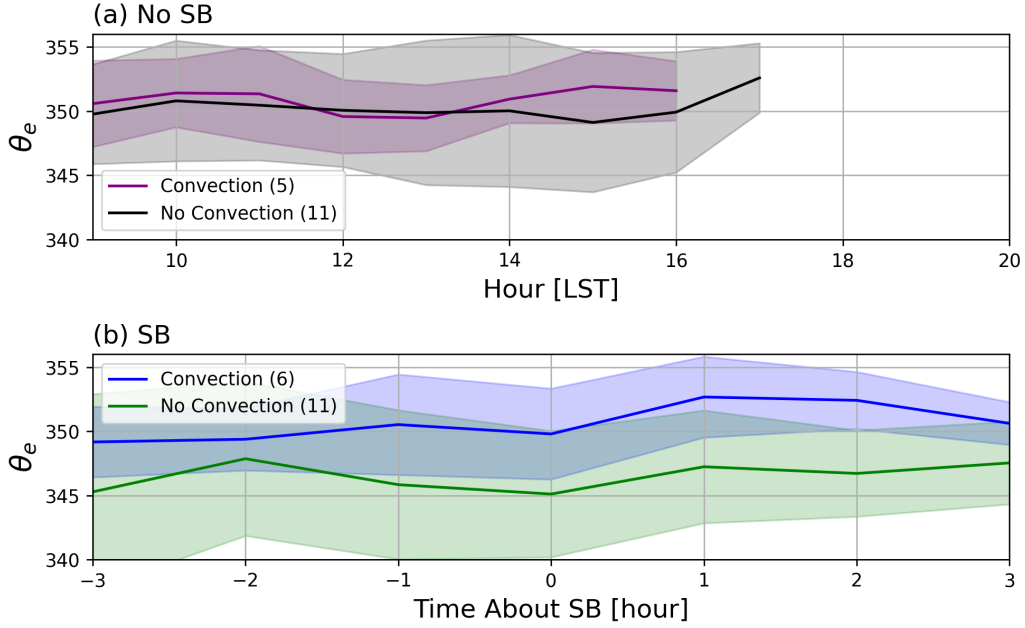


Figure 3.10: (a)  $\theta_e$  composited over the hour of the day (LST, UTC-5) for non-SB events with convection (purple) and without convection (black). (b) same as above for SB events with convection (blue) and without convection (green) centered about the SBF passage time (hours). Shading about each line represents the 1- $\sigma$  deviation from the mean

initial environment has slightly higher  $\theta_e$  but is comparable 2 h before the SB to days without CI. The two modes begin to diverge 1 h before SBF passage, as  $\theta_e$  declines until SB passage on days without convection but remains steady on convective days. Furthermore, the  $\theta_e$  increase is steeper on days with convection, and  $\theta_e$  is on average 3 K higher after the SB. The peak in  $\theta_e$  on days with convection is 1 h post-SB and then a gradual decline, although values stay above that of pre-SB for about 3 h. Without convection,  $\theta_e$  increases 2 K after the SBF and remains approximately that value for 3 h. Although, the post-SB  $\theta_e$  values without convection never reach the pre-SB mid-morning maximum. On days with successful CI, the SB moves into an ABL that is more convectively primed with steady, elevated  $\theta_e$ . Even with height-limited observations, the temporal resolution and ability to capture sharp changes in



thermodynamic variables makes the UAS observations valuable to understanding the pre-convective environment.

### 3.6 Observations of a late-onset sea breeze

On 22 September 2022, an abnormally late SB passed over UHCC at 1907 LST (0007 UTC) and was observed by colocated CopterSonde UAS and CLAMPS2 at a high resolution. A significant challenge exists when gathering observations during the SB due to its rapid evolution, varying depth, and multiple spatial scales of influence. The SBF passes UHCC 10 min before apparent sunset (0016 UTC), approximately five hours later than the average SB passage observed by the TRACER-CUBIC dataset at UHCC (Spencer et al., 2024, in prep.). As a result, the ABL has already begun the evening transition and convective turbulence has substantially decayed. Despite the late timing of the SB, the immediate temperature drop and rise in the water vapor mixing ratio is an order of magnitude stronger than the average rates of change for SBs observed during TRACER-UAS (Fig. 3.5, Table 3.1). Since this SB was anomalous in timing and magnitude, the evaluation will focus on the impact the evening transition has on the SB evolution from a thermodynamic and kinematic perspective.

Throughout the day (1600-2000 UTC), CopterSonde profiles observe light, 2–5 m  $s^{-1}$ , northerly to northeasterly (offshore and coast-parallel) winds (Fig. 3.12). The prevailing flow likely inhibits the SBF from propagating inland until the offshore winds weaken (Gilliam et al. 2004). Steele et al. (2015) showed that backdoor SBs, those with offshore and shore-parallel prevailing flow, are later and weaker in velocity than SBs with onshore prevailing flow. The observed SB in this case has similar characteristics to a backdoor SB. The ABL goes through the typical diurnal evolution (i.e., morning

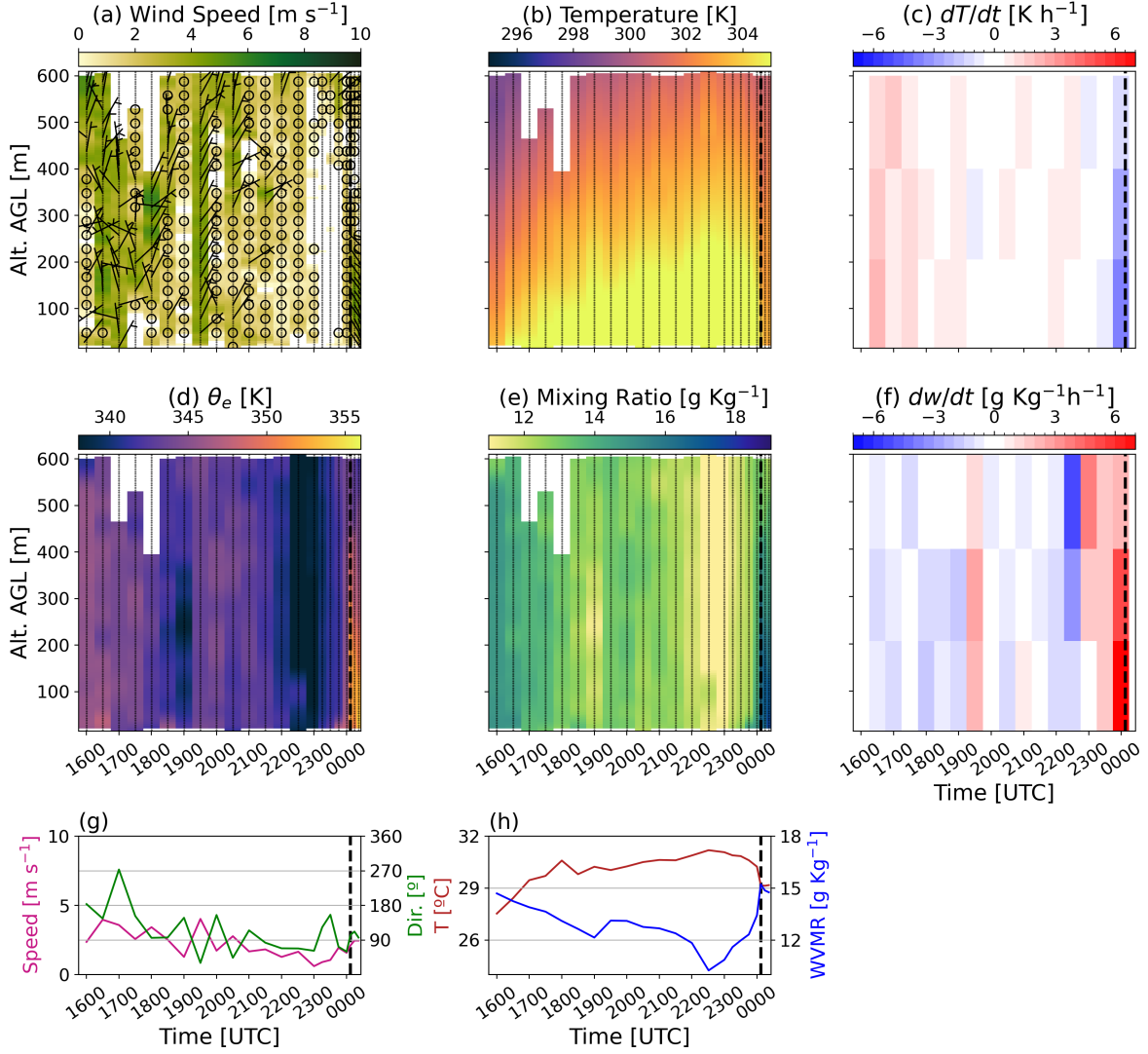


Figure 3.11: Same as Fig. 3.1 but at UHCC on 22 September 2022

transition growth, turbulent vertical motions, etc.) uninterrupted until the evening when the SB propagates inland. From 2100-2300 UTC, the wind speeds decrease to near zero, and drying increases with time (Fig. 3.12). The ABL prior to the SB passage (2330-0000 UTC) has dry adiabatic temperature profiles and a nearly uniform water vapor mixing ratio above 50 m (Fig. 3.13). The surface layer below 50 m shows signs of the evening transition through the development of a shallow temperature inversion.

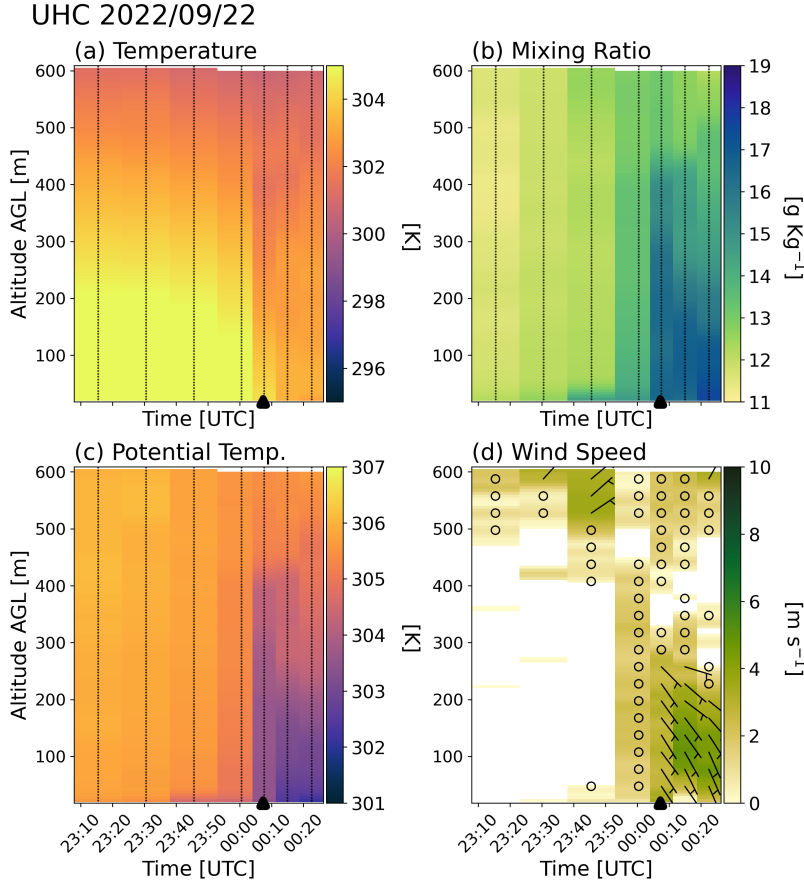


Figure 3.12: Interpolated time-height cross sections from CopterSonde observations of (a) temperature (K), (b) water vapor mixing ratio ( $\text{g kg}^{-1}$ ), (c) potential temperature (K), (d) wind speed and wind barbs ( $\text{m s}^{-1}$ ) on 22 September 2022. The black triangle indicates SBF passage time.

The first indicator of the SBF passage detected by the CopterSonde occurs at 0007 UTC with accelerating south-southeasterly flow, decreasing temperature, and increasing water vapor (Fig. 3.12). Although the onshore flow is contained below 300 m, the thermodynamic impacts are much deeper, extending up to 450 m — advected by the prominent updraft along the SBF (Fig. 3.14b). The updraft extends to 550 m, reaching a maximum updraft speed of  $2 \text{ m s}^{-1}$ , but lasts for less than 5 min (over the profiling site). From 0000 to 0007 UTC temperature decreases by  $1\text{--}1.5 \text{ }^{\circ}\text{C}$  but remains the same above 500 m. Similarly, the water vapor mixing ratio increases by  $2\text{--}3 \text{ g kg}^{-1}$

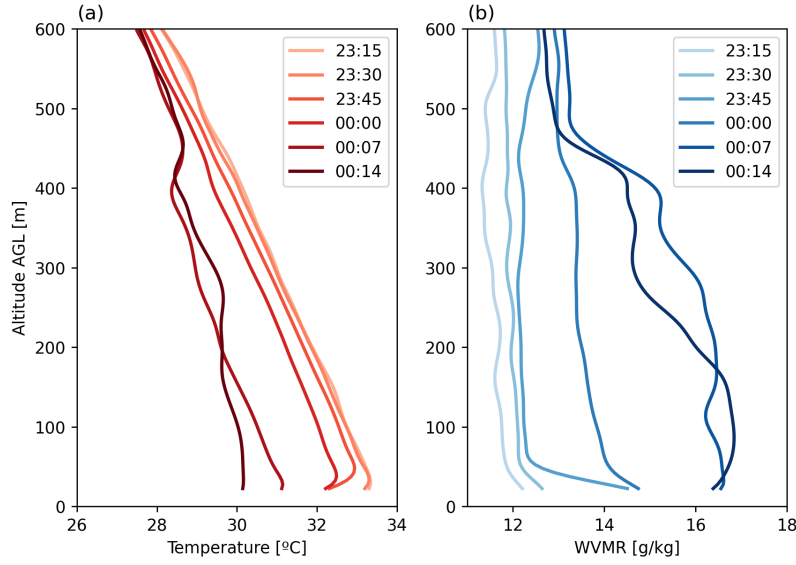


Figure 3.13: CopterSonde profiles of (a) temperature ( $^{\circ}\text{C}$ ) and (b) water vapor mixing ratio (WVMR,  $\text{g kg}^{-1}$ ) from 2315–0014 UTC. Color shade darkens with time

below 500 m. While the SB inflow layer increases moisture in a homogeneous layer through 300 m, the updraft transports moisture up to 450 m and then quickly decreases to pre-SB values above 450 m (Figs. 3.13 and 3.14b).

The elevated moisture above the inflow layer does not last long, due to apparent mixing reflected in Doppler lidar observations shortly after sunset (Fig. 3.14). These observations depict a vertical velocity couplet oscillating direction with time, associated with a Kelvin-Helmholtz (KH) wave. This KH wave is positioned above the SB inflow layer from 250–550 m. From 0007 to 0014 UTC moisture in the 200–400 m layer decreases as drier air aloft is mixed down by the KH wave. Additionally, marginally warmer air is mixed downward in this layer, reducing the lapse rate (Fig. 3.13). The winds in the KH wave layer decrease, and the VAD RMS increases due to heterogeneity. Similarly, the CopterSonde wind speeds drop below  $2 \text{ m s}^{-1}$  in the KH wave, and the winds above are northeasterly. The KH wave is only observed for 5–7 min and quickly propagates beyond the profiling site, where it may persist or dissipate beyond our

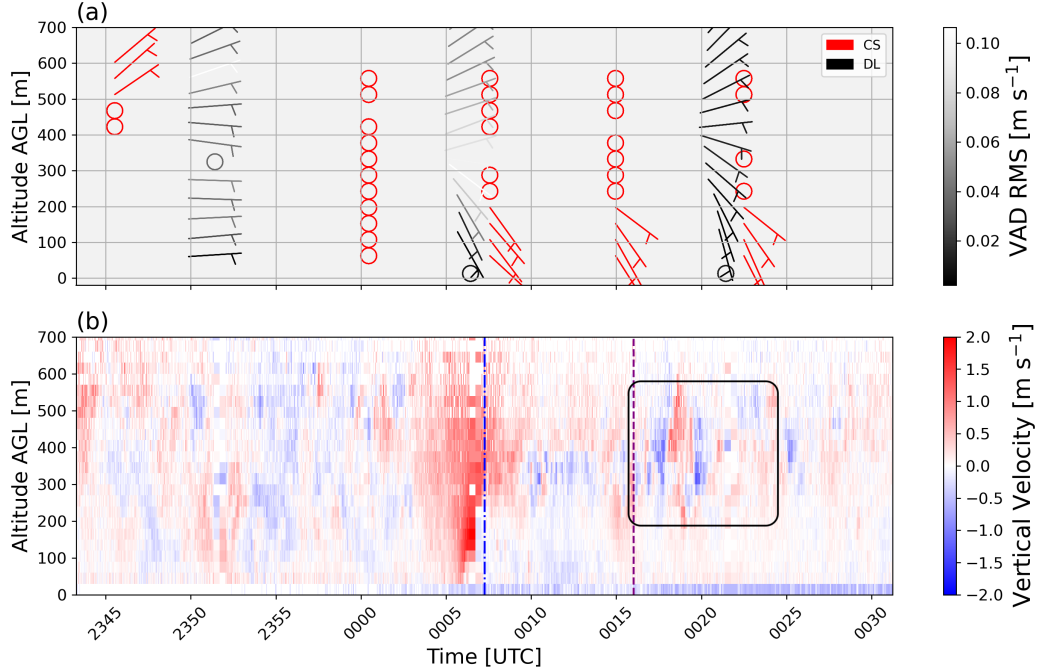


Figure 3.14: (a) Doppler lidar VAD (gray) and CopterSonde (red) observations of horizontal winds. The gray scale corresponds to the VAD RMS ( $\text{m s}^{-1}$ ). (b) Doppler lidar vertical velocity ( $\text{m s}^{-1}$ ). The blue dot-dashed line indicates the time of SB passage and the purple dashed line shows sunset time. Black box indicates the KH wave.

observational reach. The KH wave provides a good example of how the colocation of the Doppler lidar and CopterSonde provide parcel-scale insights on ABL processes with more detail than would be resolvable from either platform alone.

The evolution of the BB and SB can have a broader range of thermodynamic impacts than the typical notion of a cooler, moister, and more stable marine airmass advected onshore. The TRACER datasets sampled a broad range of SB impacts and allowed significance testing to determine the factors influencing SB intensity. The Galveston BB and time of SB passage have the largest effect on the SB-induced thermodynamic response in the ABL. A benefit of observations from the CopterSonde is that the sensors are the same across profiles, such that observations are repeated, and any sensor bias is consistent. The rate of change calculation allowed for documentation

of instantaneous changes to the ABL regardless of the sampling frequency. It also does not require finding a base state or pre-SB average, which is difficult in an environment that changes so rapidly. Mostly, rate of change provides a quantity to conduct statistical analysis on processes that are strongly influenced by outside factors. Additionally, a dataset to compute these values above the surface layer with a sub-hourly temporal resolution is novel for coastal ABL research.

As for low-level stability, the SB did not induce a significant change in thermal lapse rate, but still had a large effect on destabilization. Low-level moisture and temperature evolve on different timescales, so  $\theta_e$  is used to evaluate the influence on the moist static instability. Most SBs increase  $\theta_e$  and ones that increase  $\theta_e$  before the SBF are most likely to trigger CI. In terms of kinematic changes, ongoing work using the RAAVEN UAS observations collected during TRACER demonstrates that the buoyant production of TKE often increases following the passage of an SBF. This increase is thought to result from an increase in the temperature gradient between the surface and overlying atmosphere, driven simultaneously by the SB-driven advection of cooler air over the land surface and the reduction of cloud cover associated with the SBF passage, which accelerates solar warming of the underlying surface. Such intricacies can help to explain the drivers between different evolution pathways described in the current work, though a deep dive into these mechanisms is beyond the scope.

## Chapter 4

### Verification of coastal breeze simulations

As seen in Chapter 3, coastal breezes can induce a rapid changes in the ABL, and sometimes they cause abnormalities like warming and drying periods. This motivated evaluating how well the transition from BB to SB could be simulated by an NWP model. These breezes have a large influence on weather forecasts, and it is critical to understand the biases that can be expected. Model parameterizations can have a large impact on the characteristics of the PBL, so the following analysis focuses on the influence parameterizations have on simulating the initial convective boundary layer (CBL), the BB, and the SB. CopterSonde observations are the primary verification dataset to assess the 16 June 2022 case study for temperature, moisture, and horizontal wind speed biases, as well as the thermodynamic rate of change induced by the breezes. A discussion of the BB drivers follows to understand the influence of parameterization on the BB propagation inland.

#### 4.1 Methods

While the WoFS model (see Chapter 2) is primarily used for its probabilistic forecasts of severe weather, it also offers a way to evaluate model parameterizations with considerable realism, given extensive assimilated datasets. The model is not designed specifically for PBL studies, but provides a benchmark to evaluate commonly used

parameterizations for NWP to offer insight into best-performing combinations and potential improvements. To isolate the impacts of the PBL and SW parameterizations, only the first six EMs are evaluated. The other members were examined and show similar patterns to the first six, and are excluded from analysis for space consideration. Table 4.1 describes the parameterization combination for EMs 1–6.

#### 4.1.1 Case description

The 16 June 2022 event was chosen to investigate the interactions between the convective PBL and transition through BB and SB without the influence of precipitating convection (Fig. 4.1). Targeting a day with an observed BB is partially motivated by Caicedo et al. (2019) remarking on the importance of simulating the Galveston Bay breeze to local ozone forecasts, which is a major focus of overall the TRACER campaign. To isolate the interactions between coastal breezes and the PBL, a case with minimal compounding forces was preferred. During June 2022, coastal Texas was unseasonably hot and dry due to a strong mid-level high-pressure system positioned over the Southeast US. At this time, the SB was common but rarely triggered CI due to lacking moisture beyond the PBL. Any successful convection was localized and short-lived across the Houston-Galveston region. As a result, the BB and SB were uninterrupted by outflow boundaries providing a clear look at the inland progression. The observed BB traversed UHCC at 1730 UTC followed by clockwise rotation of the flow and acceleration of southeasterly winds at 2030 UTC, marking the SB passage (Fig. 4.1). Following the BB, moisture increased throughout the profile, and a brief reduction of potential temperature. After the SB, cooling was more pronounced while moisture advection was minimal.



Table 4.1: Parameterization combination for EMs 1–6

|             | <b>Dudhia SW Radiation</b> | <b>RRTMG SW Radiation</b> |
|-------------|----------------------------|---------------------------|
| <b>YSU</b>  | EM 01                      | EM 02                     |
| <b>MYNN</b> | EM 03                      | EM 04                     |
| <b>MYJ</b>  | EM 05                      | EM 06                     |

### 4.1.2 Verification data

Observations used to evaluate the model performance come from the CopterSonde, CLAMPS2, and SPARC. On 16 June 2022, the CopterSonde completed 18 vertical profiles at UHCC. The UAS flew to 609 m at a cadence of 30 min, except from 1745–1830 UTC when the cadence was increased to 15 min. CLAMPS2 was located at UHCC, colocated with the CopterSonde, and was used to determine the PBL depth using TROPoe retrieval data. SPARC was located south of Pearland, TX where the effects of the SB were observed, but the BB was not detected. Unfortunately, excessive heat disabled the SPARC lidar during the afternoon (1815–2200 UTC).

The CopterSonde observations are the main verification dataset due to their high vertical and temporal resolution throughout the BB and SB. Observations from SPARC in Pearland, TX are used to evaluate the SB only, because the BB does not travel that far west. SPARC observations also provide insight into how the simulated SB evolves as it penetrates inland.

### 4.1.3 Sea breeze and bay breeze identification

At each location, the BB and SB were identified to determine the accuracy of timing and intensity. UHCC is located 13 km west of Galveston Bay, which provides a distinct wind-direction shift from the BB versus the SB. Here we define the BB as sustained winds greater than  $2.5 \text{ m s}^{-1}$  coming from  $60\text{--}130^\circ$  for at least 60 min. The SB is

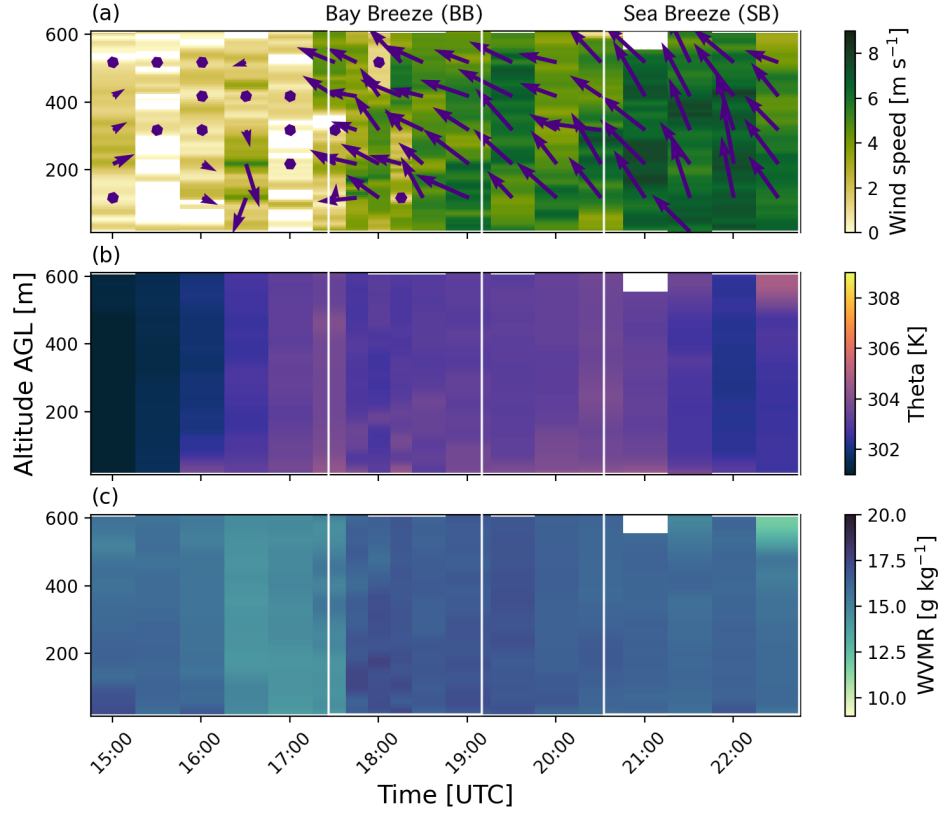


Figure 4.1: (a) Wind speed ( $\text{m s}^{-1}$ ) with direction arrows plotted, (b) potential temperature (K), and (c) water vapor mixing ratio (WVMR,  $\text{g kg}^{-1}$ ) observations from the CopterSonde at UHCC on 16 June 2022

defined as winds greater than  $3 \text{ m s}^{-1}$  coming from  $125\text{--}190^\circ$  for at least 2 h. The overlap in wind direction allows the BB to slowly transition to the SB and still meet the 2 h sustained wind direction criteria. These guidelines were motivated by the observational dataset gathered at UHCC from Chapter 3. The passage time is then marked as the first window that meets the minimum time criteria.

#### 4.1.4 Statistics

Mean bias was chosen to evaluate the model performance against observations, because standardizing the mean bias by the variable average (relative bias) overinflated values

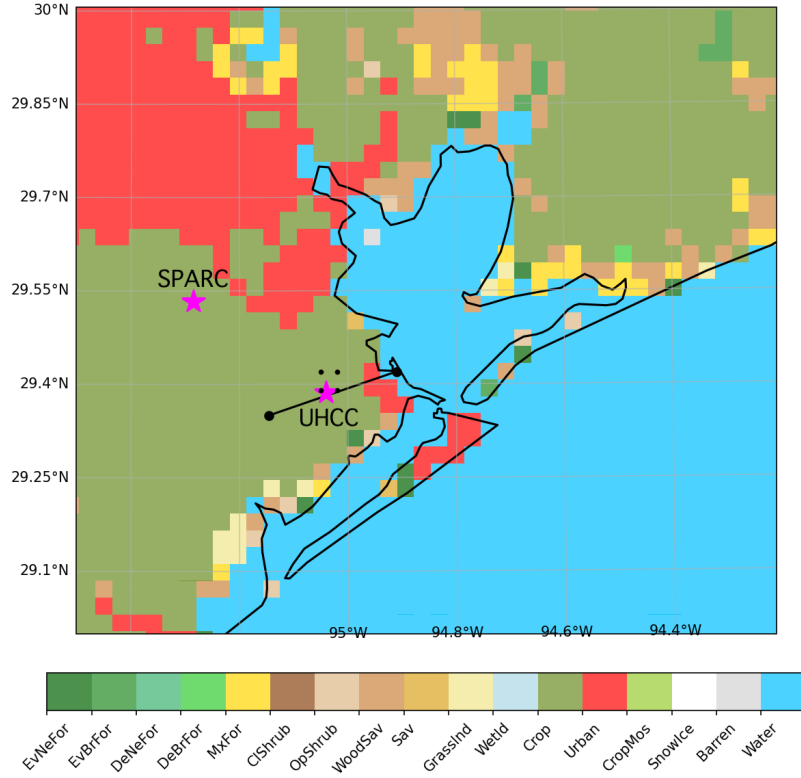


Figure 4.2: Land use map with observation locations marked by pink stars. The black dots around UHCC indicate the 4-points averaged for bias statistics. The black line intersecting UHCC marks the cross-section line used in Fig. 4.14

when mean wind speeds were near zero. First, the model was linearly interpolated to mimic the CopterSonde’s resolution of 5 m and paired to the nearest flight time. The model’s native vertical resolution below 600 m is around 50 m, so the interpolation adds approximately 10 times as many points for evaluation. A 4-point nearest neighbor average was performed around each verification site, seen in Fig. 4.2, and mean bias compared to the CopterSonde was calculated. The bias data was subdivided into height layers and time spans. The height layer 20–200 m was chosen to represent the surface layer, while 200–400 m and 400–600 m represent the mixed layer and, potentially, the top of the SB inflow layer. Since, WoFS’s vertical spacing is bigger than the CopterSonde’s, averaging the values over a deeper layer helps to mitigate the

interpolation artifacts. To understand how each breeze impacts the model performance, the forecast was divided into three categories: CBL/BB (17–19 UTC), transition (19–21 UTC), and SB (21–23 UTC). These time periods were selected to encompass the BB and SB timing for the first six EMs. The meteorological tower at UHCC was used for 10-m state variable observations.

## 4.2 Verification of PBL characteristics

Figure 4.3 show the first 6 EMs’ full forecast evolution of the lowest 1 km with Copter-Sonde observations for comparison. There is considerable spread in the flow evolution throughout the BB onset and transition to the SB. EMs 03, 05, and 06 fail to simulate a BB before the SB (Fig. 4.3g, m, p); it appears EM06 tries to initiate the easterly push but the flow is not sustained. In turn, the lack of a BB leads to missing moisture advection during the early afternoon amidst the diurnal mixing out of morning, low-level moisture. Most members are drier than the observations, except for the MYNN members (EM05-06), whose early overestimation of moisture disguises the lack of moisture advection throughout the afternoon (Fig. 4.3o, r). The EMs are typically warmer but with much more diurnal variation than seen in the observations (Fig. 4.3t). The nonlocal mixing members (EM01-02) initialize the temperature most accurately, but warm much more than observations (Fig. 4.3b, e, t); conversely, the local members (EM03-06) initialize too cool and take much longer to warm than observations (Fig. 4.3h, k, n, q). EM03-05 have the most distinct cool and moist SB inflow layers after 2100 UTC to varying depths (Figs. 4.3g-o). Some of these differences within the BB and SB can be likened to the speed of onshore flow. The MYJ members show the fastest onshore flow with the most defined thermodynamic gradient between the SB-inflow layer and residual flow aloft (Fig. 4.3m-r). Among the local members (EM03-06), the Dudhia

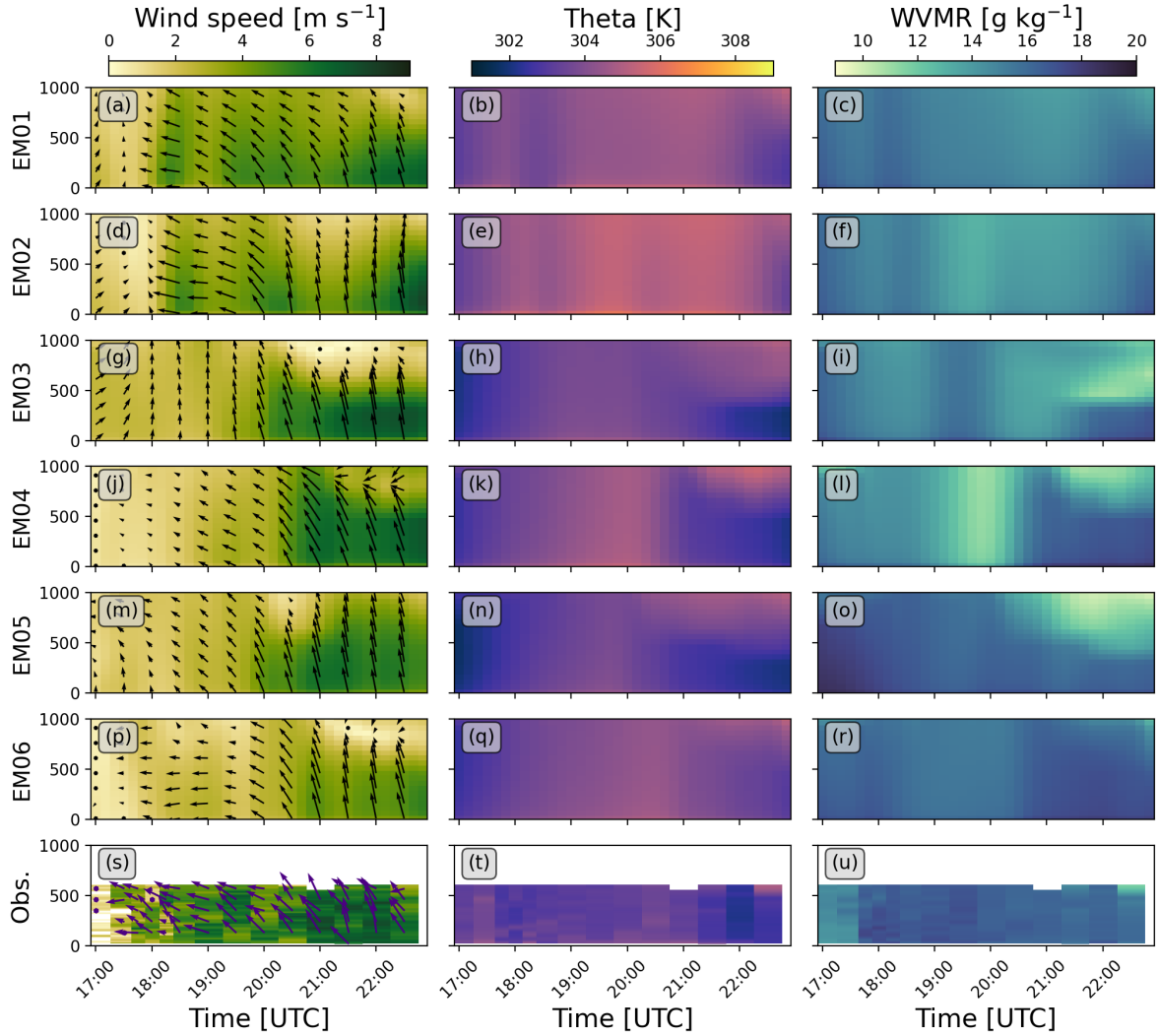


Figure 4.3: Time-height field of wind speed (first column) with wind vectors, potential temperature (second column), and water vapor mixing ratio (third column) at UHCC on 16 June 2022. The first six rows use data from EMs and the last row (s-u) uses CopterSonde observations.

members have the most distinct thermal internal boundary layers, marked by sharp shifts in temperature and moisture below 600 m (Fig. 4.3h, i, n, o). However, this does not align with the depth of onshore flow, which extends around 200 m higher in EM03 and EM05 (Fig. 4.3g, m).

Observations from SPARC can be used to compare the spatial heterogeneity of the simulated SB progression. SPARC was positioned in Pearland, Texas further inland

and away from Galveston Bay such that the region only experienced the SB passage. Unfortunately, a loss in Doppler lidar data collection from 1815–2200 UTC prevents looking at the onset of onshore flow. To identify the SB passage the thermodynamic retrievals are analyzed: retrieved potential temperature declines at 2130 UTC, but moisture increases around 2030 UTC. The lowest-level radar reflectivity was included to refine the time of SB passage, and the SB radar signature passes SPARC at 2100 UTC (not shown). The sudden surge in moisture and gradual response in moisture are similar to patterns seen in CopterSonde observations (Chapter 3).

However, the simulated SB onset is quite different compared to the evolution at UHCC (Figs. 4.3, 4.4). While all members show some onshore flow after 1900 UTC, there is a wide variation in evolution and speed. Although EM01 and EM02 have a stronger easterly component to the initial flow (1900–2100 UTC), neither meets the BB criteria. There is not a substantial thermodynamic response until after 2100 UTC when some members (EM 03-05) present onshore flow acceleration (Fig. 4.4g-o); meanwhile, the other members (EM-01, 02, 06) have very little change in moisture or temperature throughout the forecast period (Fig. 4.4a-f, p-r). However, the vertical extent of any thermodynamic change is deeper than the observations, with observed changes in potential temperature and moisture only extending to 750 m with a clear distinction (Fig. 4.4t, u). The potential temperature evolution across local and nonlocal PBL members is similar to UHCC’s evolution, but the simulated temperatures tend to be lesser than observations (Figs. 4.3, 4.4). The MYJ members capture the moisture advection by the SB most accurately of all EMs but still underestimate the post-SB magnitude of low-level water vapor (Fig. 4.4p-r). Even in the MYJ members, the SB is simulated much deeper and lacks a clear boundary between the residual CBL airmass aloft, as seen at UHCC in EM03-05 (Fig. 4.4g-o).

It is known that the depth of the SB increases as it moves inland (Garratt and Physick 1985; Melas and Kambezidis 1992), but in this case, it may be rising too quickly, leading to diluted SB thermodynamic effects. The SB flow at SPARC is much more diffuse than at UHCC, which leads to more variable kinematic evolution across EMs at SPARC. The MYJ EMs perform the best because the vertical mixing rate is the slowest and allows the SB to retain its characteristics further inland. While these are just two points, they show the difficulty in generalizing the biases across EMs with respect to time and variables of interest.

#### 4.2.1 Simulation biases

In previous works, model biases have been calculated from surface observations and radiosonde observations, which can offer seasonal or regional differences. However, these datasets lack the resolution to understand the PBL-scale impact from mesoscale processes. It is important to measure how representative surface errors are to those within the mixed layer. The following analysis compares the EM mean biases across three height layers and three time spans to identify trends across members and forecast lead times. The lowest layer 20–200 m includes the surface layer and the transition to the mixed layer. The 200–400 m and 400–600 m layers are typically in the mixed layer, but in some EMs the top of the SB inflow layer dips below 600 m (Fig. 4.3i, l, o). Additionally, surface meteorological tower observations are included to see how the traditional verification method compares to biases above the surface. To keep the verification consistent with in-situ measurements, the CopterSonde observations are used above the surface. The time bins were selected to capture the CBL or BB passage

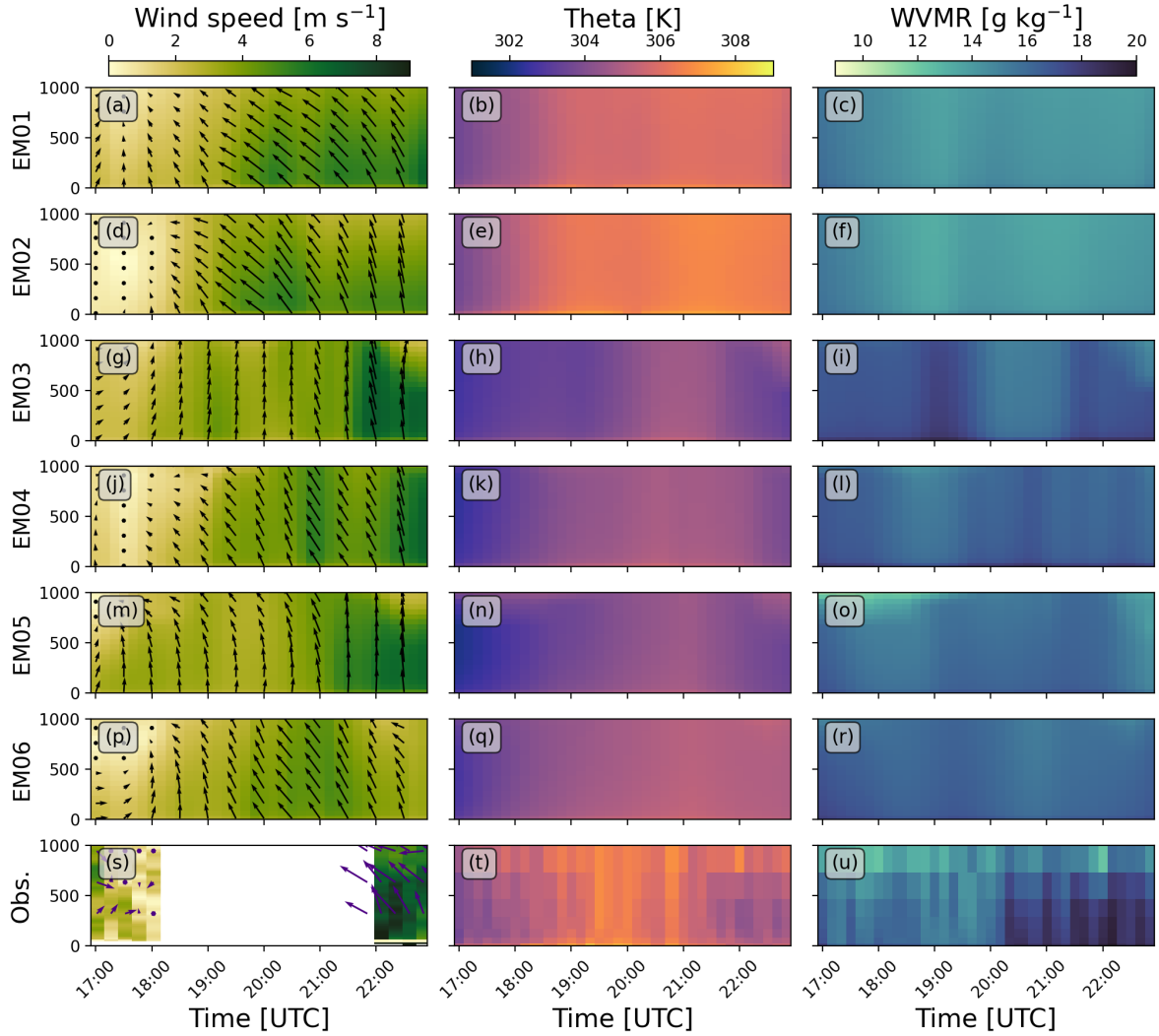


Figure 4.4: Similar to Fig. 4.3 but model data is from the grid nearest SPARC and observations are TROPoe retrievals from SPARC.

time (17–19 UTC), the BB to SB transition (19–21 UTC), and the pure SB regime (21–23 UTC).

Since EMs 03, 05, and 06 failed to produce a BB, these EMs have the largest zonal wind bias above the surface (Fig. 4.3g, m, p, Fig. 4.5). The zonal bias magnitude tends to increase with height and throughout the afternoon. The errors in the surface and mixed layer are often much more significant than what is observed near the surface, but the standard deviation at the surface is larger than above it (Fig. 4.5). With



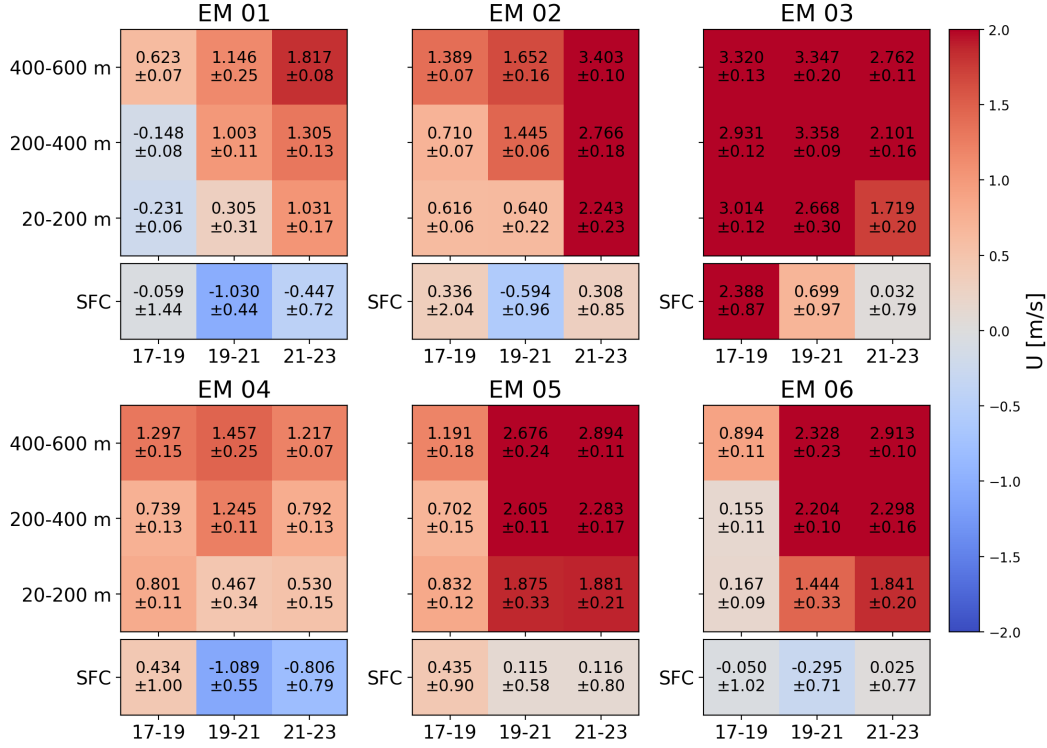


Figure 4.5: Mean bias (model-observation) heat maps for each EM for the u-component of the wind. Observations are from the CopterSonde at UHCC and the model data is a 4-point nearest neighbor to UHCC average. The mean and standard deviation are in each text box. The time spans (columns) are in UTC and height layers (rows) are in meters. SFC indicates data at 10 m.

parameterizations commonly refined using surface observations, adjustments based on surface errors could cause adverse effects in the mixed layer. If only the surface observations were used, it would appear that the model simulates the zonal wind much better than when the whole PBL was considered. Meridional wind biases are generally lesser in magnitude and peak in the BB-SB transition period (19–21 UTC) caused by inaccuracies in SB onset time (Fig. 4.6). There is also much less consistency in bias trends with height across members and time spans. Most EMs underestimate the SB wind speeds, especially the zonal component, leading to more southerly SBs than the observed south-southeasterly conditions (Fig. 4.3). This is interesting due to the

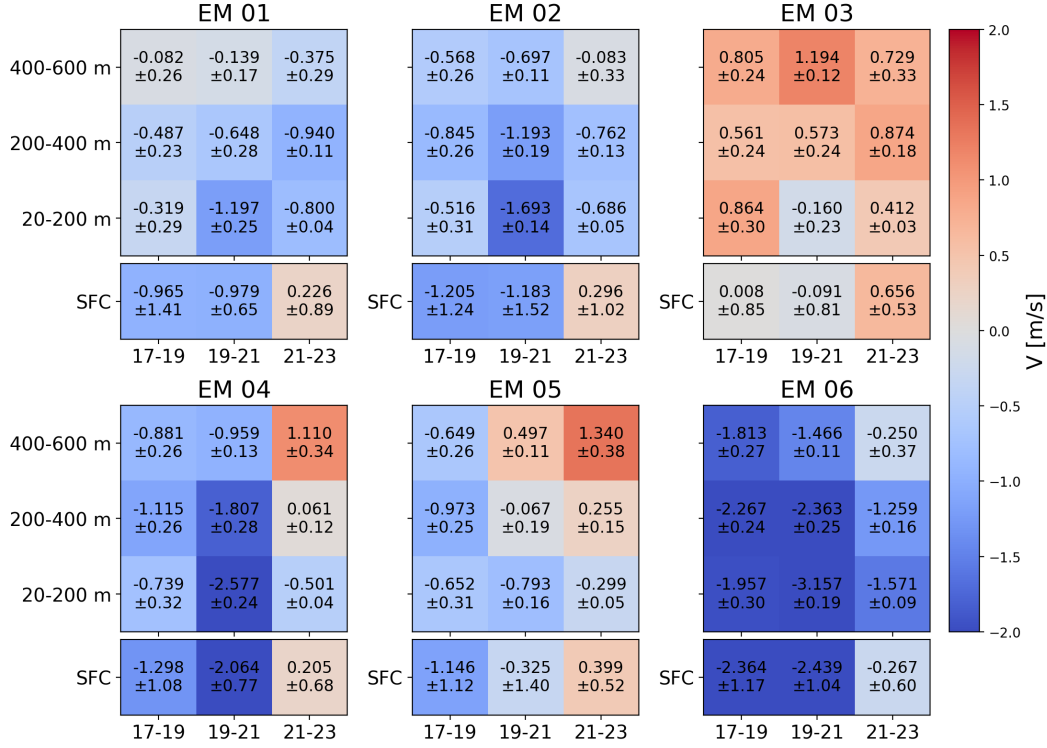


Figure 4.6: Similar to Fig. 4.5 but for the v-component of the wind

coastal geometry of the site, directly onshore flow falls near  $135^\circ$  and purely southerly flow has more land to traverse than if the flow were truly shore-perpendicular.

Similar to the meridional wind, the largest moisture biases exist in the SB transition time span from 1900–2100 UTC, as the moisture advection gradually strengthens (Fig. 4.7). Moisture biases are more uniform across the height layers for each period, but the difference in biases between the surface and mixed layer can be sizable, especially for MYNN members (EM05-06). Water vapor mixing ratio is most underestimated after the SB passage (Fig. 4.7). However, EM 04 and 06 overestimate the water vapor within the SB inflow regime (21–23 UTC) as they have the shallowest thermal internal boundary layer (Fig. 4.3 l, r). EM05 has the lowest magnitude of moisture bias, but that is due to the initial high moisture bias that equilibrates after the observed BB advects additional moisture, rather than an accurate representation

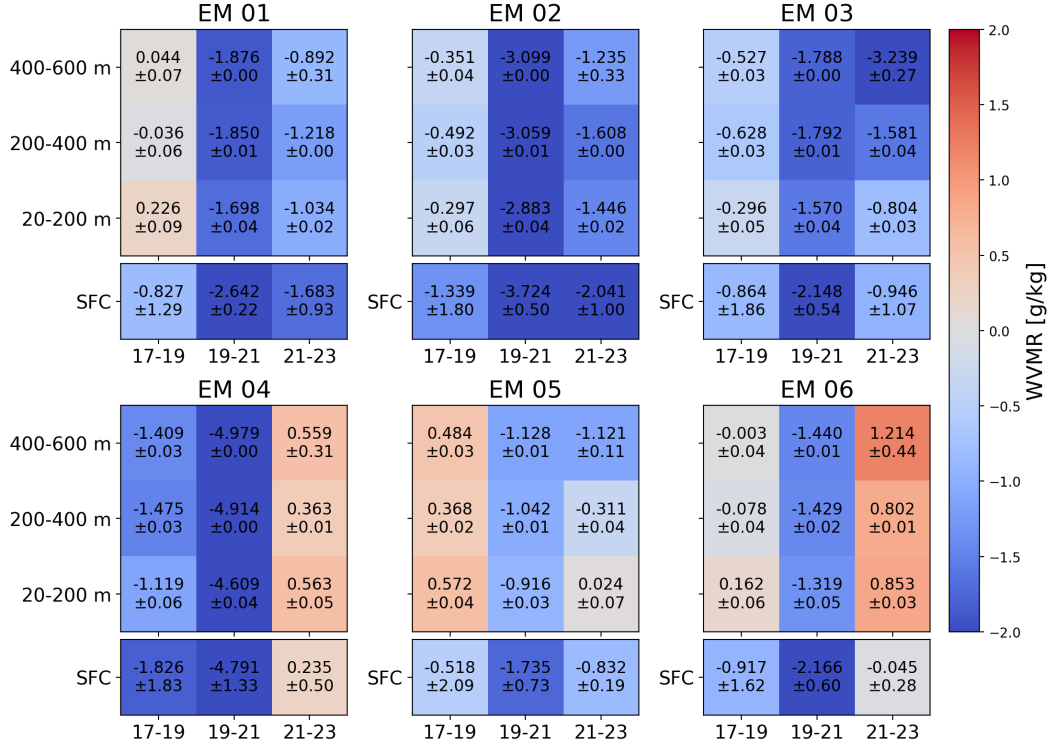


Figure 4.7: Similar to Fig. 4.5 but for water vapor mixing ratio

of the thermodynamic evolution (Fig. 4.7). The differences in temperature bias are clearly divided by type of PBL mixing, with the nonlocal mixing schemes increasing with error throughout the day as the PBL is overmixed (Fig. 4.8). Whereas the local schemes heat the PBL more slowly to begin with and then respond gradually to the changes induced by the SB, with low bias maxima in the 2100–2300 UTC timeframe. EM06 is a bit of an anomaly from this pattern because the SB is the weakest of all EMs in terms of wind speed, leading to underestimated cool-air advection (Figs. 4.3, 4.8).

How each scheme represents various processes in the PBL can lead to performance varying with the variable. For example, the YSU scheme EMs tend to perform better in the kinematic representation of the PBL and upon initialization for the thermodynamics, but quickly become too warm and overly mixed. The local mixing EMs have a lot of similarities in the temperature bias evolution but are sensitive to variations

in the SB representation. This may lead to a collapse in model spread among local members, leading to slower-developing PBLs with poorer flow representation.

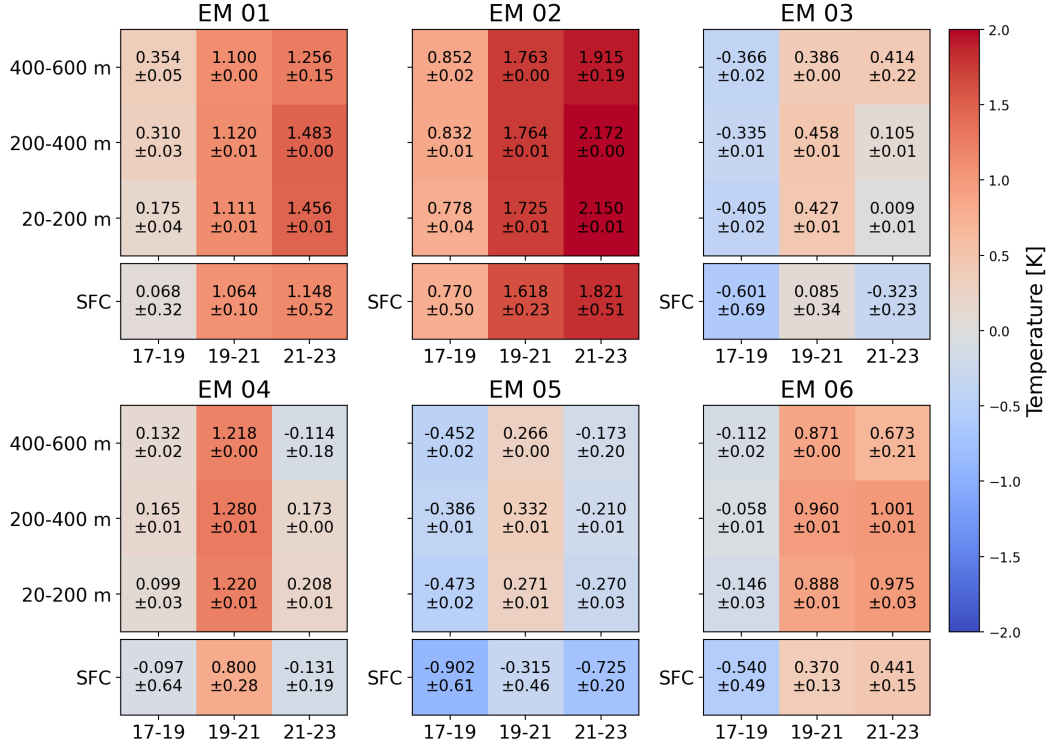


Figure 4.8: Similar to Fig. 4.5 but for temperature

## 4.2.2 Breeze characteristics

As stated previously, most NWP models will successfully signal the occurrence of the SB when synoptic conditions allow. However, the details of simulated SBs are often incorrectly represented, particularly with depth and time of arrival. The depth of the PBL is historically poorly simulated and dependent on PBL parameterization (Hu et al. 2010; LeMone et al. 2013). There is also broad variability in observed PBL depth (PBLD) based on the method, especially in the summer (Seidel et al. 2010; Sawyer and Li 2013). Furthermore, the depth of the SB inflow layer adds another important mixing

length that can be viewed from a thermodynamic and kinematic perspective. These make finding a meaningful PBLD complicated and alter the evolution throughout the afternoon and evening transition. The method to determine the PBLD is specific to the PBL parameterization, which can elicit large differences in their estimation. To standardize the PBLD detection method, the maximum potential temperature gradient method (Stull 2012) is also applied to all EMs and observations. The scheme-specific PBLD ( $h$ ) and potential temperature gradient PBLD ( $h_\theta$ ) are both shown in Fig. 4.9. It is also common to use  $h_\theta$  to determine the depth of thermal internal boundary layers, which provides an estimate of the SB depth (Garratt and Physick 1985). Each PBL scheme varies in how the  $h$  is determined: YSU selects the lowest height at which a critical Richardson number, which varies with stability, is reached; MYJ is based on where turbulence kinetic energy (TKE) is  $< 0.1 \text{ m}^2 \text{ s}^{-2}$ ; MYNN is similar to MYJ but requires a positive potential temperature ( $\theta$ ) gradient around that level.

Both  $h$  and  $h_\theta$  have similar spread across EMs through the forecast period (Fig. 4.9). The two detection methods vary most significantly for EMs 01, 02, and 05. For YSU EMs,  $h_\theta$  is more consistent throughout the afternoon and begins to decay far later than  $h$  or any other EM  $h_\theta$ . The agreement between  $h$  and  $h_\theta$  is very similar until the SB passage. Interestingly, most members estimate deeper PBLs using the potential temperature gradient method, except for the MYJ members. The YSU and MYNN schemes give weight to the potential temperature gradient when determining the  $h$ , but MYJ uses a TKE method which could be inflated by the shear driven at the top of the SB. For MYNN members,  $h$  is more steady and realistic than  $h_\theta$  since the mixing lengths account for stability changes, allowing adjustments shortly after initialization and after the SB passage. Overall,  $h_\theta$  performs worse after the SB due to a gradual transition in the thermodynamic profile.

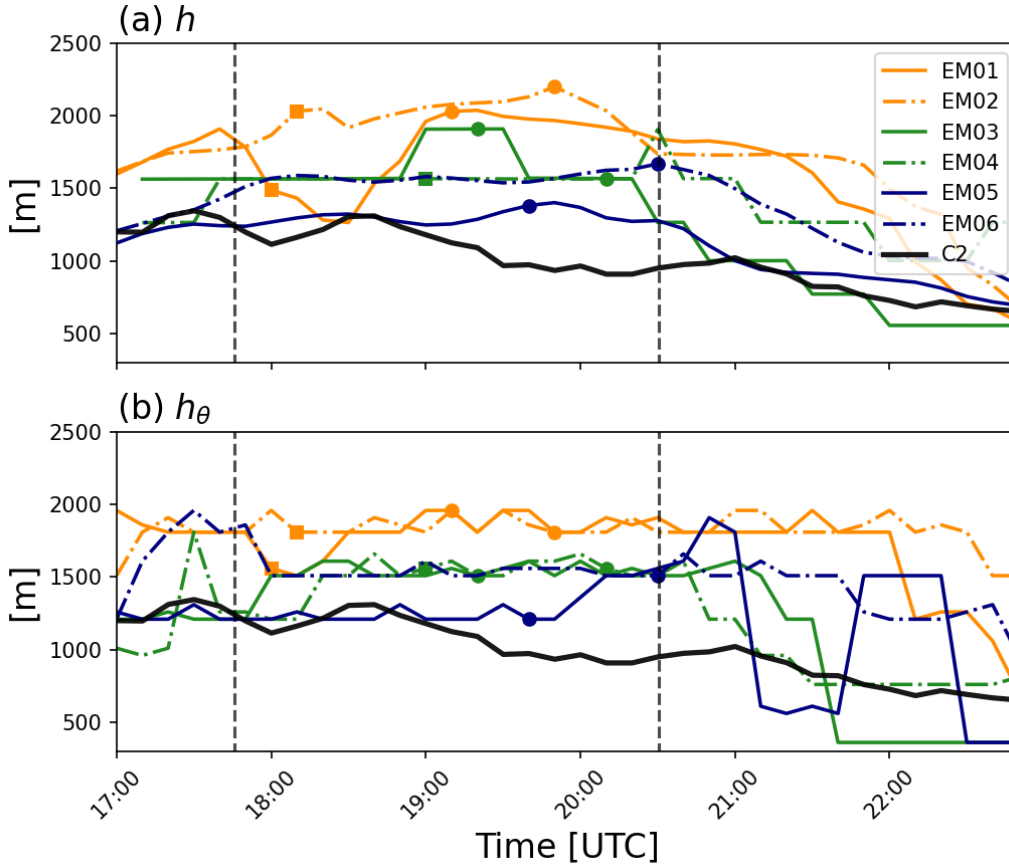


Figure 4.9: PBL depth (a) native scheme method and (b) potential temperature gradient method for each member. CLAMPS2 observations determined PBL depth (thick black line). Squares indicate BB passage and circles indicate SB passage in simulation. Dashed line at 1745 UTC is observed BB passage and dashed line at 2030 UTC is observed SB passage.

Upon initialization, EM04-06 have an accurate estimate of  $h$ , compared to observations, but without the implications of the BB, these members grow the PBL too rapidly, leading to overestimates in depth. All members tend to overestimate  $h$  and  $h_\theta$  to varying degrees. The YSU members overestimate  $h$  the most with 50–120% relative bias; however, they are the only members to represent the brief  $h$  reduction after the BB. After each simulated SB,  $h$  begins to decay, while  $h_\theta$  decays much later and more

quickly. The steady rate  $h$  decreases is more realistic in its response to the SB and afternoon transition than the abrupt decline in  $h_\theta$  in the late afternoon.

The SB passage timing follows similar complications since inaccurate heating rates over land and water can cause SB onset errors on the order of hours. Time of day not only impacts the state of the PBL but also influences the strength of the SB in terms of wind speed and thermodynamic changes (Arrillaga et al. 2018). All members, except EM06, simulate the SB earlier than observed by 30–70 min (Fig. 4.9). Conversely, NWP models often predict the SB 1–4 h later than observed (Miao et al. 2009; Caicedo et al. 2019). In comparison, the timing in this work is simulated fairly well, possibly improved by the surface data assimilated upon initialization. For this event, the observed SB moved through during the CBL afternoon transition. Because all members simulated the SB too early, the simulations are still in the CBL state, consistent with observations. If the SB had passed later than observed, it would have been during the evening transition and likely would have inflated errors. The RRTMG members have more accurate SB passage timing compared to the Dudhia members. The RRTMG members better depict the radiative transfer through moist air (Montornès Torrecillas 2017), allowing the circulation to develop slower than the Dudhia members.

Up until now, the thermodynamic evaluation has focused on the PBL with influences from the BB and SB. However, the accuracy of simulating the breeze intensity is equally important. Even small errors in the magnitude of moisture and temperature advection can greatly impact the pre-convective environment. Figure 4.10 shows the rate of change for temperature ( $dT/dt$ ) and water vapor mixing ratio ( $dw/dt$ ) as a function of the BB and SB passage. Prior to the BB passage, the members are in good agreement with the observation for the diurnal warming and drying of the early afternoon PBL (Fig. 4.10a, c). After the BB, the magnitude of cooling and moistening is underestimated by all BB-simulating EMs for 1.5 h. EM01 has the best representation

of slight cooling at BB passage but it transitions to a warming trend after 1 h, where the observations show near-zero temperature change for 2 h after the BB (Fig. 4.10a). The moisture response for EM01 is even shorter lived, but is still the most representative of the observed environment (Fig. 4.10c). The other members (EM02 and EM04) show an enhanced drying response within the BB, indicating that the BB has very little impact on reducing simulated convective mixing.

There are some similarities with the SB response, with better agreement prior to the SB passage, and increased spread in moisture advection after the SB passage. Without thermodynamic influence from the BB, most members have warming and drying rates that are stronger than observed (Fig. 4.10b, d). The error magnitude for the SB  $dT/dt$  is small, as are the overall cooling rates. Meanwhile, the  $dw/dt$  errors show overestimation after the SB (Fig. 4.10d). Some members (EM02, 04, and 06) forecast strong moisture advection with the SB, which is not observed due to the influence of the BB. EM05 has the smallest overall difference for  $dT/dt$  and  $dw/dt$  after the SB passage, even though it lacks a simulated BB. To some extent, simulating the BB is not necessary to accurately represent the SB; however, slowing the CBL growth is important for cooling potential.

### 4.2.3 Bay breeze drivers

As previously mentioned, only half of the ensemble members simulate a BB that is observed to pass through the UHCC site at 1730 UTC. There are some obvious differences in the way the BB is simulated across the PBL schemes. The YSU scheme EMs have the earliest, most intense BB with a gradual weakening in the wind speeds as it transitions to the SB (Fig. 4.3a, d), and have the only noticeable moistening response to the increasing easterly flow (Fig. 4.3). EM04 is the only other EM to simulate the



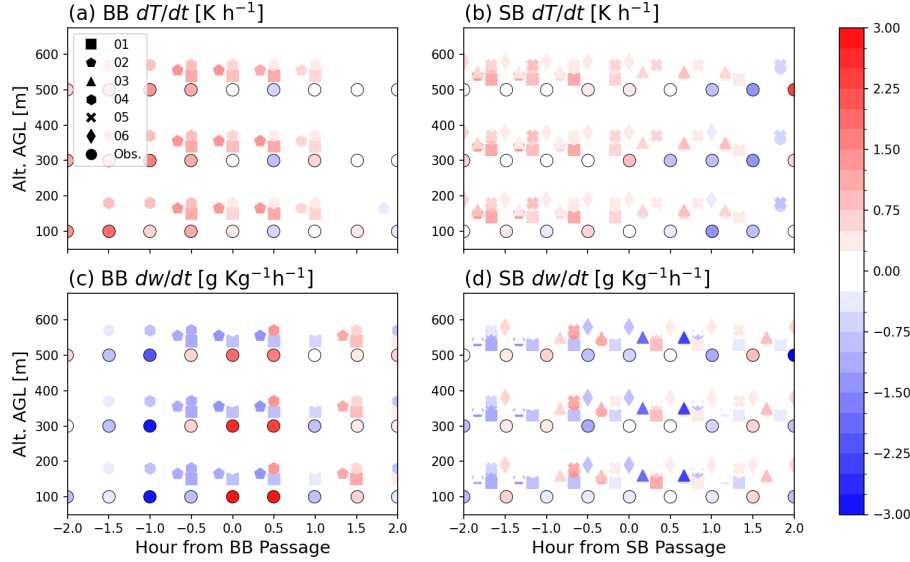


Figure 4.10: Rate of change for temperature ( $\text{K h}^{-1}$ ) by the (a) BB and (b) SB and rate of change of water vapor mixing ratio ( $\text{g kg}^{-1} \text{h}^{-1}$ ) by (c) the BB and (d) SB

BB, but its onset is more gradual, later, and has no thermodynamic reaction (Fig. 4.3j-l). EM06 has a brief period of easterlies around 1845 UTC, but it is too short-lived to meet the criteria of a BB. Overall, EM01 has the best thermodynamic response to the BB of all the members, with stronger cooling and moistening than EM02. To inform future simulations of the BB near the coast, we look at the forcing behind the BB to identify where parameterizations diverge.

The BB circulation is induced by the surface temperature gradient across Galveston Bay, but is weaker and does not propagate as far inland as the SB. Figure 4.11 shows the land-water gradient across Galveston Bay is 2–4 K less than the gradient across the Gulf of Mexico, but the separation across the members is similar. The YSU members have the largest land-water temperature contrast early on, correlating with the largest sensible heat flux ( $H$ ) over land, similar to scaling relations from Crosman and Horel (2010). The BB induces a reduction in  $H$  and temperature gradients due to the clouds

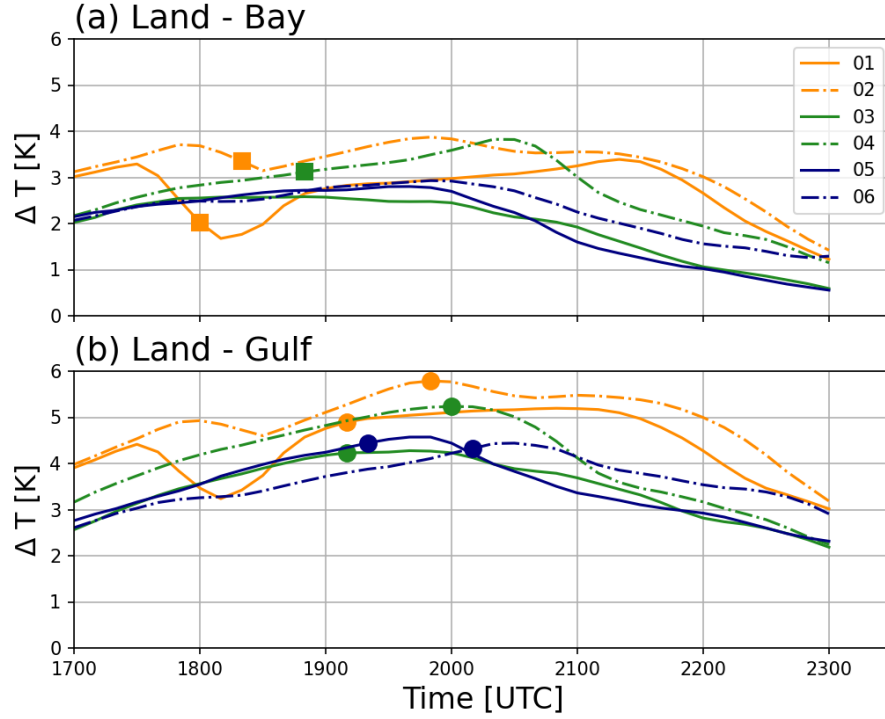


Figure 4.11: (a) 10-m temperature gradient (K) between 4-point nearest neighbor average at UHCC (29.39N, -95.04W) and grid point over Galveston Bay (29.45N, -94.81W). (b) 10-m temperature gradient (K) between 4-point nearest neighbor average at UHCC and grid point over the Gulf of Mexico (29.08N, -94.75W). Squares represent the time of BB passage and circles represent the time of SB passage

pushed inland, which is more drastic for EM01 due to the simpler cloud representation (Fig. 4.11, 4.12). The land-bay temperature gradient for EM04 increases slightly more than the other local EMs due to minimal cloud cover (Fig. 4.12). The differences across EM temperature gradients are 0–2 K, with the most spread after the SB due to different cooling rates.

The surface heat fluxes have similar distinctions from local and nonlocal EMs. The local EMs have similar magnitudes of  $H$  that evolve gradually, whereas, the YSU EMs produce larger  $H$  that is more sensitive to changes in cloud cover. After the SB,  $H$  declines for all members and the spread collapses across the MYNN and MYJ members

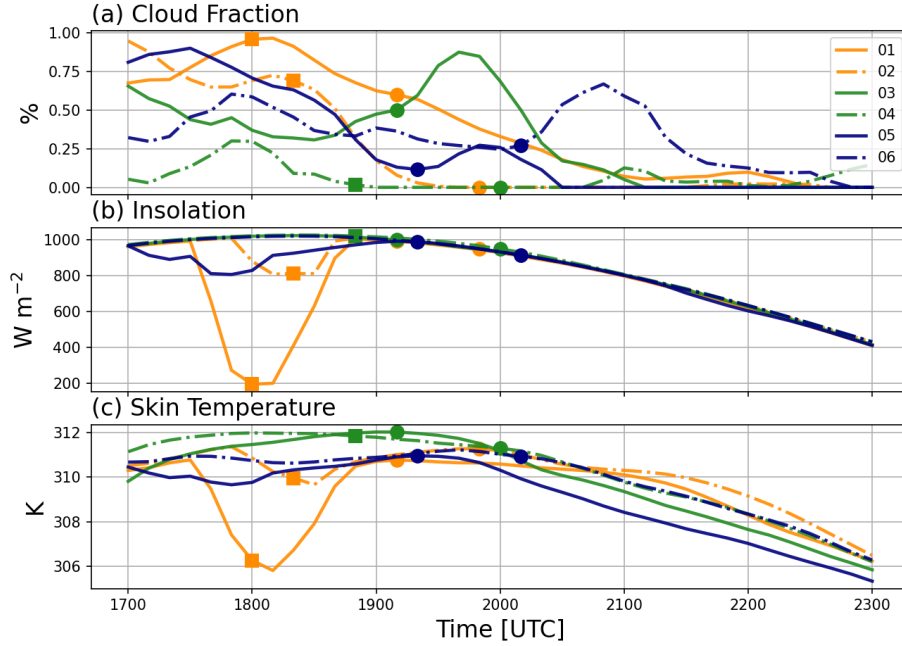


Figure 4.12: Time series from each EM of (a) low-level cloud fraction (%), (b) incoming SW radiation ( $\text{W m}^{-2}$ ), and (c) skin temperature (K). Computed as 4-point nearest neighbor average closest to the UHCC site. Squares represent the time of BB passage and circles represent the time of SB passage

(EM03-06). Similarly, this is true for latent heat flux ( $LH$ ), but the magnitude of  $LH$  is very dependent on the PBL scheme (Fig. 4.13a). The MYJ EMs have markedly higher  $LH$  and comparable  $H$  to MYNN, which is atypical in previous climatologies (Shin and Hong 2011; Milovac et al. 2016). The Bowen ratio evolution is more steady than  $H$  or  $LH$ , aside from the drastic reduction due to clouds in the YSU EMs (Fig. 4.13c).

The SW radiation scheme also influences surface fluxes. This is most obvious when there are broken clouds and radiative processes are most complex. Figure 4.12a shows that most cloud variability exists in the morning, with a general decrease through the afternoon. After the SB, cloud cover briefly increases and then declines to near zero (Fig. 4.12a). As compared with RRTMG, Dudhia EMs tend to have higher cloud

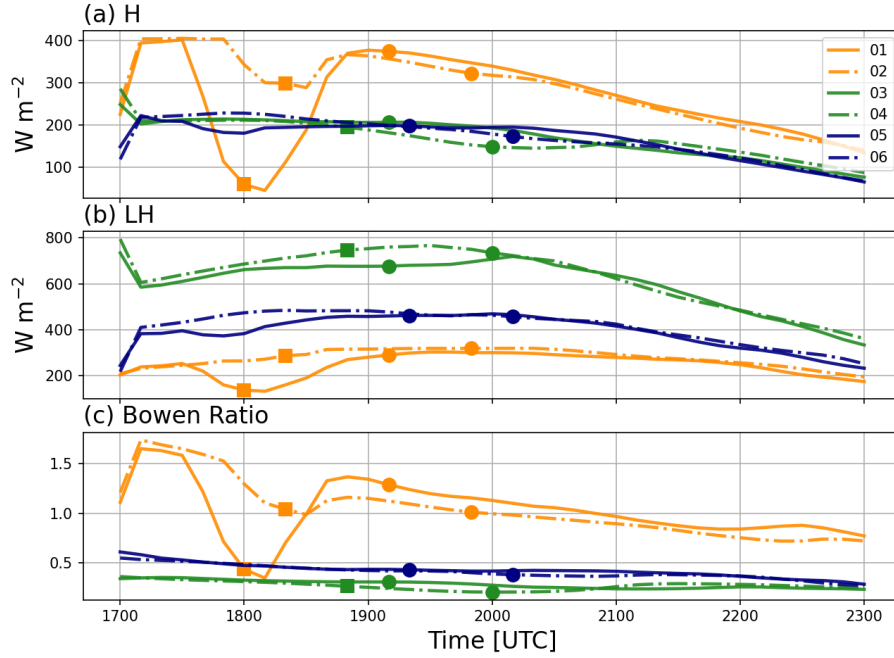


Figure 4.13: Time series from each EM of (a) sensible heat flux ( $W m^{-2}$ ), (b) latent heat flux ( $W m^{-2}$ ), and (c) Bowen ratio (unitless). Computed as 4-point nearest neighbor average closest to the UHCC site. Squares represent the time of BB passage and circles represent the time of SB passage

fractions, leading to less insolation reaching the surface and lower skin temperature (Fig. 4.12). This is especially impactful on the nonlocal (YSU) EMs, as surface temperature is most sensitive to incoming SW radiation (Jia et al. 2023). Meanwhile, the surface temperature of the local PBL schemes (EM03-06) is more persistent prior to the SB, because it is sensitive to  $H$  which is steady throughout the early afternoon (Figs. 4.12c, 4.13a).

The first 3 h of the forecast have the most variability at UHCC, so the next analysis focuses on the 1730-1930 UTC period to capture the time the BB forms and passes through the region. Multiple factors impact coastal breeze inland propagation, such as  $H$ , PBL turbulence, and temperature gradients. To evaluate the BB environment, a cross-section from the Galveston Bay coastline across the UHCC and further inland

(Figs. 2.1, 4.14) was selected to determine the penetration distance of the BB and variability of driving forces. The fields were averaged from 1730–1930 UTC to capture consistent patterns. A BB is defined as having a minimum wind speed of  $2.5 \text{ m s}^{-1}$  sustained for 1 h with wind direction from the bay coastline ( $60^\circ$ – $130^\circ$ ). Fig. 4.14a designates the span of zonal wind that meets the criteria shaded in gray, and once the zonal wind speed is below that threshold, then, the BB has ended its propagation inland. The BB in EM01 and EM02 travel the furthest inland, between 13–15 km, while in EM03 and EM05 the BB penetrates the least distance, and does not reach UHCC. The BB in EM04 and EM06 travel about the same distance inland, but the BB flow in EM06 did not last long enough at UHCC to meet the criteria.

The drivers of the BB are divided by the type of PBL mixing scheme. Nonlocal mixing scheme EMs are more successful at producing a BB that reaches UHCC than local EMs. The YSU members have preferential BB development due to faster vertical transport of heat to generate baroclinicity. For these EMs, the land-water temperature gradient at 9 m is initially the largest, even though the skin temperature gradient is the lowest (Figs. 4.11, 4.14). YSU EMs have the largest heat transfer coefficient, leading to a well-mixed surface layer and warm air over land (not shown). This allows the BB circulation to develop quickly, even with more cloud coverage over land (Fig. 4.12). The local schemes are more sensitive to cloud cover because they require a higher initial surface temperature to induce a BB. Initially, EM03 and EM05 have the highest cloud fractions over UHCC, among local EMs, leading to marginally lower surface temperatures than their RRTMG counterparts (Fig. 4.12a, c). As a result, the land-bay temperature gradient builds slowly and is not sufficient to force the BB as far inland as UHCC. EM06 is interesting because it appears to reach UHCC in Fig. 4.14a, but does not meet the BB criteria. Compared to EM06, EM04 has faster zonal winds closer to shore that provide the BB with more inertia to reach UHCC. Using the

same BB and SB passage detection applied to all EMs (EM01-18) at UHCC, these patterns follow, with 83% of YSU EMs simulating a BB, while MYJ and MYNN do so at 66% and 33%, respectively. While the MYJ and MYNN schemes are overall very similar, MYNN EMs have lower surface temperatures over land and weaker land-water temperature gradients (Figs. 4.11, 4.14d).

Previous studies, like Miao et al. (2009) and Gómez et al. (2016), have analyzed the impact of PBL parameterizations on SB characteristics, but their verification datasets have lacked adequate resolution to cover the scales on which the PBL evolves. The work herein shows the importance of evaluating PBL variables beyond the surface layer since biases in the mixed layer can vary in sign and magnitude compared to surface observation biases. Furthermore, the type of PBL mixing scheme can greatly impact the ability to simulate the weaker-forced BB because local mixing schemes are more sensitive to initialization. Additionally, the different PBL mixing schemes manifest in variations in SB characteristics and evolution. Using the first 6 EMs helps to deduce the impacts caused by the combination of parameterizations on a fine scale. While there are slight deviations across all EMs based on changes in initial conditions, the broad patterns hold, and this is useful moving forward in analyzing the parameterization influence on WoFS.

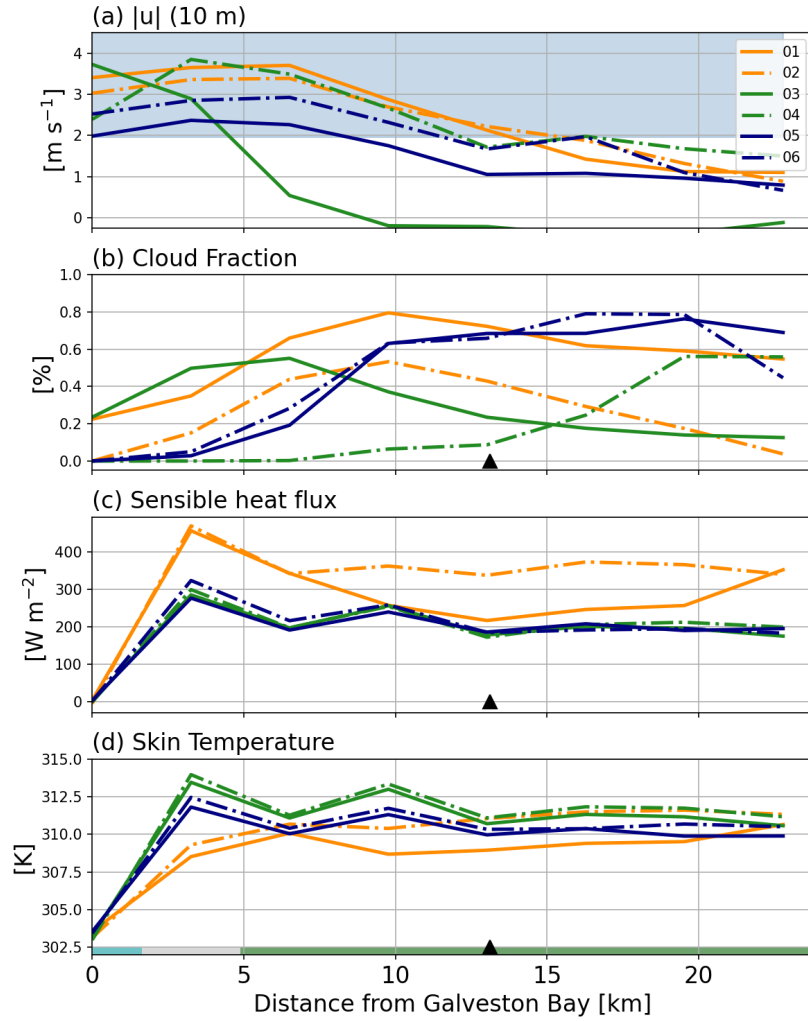


Figure 4.14: Cross-section from the Galveston Bay shoreline averaged from 1730-1930 UTC. The gray shading in (a) indicates the threshold for BB onshore flow. The black carat indicates the point in the cross-section UHCC lies. The bars at the bottom of (d) indicate the land use throughout the cross-section with blue-water, gray-urban, and green-croplands.

## Chapter 5

# Evaluating the impact of sea breeze simulations on convection initiation and evolution

The PBL parameterization has a strong influence on how the SB is simulated and the rate it alters the PBL. Convection initiation (CI) is highly sensitive to changes in moisture and heat fluxes, so the differences in SB propagation caused by PBL parameterization are likely to translate into convection initiation and evolution. The following sections aim to determine how the PBL parameterization alters storm timing, preferential region, and frequency. Furthermore, the drivers of CI and their dependence on the SB are investigated.

## 5.1 Methods

### 5.1.1 Cases

Of the dataset of simulated events, two were prioritized for analysis since the SB triggered observed CI without the influence of strong synoptic forcing. Both occurred in July 2022 under mid-level, high-pressure systems, with high temperatures and a chance of scattered showers forecasted in the early afternoon. On 13 July, the SB was not anticipated due to early convective activity offshore, but residual clouds and outflow boundaries dissipated by 1500 UTC allowing the ABL to recover and develop



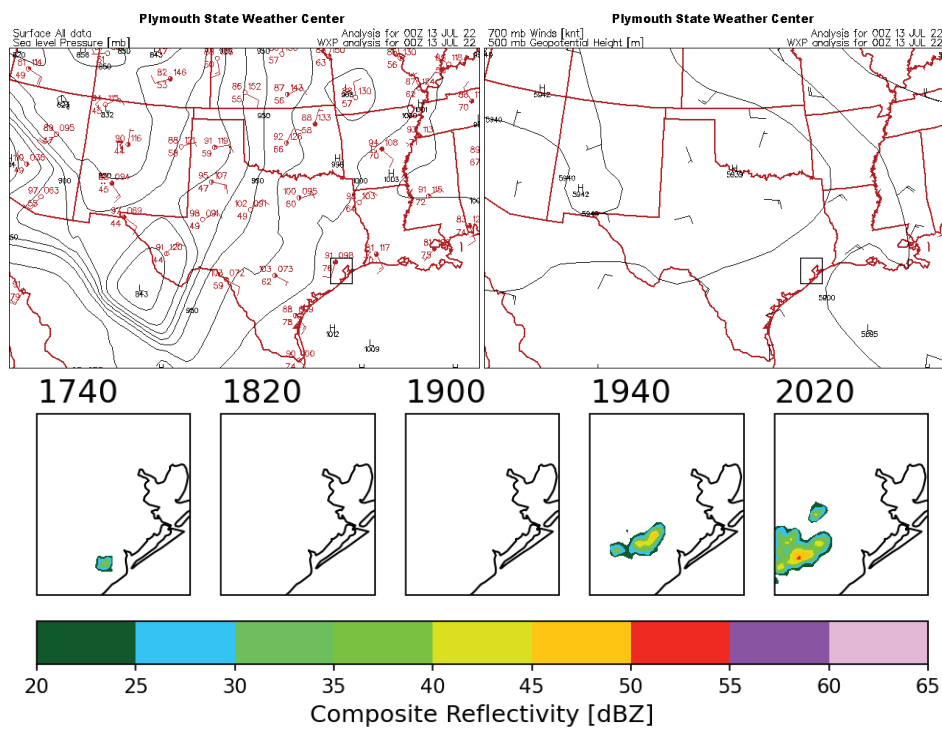


Figure 5.1: 13 July 2022 00 UTC regional observations of (top left) surface stations and sea level pressure contours (black) and (top right) 500 hPa geopotential height contours with 700 hPa wind barbs. The black boxes signify the region seen in the bottom panel plots. (bottom panel) MRMS composite radar reflectivity, times in UTC.

a shallow cumulus field. The SB began to move onshore at 1730 UTC, which initiated one cell close to the Gulf coastline (Fig. 5.1). There was a pause in convection until 1940 UTC when the SB traveled further inland with cells moving west. The cells shown at 2020 UTC continue until 2130 UTC. The easterly winds at 700 hPa across southern Texas caused the storm propagation westward (Fig. 5.1). On 25 July, the chances for CI were lower and expected to stay isolated to the SBF and close to the coastline. The SB began to move onshore around 1800 UTC but did not trigger CI until 1900 UTC when cells moved northwest with the SB (Fig. 5.2). Storms dissipated by 2030 UTC as available moisture decreased inland.

Since WoFS was designed to forecast high-impact weather, most of the validation studies have centered around events like tornadic supercells and quasi-linear convective systems. Nevertheless, it is important to understand the forecast performance for more frequent but less impactful weather events. Events like this are also better for isolating the PBL's role in CI without compounding factors like storm-altered environments.

### **5.1.2 Radar observations**

A continuous, quality-controlled radar product is necessary to verify simulated storm objects with observations. Multi-Radar/Multi-Sensor System (MRMS) combines observations from the network of WSR-88D Doppler radars to create a gridded radar product across CONUS (Zhang et al. 2005). The MRMS observations are natively on a 1 km horizontal grid, but they were interpolated using Cressman weighting to match the 3 km grid of the WoFS simulations. Previous verification studies for WoFS simulations have relied on MRMS to verify reflectivity (Skinner et al. 2018; Potvin et al.

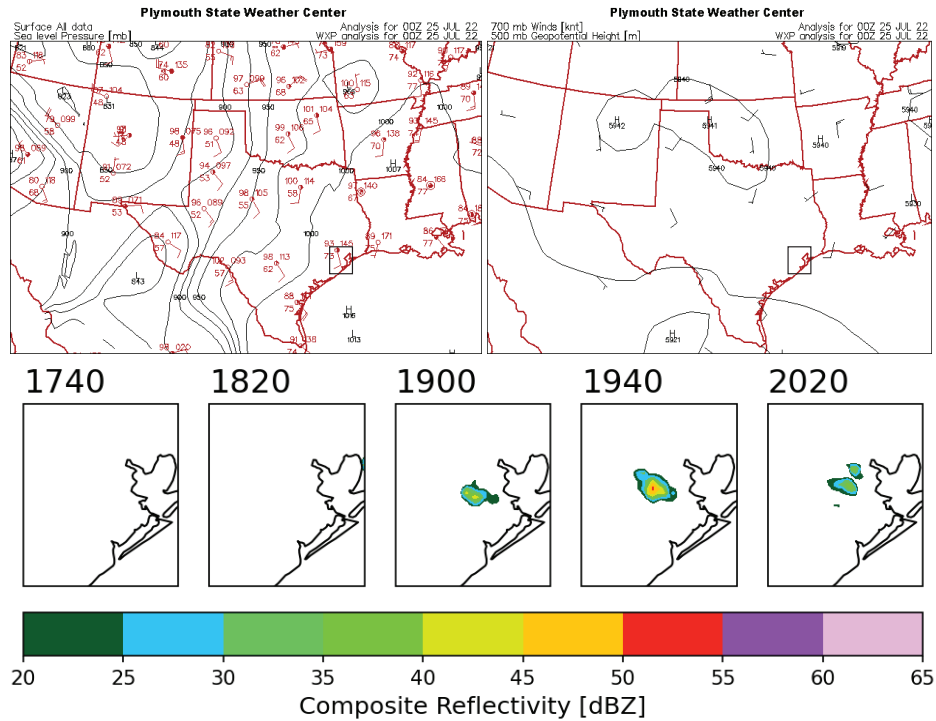


Figure 5.2: Same as Fig. 5.1 but for 25 July 2022

2020). The MRMS quality-controlled composite reflectivity observations will be used to identify and match storm objects with simulations.

### 5.1.3 Object-based verification

Verifying convection in NWP models can often be difficult since success can have various definitions and degrees given the forecast goal. Davis et al. (2006) discusses the issues with traditional grid-to-grid matching for rainfall forecasts and observations; the skill scores derived from these techniques often lack reasoning behind performance. For example, if a forecasted storm is spatially displaced from the observed storm it is regarded as a complete miss, as if the model simulated no storm at all. This provides no useful feedback on how the model should be improved. Object-based identification and matching mitigate some of these issues by allowing for defined spatial displacement

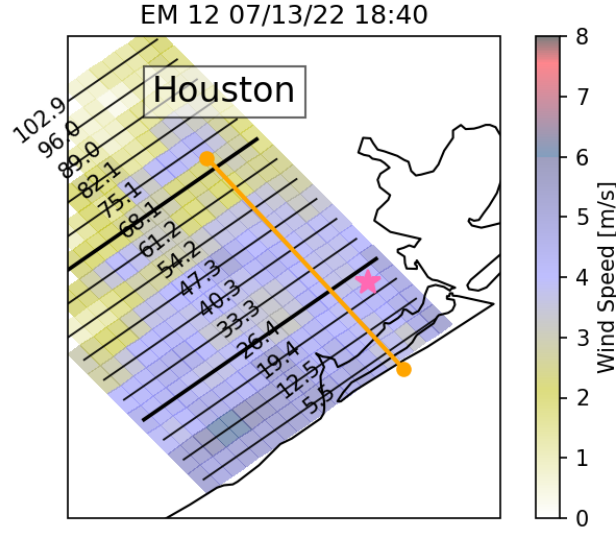


Figure 5.3: Cross-section of wind speed (shaded,  $\text{m s}^{-1}$ ) from EM12 at 1840 UTC 13 July 2022. The numbered lines indicate the center of the slices and the distance (km) from the Gulf of Mexico coastline. The orange line indicates the region used in the vertical cross-section in Fig. 5.19. The pink star signifies UHCC.

or differences in reflectivity magnitude. Storm object identification and matching use techniques described in Skinner et al. (2018), with alterations to the parameters to fit single cellular thunderstorms rather than supercells. Since the observed convection was discrete, a single-threshold identification method was employed with a reflectivity threshold of 30 dBZ based on convective cell characteristics from Sharma et al. (2024). To match observed and simulated objects, one-to-one matching was chosen with a maximum centroid displacement distance of 25 km from the observed object to the simulated object. Objects within 25 km of each other were merged before matching.

This type of object matching provided statistical verification metrics. Hits are when an object pair is matched in forecast and observations (A in Fig. 5.4). False alarms are where a storm is simulated but not observed (B in Fig. 5.4). Misses are the converse when an observed storm object exists but is not simulated (C in Fig. 5.4).

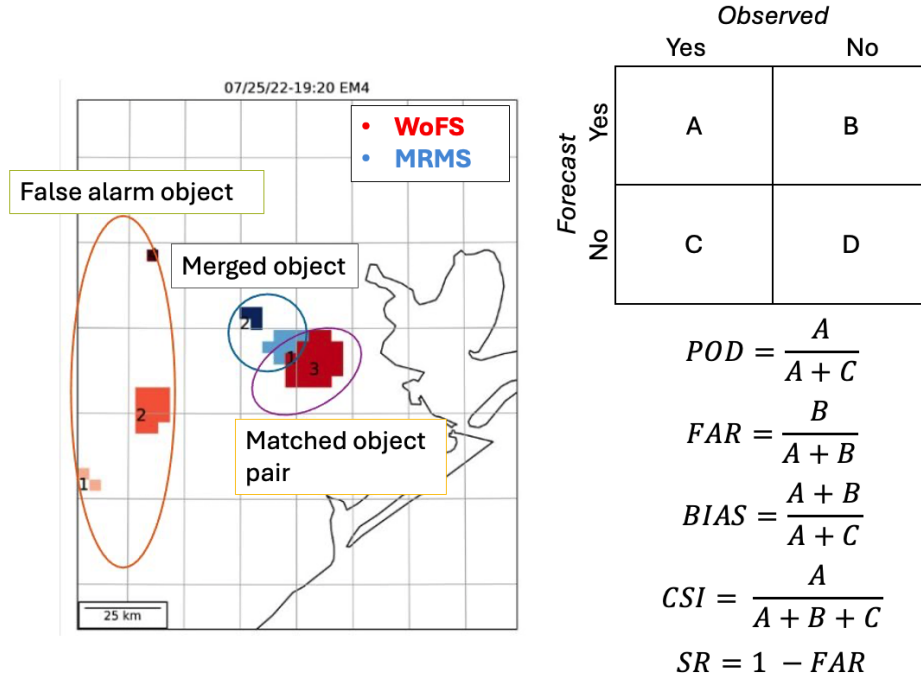


Figure 5.4: Annotated example of object identification and matching for EM 04 at 1920 UTC 25 July 2022 and how the performance metrics are calculated based on Skinner et al. (2018). Abbreviations have the following definitions: POD (probability of detection), FAR (false alarm rate), CSI (critical success index), SR (success ratio)

The probability of detection (POD) measures the ratio of matched storm objects to observed objects (hits and misses). False alarm rate is the likelihood of simulating a storm that is not matched to observations. To assess both in one metric, critical success index (CSI) is the proportion of correctly matched pairs (hits) to all possible outcomes (hits, misses, and false alarms). Lastly, bias describes the frequency of forecasted objects to observed objects. Figure 5.4 illustrates how these parameters are applied to identified objects and how the verification metrics are calculated.

#### 5.1.4 Analysis techniques

In this chapter, all EMs will be analyzed from the 1700 UTC initialization WoFS forecast for each case date. Focusing on the region of TRACER observations, the

domain is on the west side of Galveston Bay from the Gulf of Mexico coastline to downtown Houston. Figure 5.3 shows an example of the x-y cross-section plane that divides a portion of the domain into slices parallel to the coastline, each 6.95 km wide. Each slice is divided into 19 grid cells (each 4 km in length) that are averaged for each slice. This method was employed to analyze the SB across a region rather than a set point. Additionally, this technique allows Hovmöller diagrams to be created by averaging the slice to understand the time evolution across the domain. Furthermore, the averaged slices determined the SB passage timing, using a sliding window threshold method of greater than  $4 \text{ m s}^{-1}$  in the onshore direction, similar to methods used in Chapter 4. Two slices are selected to track the SB location, 26.4 km inland that aligns with UHCC, and 68.1 km inland that transects downtown Houston. For example, in Fig. 5.3, the SB threshold would be reached at 26.4 km but not 68.1 km. The x-y cross-sections are primarily used to understand the timing and location of storm objects with relation to the SB and areas of large  $\theta_e$ . The performance metrics are calculated across the broader domain in Fig. 5.3, not just the shaded x-y cross-section plane.

With the goal of understanding how the PBL parameterizations affect the pre-convective environment and CI occurrences, EMs with the same PBL parameterization are composited across the domain. Spatially averaging the EMs into three groups (YSU, MYJ, and MYNN) highlights the coherent patterns caused by PBL parameterization. First, the magnitude of inter-EM variability is calculated in Table 5.1 using the coefficient of variation ( $\frac{\sigma}{\mu} \times 100$ ), where  $\sigma$  and  $\mu$  are standard deviation and mean, respectively. The coefficient of variation is calculated for surface temperature, water vapor mixing ratio, and horizontal wind components to understand if the average across six EMs is still representative of each EM. The coefficient of variation is lowest in the first 1.5 h, prior to the influence of convection, and typically increases with

Table 5.1: Coefficient of variation for 25 July across the 6 members that share a PBL scheme, as a percentage. Values were averaged over the domain and the range is across time.

|                                        | <b>Temperature</b> | <b>QV</b> | <b>U</b> | <b>V</b> |
|----------------------------------------|--------------------|-----------|----------|----------|
| <b>YSU</b> (EM01, 02, 07, 08, 13, 14)  | 0.5–1.8            | 4.2–5.6   | 50–200   | 10–100   |
| <b>MYJ</b> (EM03, 04, 09, 10, 15, 16)  | 0.8–1.9            | 3.8–5.1   | 40–500   | 5–50     |
| <b>MYNN</b> (EM05, 06, 11, 12, 17, 18) | 0.7–1.6            | 3.5–5.5   | 30–200   | 15–85    |

forecast time. The magnitude of variation for temperature and moisture are within a reasonable range ( $< 5\%$ ), but the differences in wind components are too large to composite confidently. The zonal wind component differences are much larger than meridional because the mean zonal wind is close to zero. Motivated by minimizing the amount of inter-EM spread for the PBL scheme, only the thermodynamic variables will be spatially composited across the domain and from 1700-1800 UTC.

## 5.2 Performance of simulating convection

Figure 5.5 shows the performance diagram for 13 and 25 July 2022 based on storm object matching. For both days, the CSI for most EMs is between 0.3–0.4 which is within the expected values of a full WoFS forecast (Skinner et al. 2018; Potvin et al. 2020). On 13 July, the spread among EMs is much smaller than on 25 July and tends to overestimate convection with a frequency bias around 2. Of note, EMs 06, 12, and 18 share PBL and radiation parameterizations, but have varying success ratios dependent on the initial conditions (Fig. 5.5a); meanwhile, these EMs have similar performance metrics on 25 July (Fig. 5.5b). This difference is further investigated in Section 5.3.

The performance on 25 July is more spread in both success ratio and probability of detection (Fig. 5.5b). There is some clustering of EM’s performance based on PBL

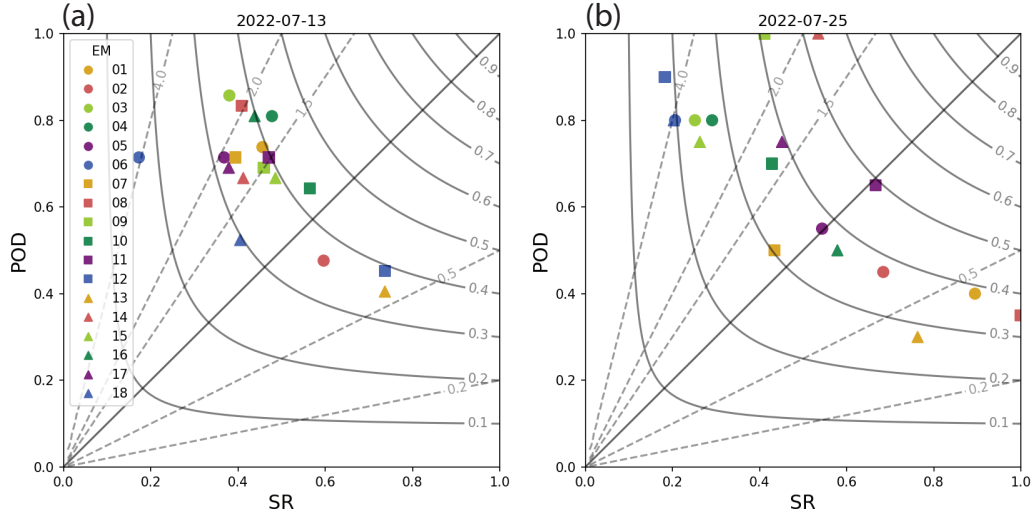


Figure 5.5: Performance diagrams of matched storm objects on (a) 13 July 2022 and (b) 25 July 2022. The dashed diagonal lines are the frequency bias and the solid curves ranging from 0.1-0.9 are contours of critical success index. Abbreviations have the following definitions: POD (probability of detection), FAR (false alarm rate), SR (success ratio). Colors indicate the matching parameterization combinations. Gold and red are YSU EMs, greens are MYJ EMs, and blue and purple are MYNN EMs.

parameterization with a tendency for local PBL scheme EMs to have high-frequency bias and nonlocal mixing EMs to have lower frequency biases of storm objects. Most of the local EMs have higher POD and FAR due to overzealous convective coverage. The nonlocal EMs tend to have lower FAR and POD. This performance distinction between PBL mixing schemes goes against the findings in Potvin et al. (2020) that suggest the PBL scheme has very little influence on performance diagnostics. This is likely because the PBL scheme is more influential on CI under weakly forced conditions than in a highly dynamic supercell environment. While the performance on 13 July is less impacted by the PBL scheme, there is more impact than in Potvin et al. (2020).

While the synoptic setup is similar for 13 and 25 July (Figs. 5.1, 5.2), the model performance is markedly different (Fig. 5.5). Using the x-y cross-section domain, the



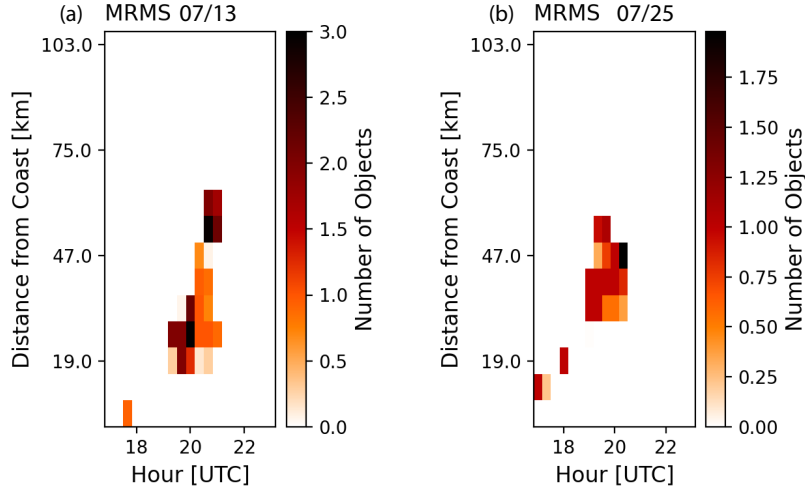


Figure 5.6: Frequency of MRMS observed storm objects with time (UTC) and distance from the Gulf of Mexico coastline (km) across the x-y cross-section domain for (a) 13 July and (b) 25 July

frequency of storm objects can be summed over slices to understand where CI is occurring with time and distance from the coastline. Figure 5.6 shows the storm object frequency from MRMS observations for both cases. Both cases evolve similarly with a short-lived cell close to the coastline around 1800 UTC and then a maximum in storm occurrence around 2000 UTC. On 13 July, storms continue further inland and last longer into the day than 25 July. No cells travel north of downtown (75 km) and are primarily in the 20-60 km inland, which is similar to findings from Wang et al. (2024) on precipitating cell frequency during the TRACER campaign.

Similar to Fig. 5.6, the same methods are applied on each EM (Figs. 5.7, 5.8). The SB passage time estimate is used to connect the frequency of storm objects to the location of the SB. This method is only an estimate because outflow from nearby convection can influence identifying the SB, leading to unrealistic SB propagation speeds. On 13 July, the coverage of storm objects is similar across most EMs (Fig. 5.7). Once the SB initiates, CI occurs throughout the domain until 2200 UTC, for the majority of

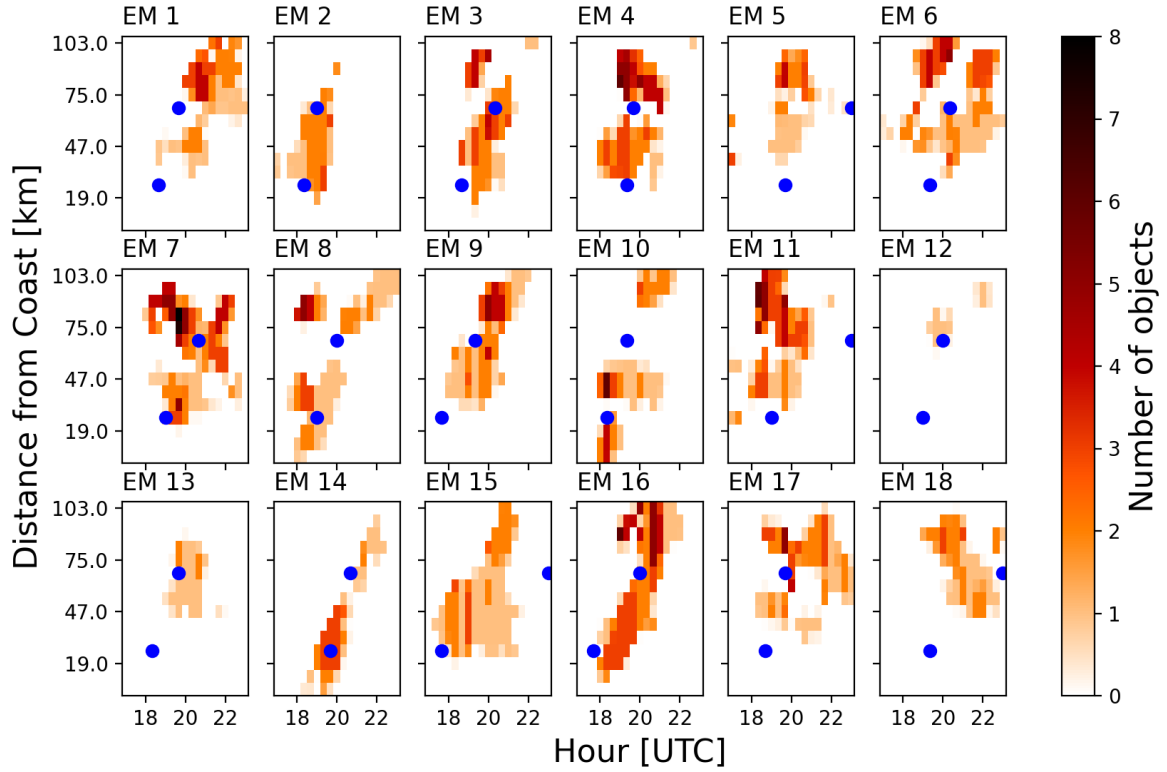


Figure 5.7: Frequency of simulated storm objects with time (UTC) and distance from the Gulf of Mexico coastline (km) for each EM on 13 July 2022. The two blue dots indicate the estimated time of SB arrival at 26.4 and 68.1 km inland.

EMs. Appendix B shows the simulated reflectivity divided by PBL parameterization on 13 and 25 July.

On 25 July, the storm coverage is much more variable across the EMs (Fig. 5.8). The frequency of storms and coverage inland varies with the PBL parameterization scheme. Similarly on 13 July, most CI occurs further inland than 20 km from the coastline (Fig. 5.7, 5.8). Nonlocal PBL EMs have significantly fewer storms, causing the low frequency bias seen in the performance diagram (Fig. 5.5b). The local PBL scheme EMs tend to have more convective coverage in space across longer time spans (Fig. 5.8 columns 3-6). Local EMs also have more instances of CI ahead of the SB

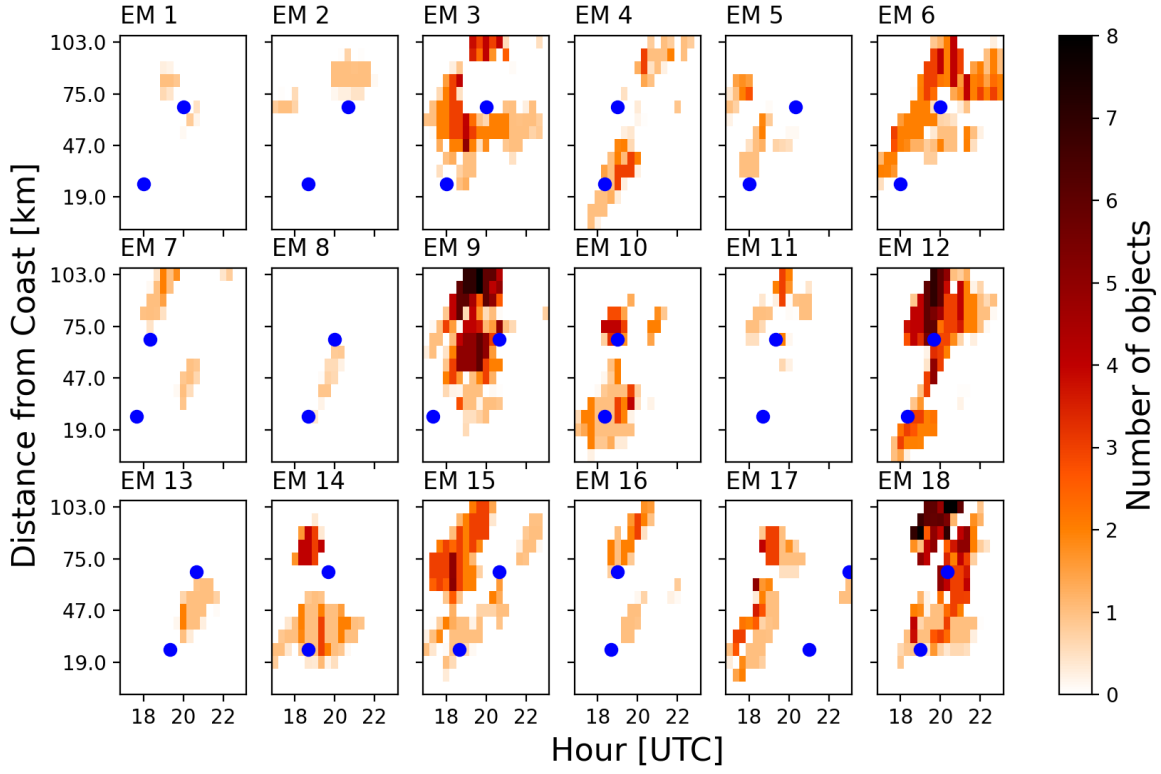


Figure 5.8: Same as Fig. 5.7 but for 25 July 2022

(Fig. 5.8 columns 3-6), while nonlocal EMs have CI primarily within 5 km of the SBF (Fig. 5.8 columns 1-2).

To quantify these differences, the number of storm objects is accumulated across the cross-section domain through the full forecast, and displayed by EM in Fig. 5.9. It is clear the MYJ EMs (greens) simulate the most storm objects and YSU EMs (red, orange) produce the least (Fig. 5.9). Across the different initializations for concurrent parameterization combinations, there is some variability in the number of objects but the patterns are relatively consistent. MYNN EMs have a strong disparity with respect to the SW radiation scheme, the MYNN-RRTMG (blue) EMs have significantly more counts of storm objects than the MYNN-Dudhia EMs. The discrepancy, which is due to the SW parameterization scheme, will be analyzed after discussing the influence of

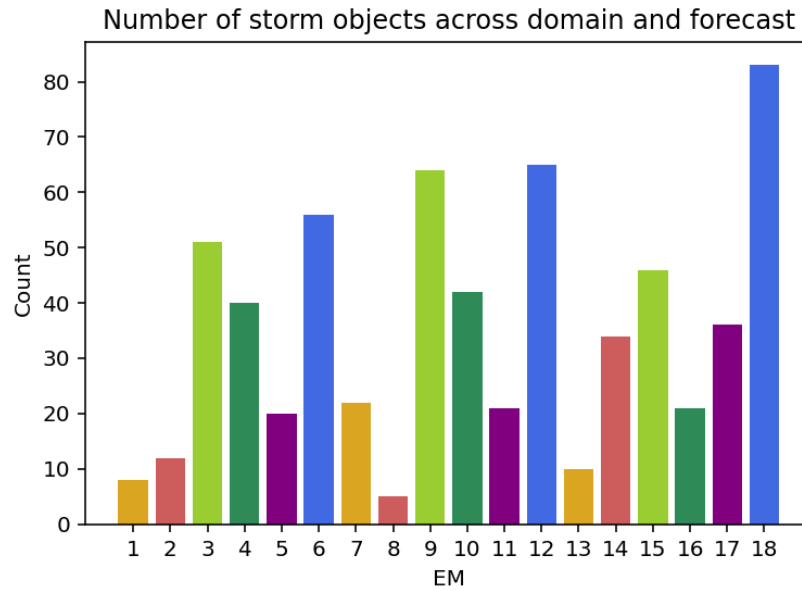


Figure 5.9: Number of storm objects across the domain for the full forecast period (1700-2300 UTC) for each EM on 25 July 2022. Gold and red are YSU EMs, greens are MYJ EMs, and blue and purple are MYNN EMs.

the PBL parameterization on convective variables. This disparity does not exist for 13 July and the number of storms across EMs is more consistent.

### 5.3 PBL parameterization influence on convective variables

Beginning with traditional convective variables, Fig. 5.10 shows mixed-layer CAPE and CIN composited across the whole domain. Overall, CIN is close to zero across the land with larger CIN values over Galveston Bay. There is more variation across the PBL schemes for CAPE, with YSU having significantly less CAPE across over land compared to the local EMs (MYJ and MYNN). This agrees with results from Potvin et al. (2020), who found that MYJ and MYNN overestimate mixed-layer CAPE, while YSU is unbiased compared to radiosonde observations. Of note, there are pockets of larger CAPE throughout the inland domain for MYJ and MYNN, but for YSU the largest CAPE values are close to the shoreline and extend slightly offshore. This suggests that the SB in MYJ and MYNN members have less CAPE than over the land, but YSU has a more accurate depiction of the SB advecting more moisture to increase instability, as seen in Chapter 3. The SB propagating into a more convectively unstable region in part explains the overestimation of storm objects for local PBL members.

The PBL scheme also controls the PBL depth (PBLD) and influences the level of free convection (LFC) through low-level stability and surface conditions. Lower LFC heights make the environment easier to initiate convection because updrafts do not have to extend as high and risk dilution. YSU EMs have higher LFC heights and PBLD than MYJ and MYNN (Fig. 5.11). MYJ and MYNN EMs are similar in PBLD and LFC height but the method of PBLD calculation causes some differences in heterogeneity. MYJ uses a TKE threshold approach to determine the PBLD, which leads to more variability across short distances than MYNN, but the magnitude is nearly the same (Fig. 5.11e, f). It is also of note that the PBLD over the Gulf of Mexico is on the order

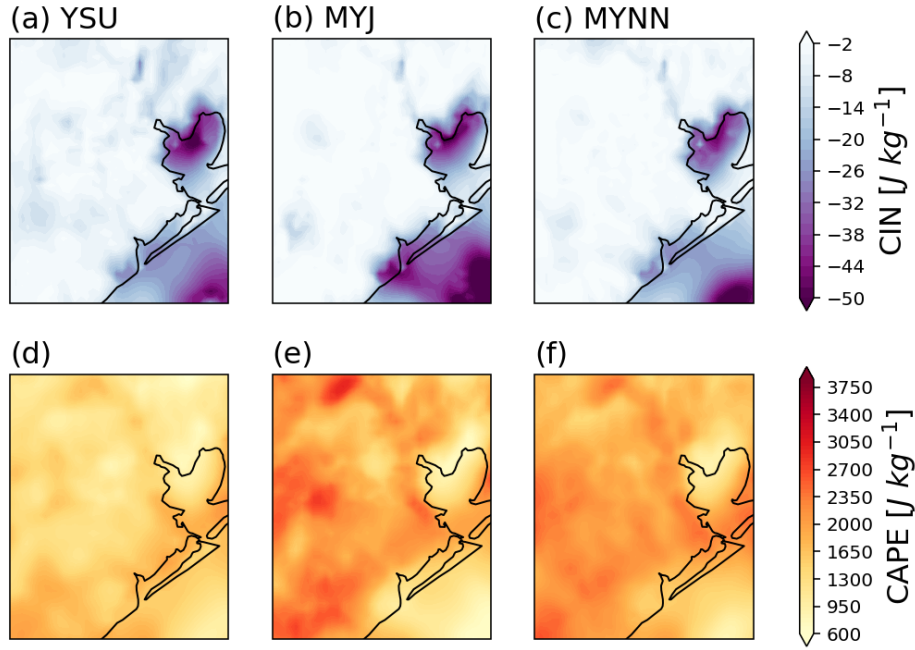


Figure 5.10: Composite of mixed-layer CIN (a-c) and CAPE (d-f) from 1700-1800 UTC for (a, d) YSU, (b, e) MYJ, and (c, f) MYNN EMs on 25 July 2022

of 10 m for YSU and MYJ, but is about 500 m for MYNN, which may alter the depth of onshore flow.

In altering the LFC and PBLD, the PBL scheme can influence CI by determining the ease of surface-based parcels to reach the LFC, thus accessing positive buoyancy in the free atmosphere. To understand how readily parcels within the PBL can reach the LFC, Fig. 5.11g-i shows the LFC height scaled by the PBLD. It provides a ratio to gauge whether the parcels can freely reach the LFC by convective mixing ( $\text{LFC}/\text{PBLD} < 1$ ) or if additional lifting would be required for parcels to reach the LFC ( $\text{LFC}/\text{PBLD} > 1$ ). When the ratio is close to one, parcels can reach the LFC but may be diluted with drier air in the entrainment zone. For this method, compositing results show the median instead of the mean to mitigate the influence of convective cloud outliers. Figure 5.11h shows the MYJ EMs have lower LFC/PBLD ratios by 15–20% compared to YSU and MYNN. Even though MYJ and MYNN appear to have similar LFC heights

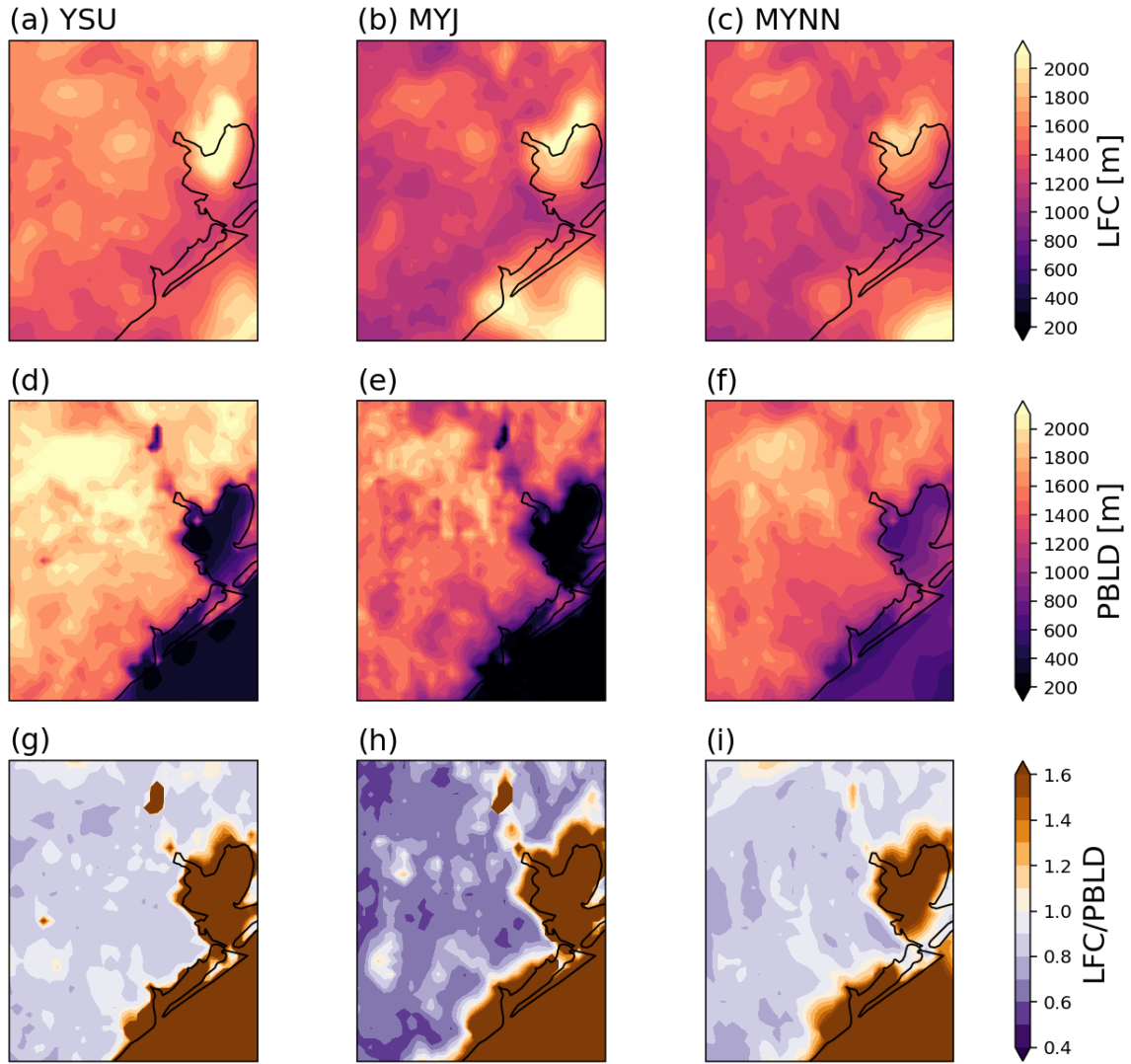


Figure 5.11: Composite of mixed-layer LFC ([m], a-c), PBLD ([m], d-f), and the ratio of LFC/PBLD from 1700–1800 UTC for (a, d, g) YSU, (b, e, h) MYJ, and (c, f, i) MYNN EMs on 25 July 2022

and PBLDs, the fractional differences are not noticeable until they are combined. For MYJ EMs, the continental CBL is already primed for surface-based CI and subtle changes to vertical motion can initiate convection. Since there is virtually no CIN, the minuscule variations in convective length scales can have large impacts on CI.

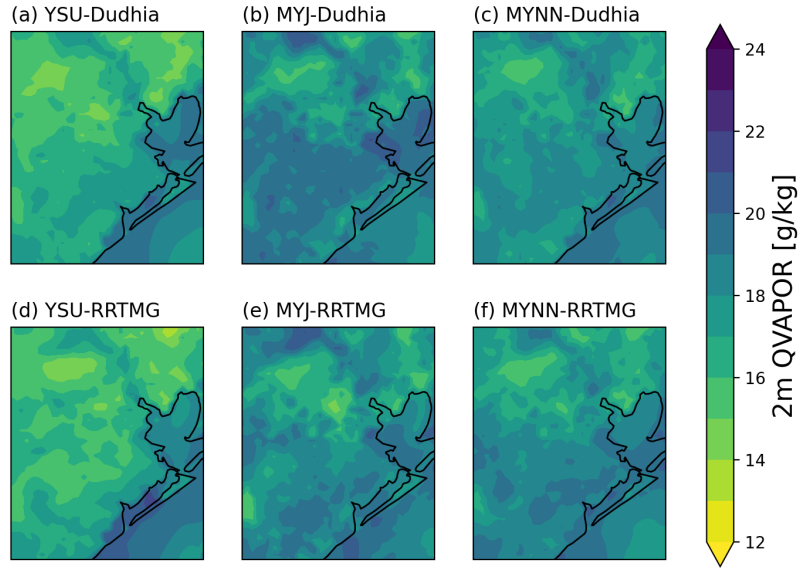


Figure 5.12: Composite of 2-m water vapor mixing ratio (g/kg) from 1700-1800 UTC for (a, d) YSU, (b, e) MYJ, and (c, f) MYNN EMs on 25 July 2025. The top row corresponds to Dudhia SW radiation EMs and the bottom row with RRTMG SW radiation scheme EMs

The convective coverage and storm frequency are different depending on MYNN's radiation scheme, more so than any other PBL scheme (Figs. A.5-A.7). For MYNN-Dudhia, storm frequency is comparable to YSU EMs (Fig. 5.8, 5.9). However, for MYNN-RRTMG, the coverage and count are more similar to that of MYJ EMs. Figure 5.12 shows that all local EMs have more low-level moisture than the nonlocal EMs. Before the SB moves further inland, the region west of Galveston Bay has slightly more moisture in MYNN-RRTMG EMs than MYNN-Dudhia EMs (Fig. 5.12c, f). Also, the MYNN-RRTMG EMs have a stronger  $\theta_e$  increase along the SB than the Dudhia EMs (Fig. 5.13 columns 5, 6). This is because MYNN utilizes the radiation scheme as a



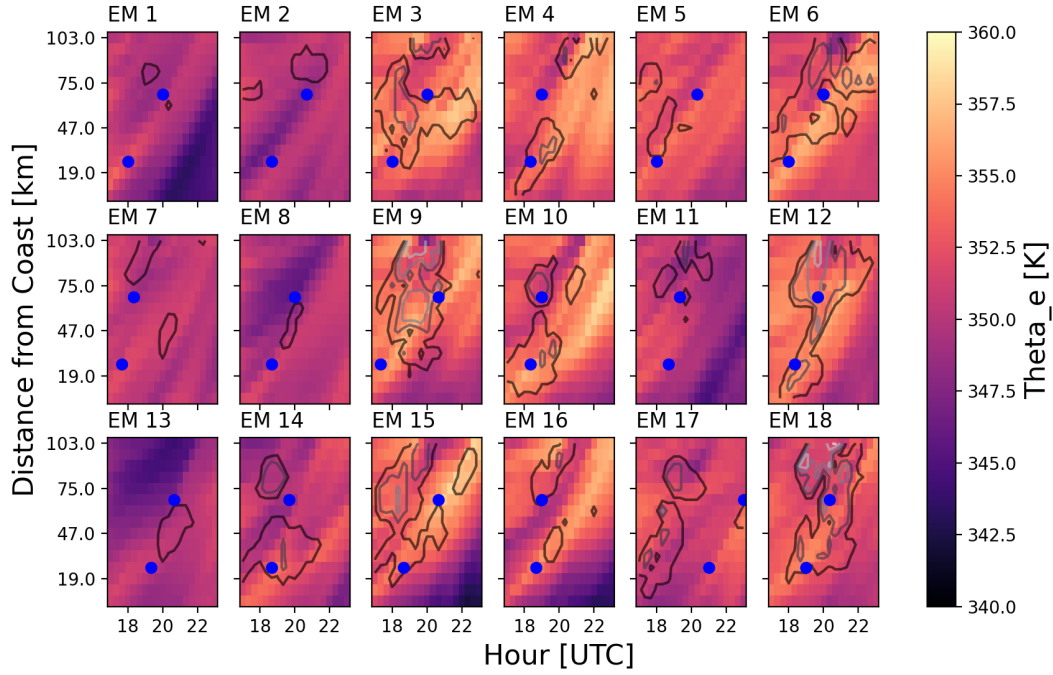


Figure 5.13: Similar to Fig. 5.7, but the shading is  $\theta_e$  (K) on 25 July 2022. The contours represent storm objects

subroutine for cloud water content and more moisture is transferred between layers by RRTMG than Dudhia.

Another major difference across the PBL schemes is the location of convection in relation to the SB. MYJ and MYNN-RRTMG EMs have more widespread convective coverage than observed across the entire forecast period (Fig. 5.8 columns 3, 4, and 6). As discussed in Chapter 3, identifying the regions of enhanced  $\theta_e$  can help deduce regions that are preferential to CI. It is clear that MYJ and MYNN EMs have higher  $\theta_e$  values across time and space, and more so for MYNN-RRTMG than MYNN-Dudhia EMs (Fig. 5.13). Notably,  $\theta_e$  is higher between 1700–1900 UTC across the whole spatial domain for MYJ and MYNN-RRTMG EMs than the others, aligning with the higher frequency of storms in the associated region. For many EMs there is an intensification of  $\theta_e$  along the SBF (Fig. 5.13). However, CI is rarely seen after the SBF has passed a location due to the SB changing the PBLD and LFC. Figure 5.14 shows that early

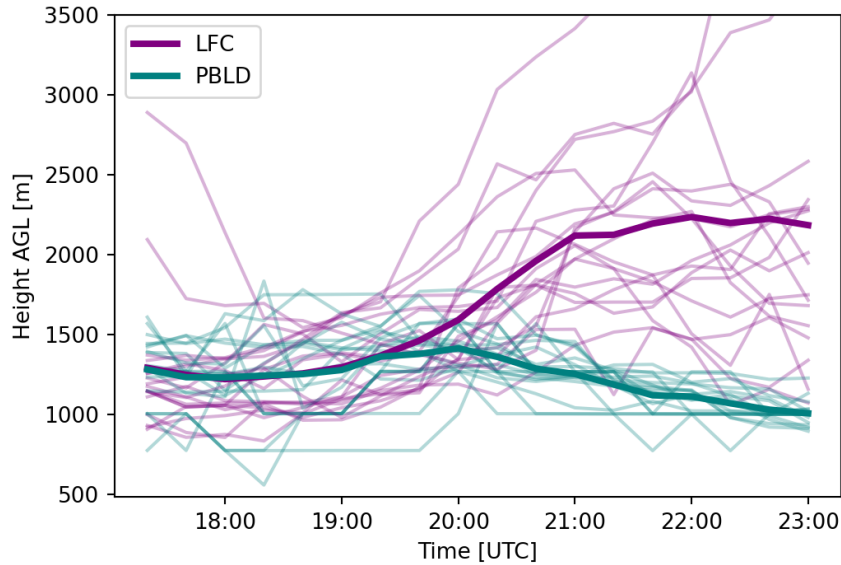


Figure 5.14: LFC height (purple) and PBLD (teal) time series for all EMs on 25 July 2022, with ensemble average in bold

on in the forecast the LFC and PBLD are close to unison, but throughout the day, the LFC increases and the PBLD decreases creating a gap that would require substantial lifting for CI. The PBLD decreases behind the SBF because the PBLD over the water is lower due to weaker TKE. Meanwhile, the LFC increases rapidly because of cooling. In contrast, Boyer et al. (2025) found the lake breeze reduces the LFC, and Sharma et al. (2024) found a negligible change in LFC height from radiosonde observations before and after the SB.

Local mixing schemes are slower to transport moisture vertically which delays the growth of the CBL. In environments that are initially rich in moisture, local EMs can create CBLs with an overestimation of convective instability (CAPE and  $\theta_e$ ) up to 2 h after initialization. This becomes an issue for overproducing convection when the PBLD is deeper than the LFC and there is no CIN to inhibit the updrafts. As a result,

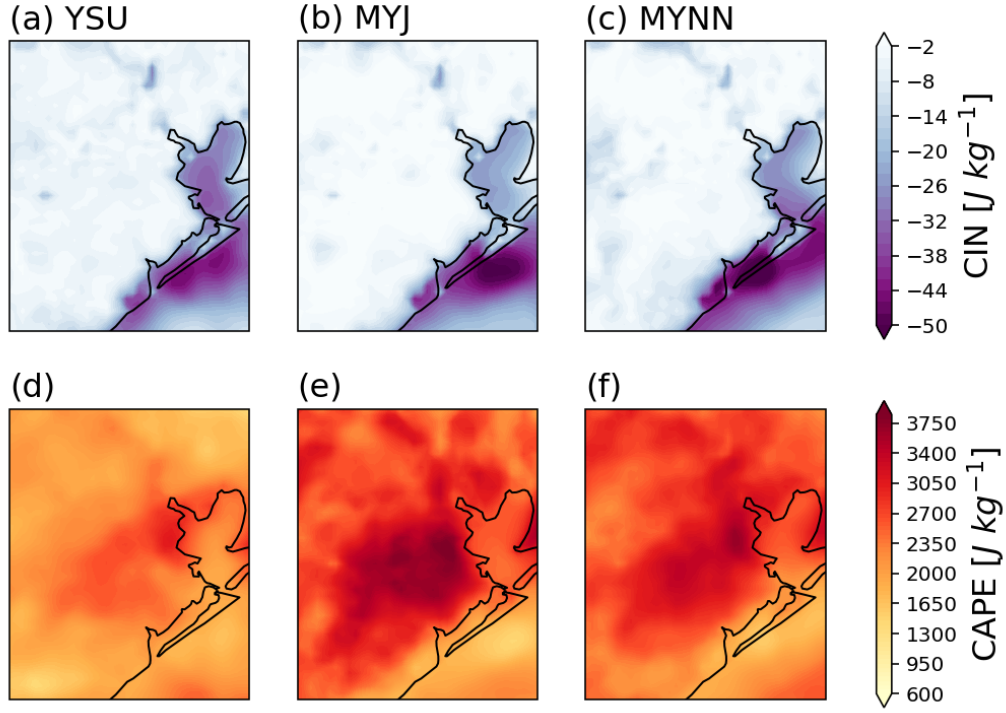


Figure 5.15: Same as Fig. 5.10 but on 13 July 2022

the subtle lifting over land induced by the SB circulation is triggering CI well before the SBF reaches a location.

The following analysis aims to answer why the PBL parameterization's influence on convection characteristics is not as impactful on 13 July. A key difference between 13 and 25 July is the convective potential within the CBL throughout the forecast. Before moving forward, standard deviation testing was performed for 13 July in the same manner from Table 5.1, and all values fall within the same range as Table 5.1 with no marked difference in ensemble spread. Figure 5.15 shows the available CAPE across the region is 1000–1500 J kg<sup>-1</sup> greater than on 25 July with negligible values of CIN. Similar to 25 July, there is a local minimum in CAPE near the Gulf of Mexico coastline that would be advected with the SB. The enhanced instability is consistent during the full forecast, visible through  $\theta_e$  (Fig. 5.16). All EMs have larger  $\theta_e$  values, with the

only decrease in magnitude being connected to convection-driven cooling at the surface (EM09, EM15, EM16). There is also less of a distinct change in  $\theta_e$  along the SBF than on 25 July (Figs. 5.13, 5.16). Even though the SB circulation takes longer to develop, the CBL remains moist and unstable for all EMs (Fig. 5.16). As observations show in Chapter 3, CI is preferential to environments that already have enhanced  $\theta_e$  values prior to SBF-lifting, and the abundance of unstable air across the simulation domain on 13 July allows for CI to happen more readily and is less dependent on forcing from the SB.

As previously mentioned, the EM performance has minimal spread, except for the MYNN-RRTMG EMs (EM06, 12, 18), which have a wide spread in performance depending on the initial conditions (Fig. 5.5). EM06 overestimates the number of simulated storms, while EM12 underestimates, and EM18 is close to unbiased. Figure 5.17 shows the  $\theta_e$  anomaly relative to the ensemble mean for the three EMs with varied performance. Figure 5.17b shows a negative  $\theta_e$  anomaly near the Gulf of Mexico and Galveston Bay shorelines from the advection of lower  $\theta_e$  fluid onshore. As a result, the convective potential decreases in the region and all CI occurs beyond 60 km inland, where the extent of Galveston Bay ends. This region also has much larger LFC/PBLD ratios (Fig. 5.18b). The BB simulation is different in EM12 as it is observable on the north and west sides, while the EM06 and EM18 only have the northerly portion (Fig. 5.17). Without the reduction in  $\theta_e$ , EM06 and EM18 produce cells earlier that last longer (Fig. 5.7). The difference between EM06 and EM18 is subtle, but EM18 has more area of high LFC/PBLD ratio than EM06 (Fig. 5.18). The pockets of large LFC/PBLD ratio in the northwest corner of EM06 are caused by ongoing convection (Fig. 5.7, 5.18a). The higher LFC heights with comparable PBLD for EM18 compared to EM06 delay the start of CI until the SB passage. As for EM12, the BB strongly

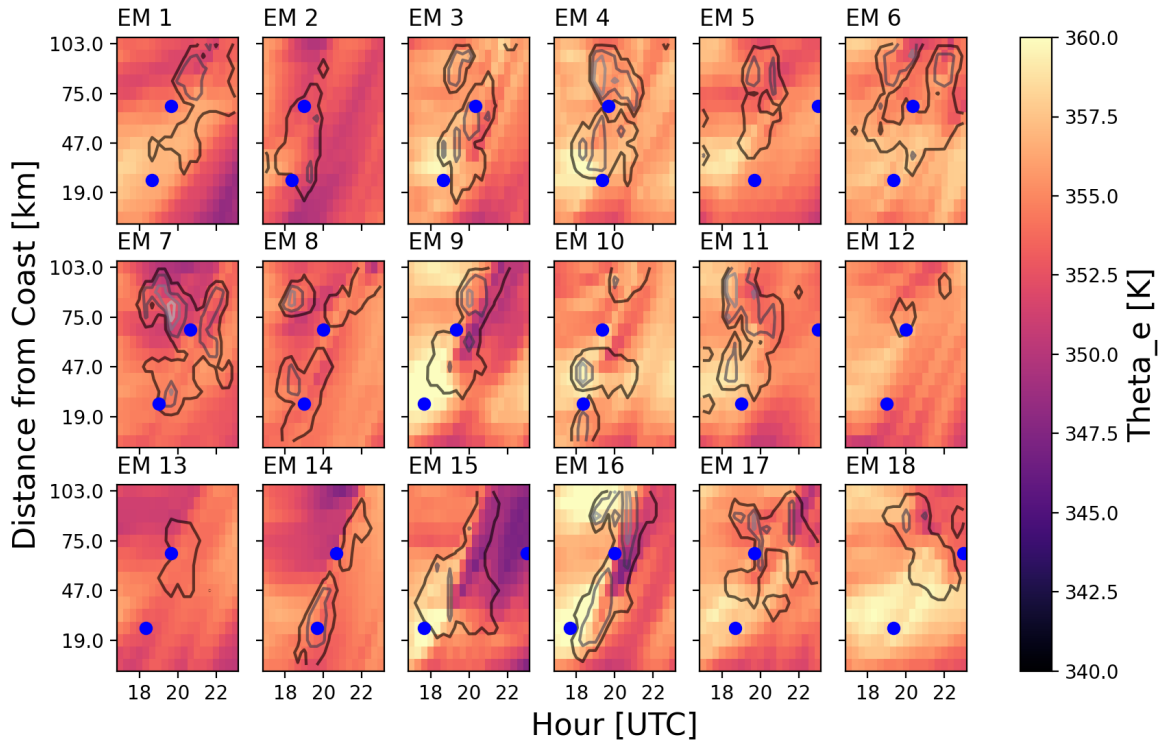


Figure 5.16: Same as Fig. 5.13 but on 13 July 2022

impacts the convective environment near the coast by reducing convective instability by cooling the surface. As discussed in Chapter 4, the local EMs are more sensitive to the initial conditions when it comes to simulating the BB.

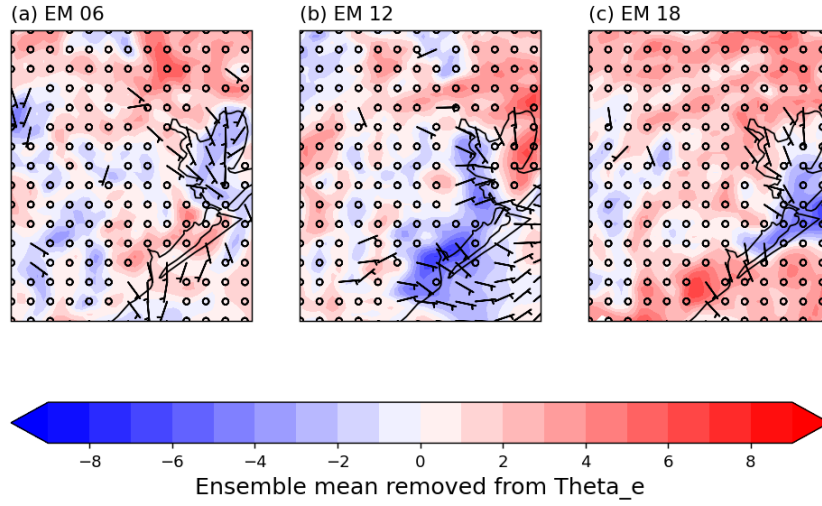


Figure 5.17: 1700–1800 UTC composite of  $\theta_e$  with the ensemble average  $\theta_e$  field removed from with 10-m wind barbs for (a) EM06, (b) EM12, and (c) EM18 on 13 July 2022

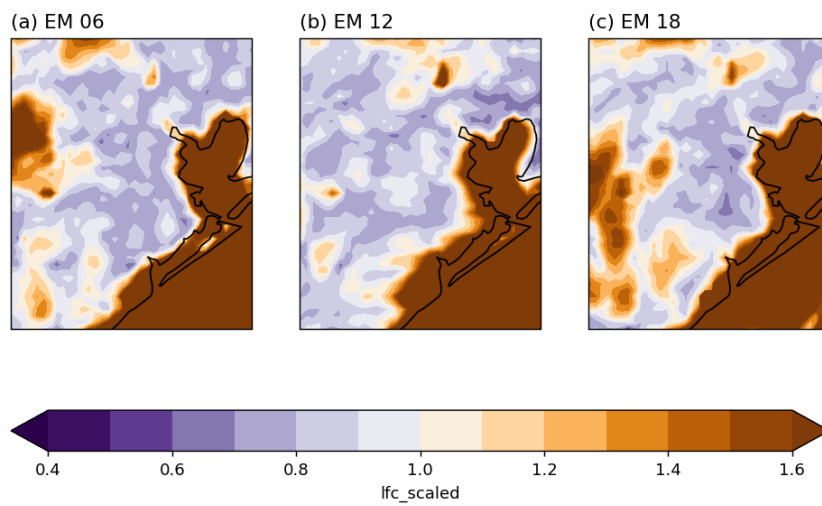


Figure 5.18: 1700–1800 UTC composite of the LFC/PBLD ratio for (a) EM06, (b) EM12, and (c) EM18 on 13 July 2022

## 5.4 Drivers of CI

Pivoting back to 25 July, a vertical cross-section is shown in Fig. 5.19 to investigate the structure of the SB and its interactions with the existing CBL from the coastline to Houston. Four EMs were selected to highlight the range of forecast performance. EM08 has the highest success ratio with an underestimation of storm objects. The converse is EM09 with the highest probability of detection and an overestimation of storm objects. EM11 and EM14 have similar critical success indices but EM11 is unbiased in storm frequency. These EMs span all PBL schemes with EM08 and EM14 using YSU, EM09 using MYJ, and EM11 using MYNN.

The time (1830 UTC) allows the SB to propagate onshore with some EMs initiating CI (EM09 and EM14) in the vicinity of the vertical cross-section, while the others have CI shortly after (Fig. 5.8). Figure 5.19 shows the SB manifests differently across the EMs, but there are some similarities based on the PBL mixing type. EM08 and EM14 have more distinct thermodynamic responses aligning with flow acceleration at 38 km and 28 km, respectively (Fig. 5.19a, d). The faster vertical mixing in the CBL for nonlocal EMs causes a more defined SB response with an increase in moisture and a decrease in temperature. The SB in EM09 and EM11 is harder to distinguish as the onshore flow is stronger and moisture is more consistent through the cross section (Fig. 5.19b, c). Evaluating the changes to the vertical motion and PBLD adds some insight into the location of the SB for EM09 and EM11 (Fig. 5.20b, c). In EM09, a subtle updraft and decrease in PBLD at 38 km inland aligns with the accelerated flow, but there is a decrease in moisture behind the SBF (Figs. 5.19b, 5.20b). For EM11 the decline in PBLD and increase in southerly wind component indicates the SBF near 28 km inland (Fig. 5.19c, 5.20c). The SBs produced in EM09 and EM11 advect less



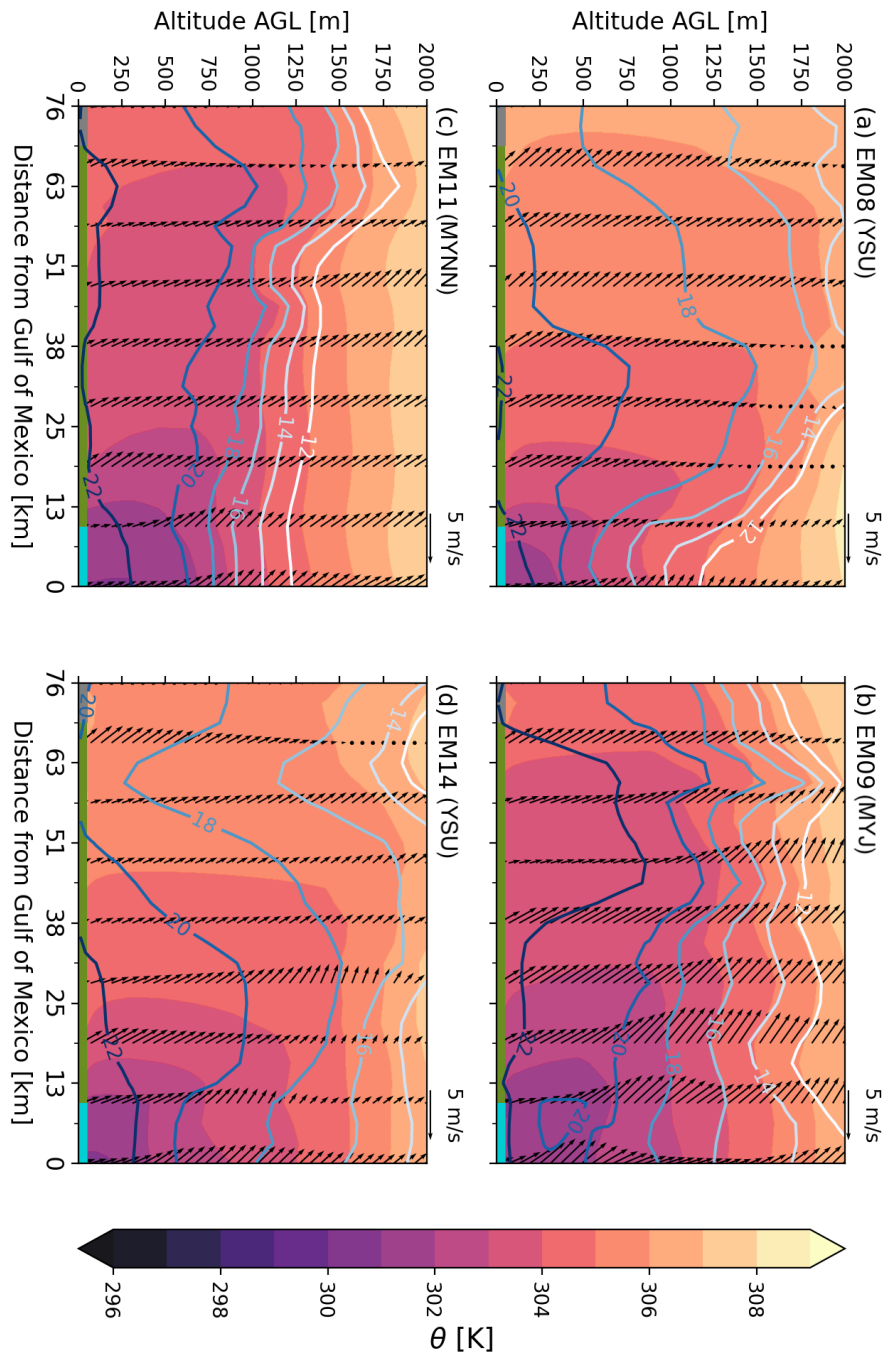


Figure 5.19: Vertical cross-section valid 1830 UTC 25 July 2022 of potential temperature (shaded, K) with water vapor mixing ratio (contours,  $\text{g kg}^{-1}$ ), and horizontal wind vectors. The location of the cross-section is indicated by the orange line in Fig. 5.3. (a) is EM08, (b) is EM09, (c) is EM11, and (d) is EM14

moisture and  $\theta_e$  than is already in the CBL, while the contrary is true for EM08 and EM14.

There are a variety of theories on how lifting caused by the SB triggers CI; Fovell (2005) theorized that KH waves collide with horizontal convective rolls ahead of the SB provide enough lift to trigger CI, while Fu et al. (2021) claim only the SBF provides enough lift and moisture for CI. EM08 and EM14 have the strongest lifting around the SBF. Even though EM08 and EM14 have similar SB characteristics, EM14 has more storms simulated because the updraft along the SBF transports  $\theta_e$ -rich air beyond the LFC. Unlike most EMs, EM14 has sustained convection in the SB inflow layer, because it does not have a sudden increase in LFC (Fig. 5.20d). EM08 has a similar increase in  $\theta_e$  but it is not as deep and does not penetrate the LFC (Fig. 5.20a), causing delayed CI that is smaller than cells in EM14.

EM11 has the weakest lifting with no clear maximum in the vertical cross-section (Fig. 5.20c). EM09 has weak vertical motion similar to EM11, but the LFC is low enough for moist and unstable parcels to reach it without additional lifting (Fig. 5.20b). Since the airmass inland is so rich in moist static instability and the LFC lies below the PBLD, CI is easily attainable without additional lifting (Fig. 5.20b). This enhanced  $\theta_e$  air inland is similar in EM11 but with a slightly higher LFC than the depth of elevated  $\theta_e$  (Fig. 5.20c). As a result, convection in EM11 is all further inland than 50 km, likely influenced by enhanced vertical motion over the urban Houston land surface (Fig. 5.8).

In terms of the distribution of  $\theta_e$  and convective coverage, the EMs on 13 July resemble the MYJ EMs from 25 July (Figs. 5.13, 5.16). Even though the LFC/PBLD ratio is not as low as the 25 July MYJ EMs (Fig. 5.18), all EMs tend to produce storms ahead of the SBF. The vertical cross-section analysis is similarly performed for 13 July, but due to the increased convective coverage in EM08 and EM09, there are more storm

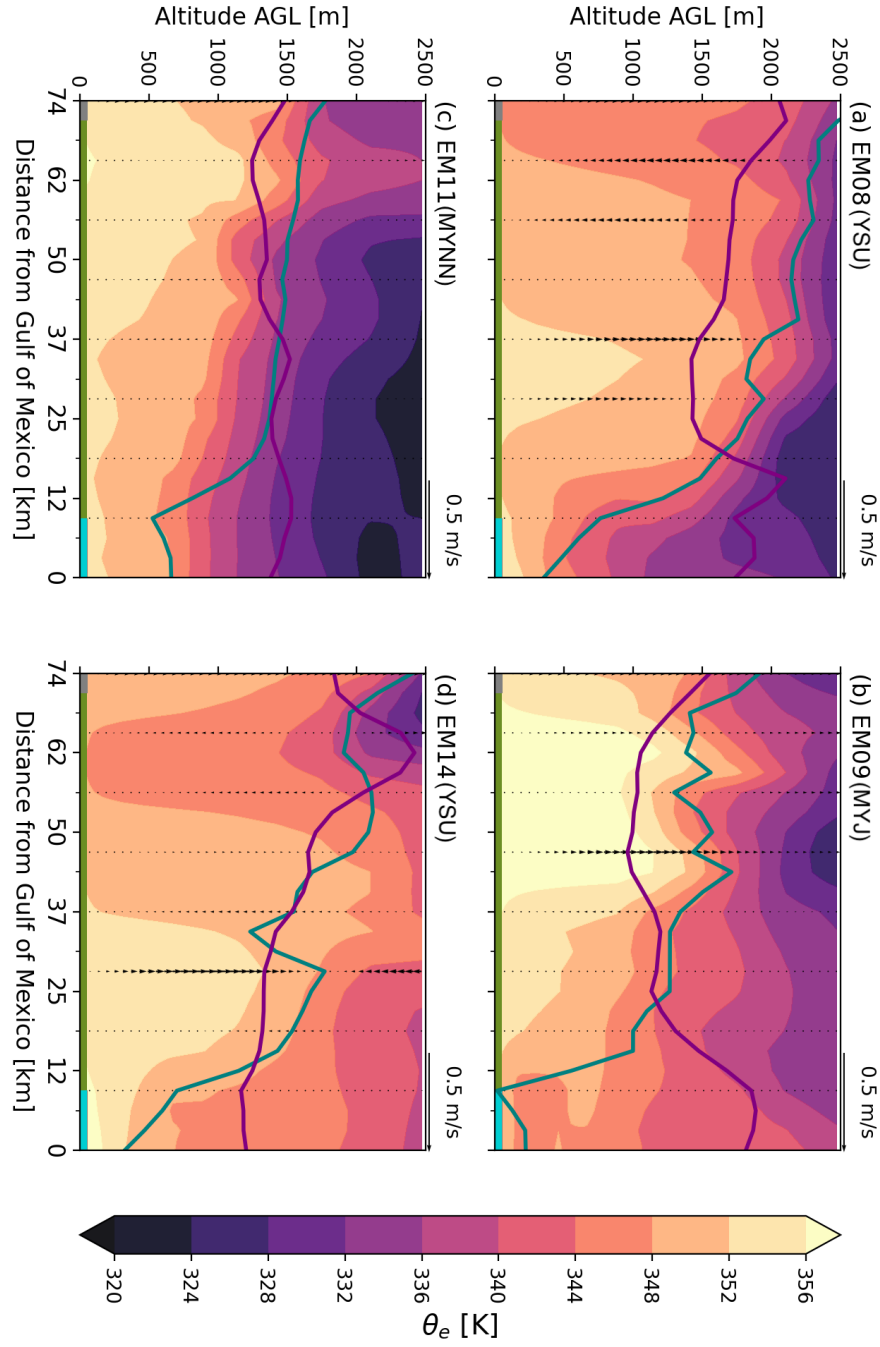


Figure 5.20: Same time and location as Fig. 5.19 but with  $\theta_e$  (shaded, K) and wind vectors represent the vertical motion. The teal line is the PBLD and purple line is the LFC height

artifacts in the PBLD (Fig. 5.21a, b). Similar to Fig. 5.20b, the largest  $\theta_e$  values on 13 July are far inland, ahead of the SBF. Vertical motion is weak for EM09 and EM11

and ahead of the SBF, but for EM09 the strongest updraft is along the SBF, similar to on July 25. All EMs besides EM08 have primarily deeper PBLDs than LFCs, except where convective influence has largely reduced the PBLD (Fig. 5.21). The LFC for EM14 is the only one deeper than the vertical extent of elevated  $\theta_e$  and as a result, has CI along the SBF (Figs. 5.7, 5.21d). The environment across these EMs on 13 July is most similar to EM09 on 25 July, and this results in an overzealous simulation of convection across all EMs. The lifting along the SBF is even less important to CI than on 25 July because the airmass ahead of the SB is already unstable.

In some ways, the frequency of simulated convection is more dependent on the CBL than the SB. The enhanced  $\theta_e$  inland allows for CI to occur before the SBF-forced updraft in EM09 and EM11 on 25 July and EM08, EM09, and EM11 on 13 July. In line with findings from Chapter 4, the enhanced inland CI is likely because local EMs transport moisture throughout the PBL too slowly, which leads to an overestimation of moisture and  $\theta_e$  after initialization. When this is coupled with low LFC/PBLD fractions across the domain, the environment is primed for CI even without lifting from the SB. The CBL updrafts in EM14 align with the forcing along the SBF to create a broad region of ascent, but since the highest  $\theta_e$  is within the SB inflow layer, CI is contained relatively close to the SBF, contributing to its high critical success index on 25 July (Fig. 5.20d). Even though the LFC is much lower than the PBLD for EM08 it takes the SBF updraft to transport the moist unstable air to the LFC, leading to fewer storm objects with no false alarms, but also an underestimation of object frequency. While this work only investigated the influence of an SB on CI, there are similarities across other surface-driven convection like along drylines or frontal boundaries (Trier et al. 2015; Hanft and Houston 2018).

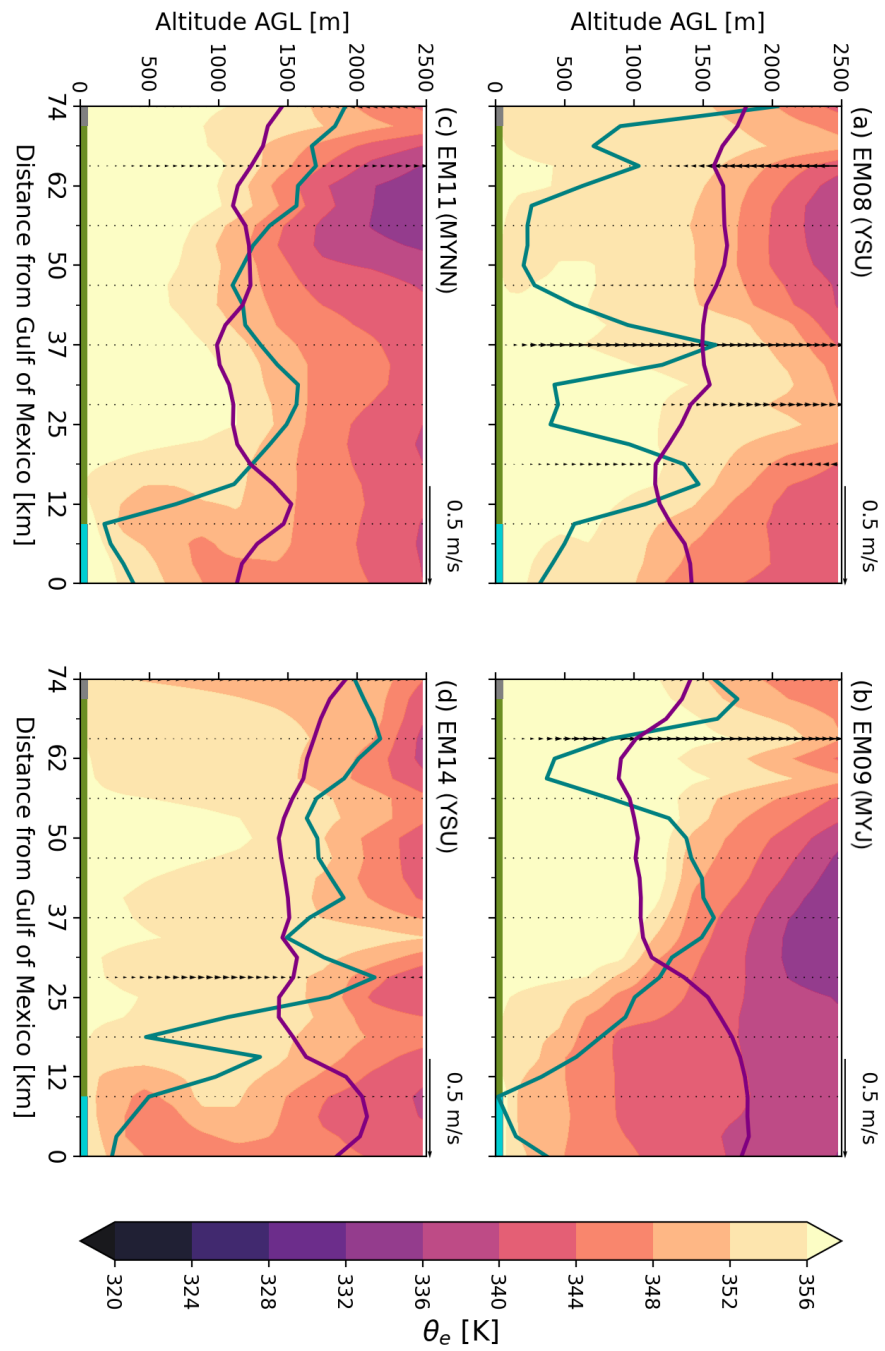


Figure 5.21: Same as Fig. 5.20 but for 13 July 2022

## Chapter 6

### Summary and Conclusions

#### 6.1 Discussion

The TRACER-UAS dataset provides a uniquely high-resolution look at the ABL's vertical structure. However, with all observational research, there are some limitations to the study. Due to a conflicted airspace with multiple airways, the flight ceiling was limited to 609 m and the entire SB circulation was rarely observed by the CopterSonde. Thus, we lack information about the evolution of the depth of the marine inflow layer. This creates a challenge to understand the SB influence on thermodynamic stability using the thermal lapse rate and traditional convective indices. Without a complete profile of the ABL, it is still safe to assume the SB inflow layer is shallower than the ABL depth (Chiba et al. 1999; Medeiros et al. 2021; Reddy et al. 2020), such that  $\theta_e$  is only altered in the SB inflow layer. It is confirmed by radiosonde observations in Fig. 3.8 that  $\theta_e$  is not significantly altered above the SB inflow layer, similar to Soderholm et al. (2017). Thus, an increase in low-level  $\theta_e$  would cause  $d\theta_e/dz$  to become more unstable compared to the well-mixed values in the non-SB ABL. Most convective cells are initiated before or along the SBF, suggesting that the frontal lift of initially unstable air provides enough rising motion for successful CI. Within this dataset, there were no instances of CI at the sampling sites after the SBF had propagated inland, even though  $\theta_e$  increased.

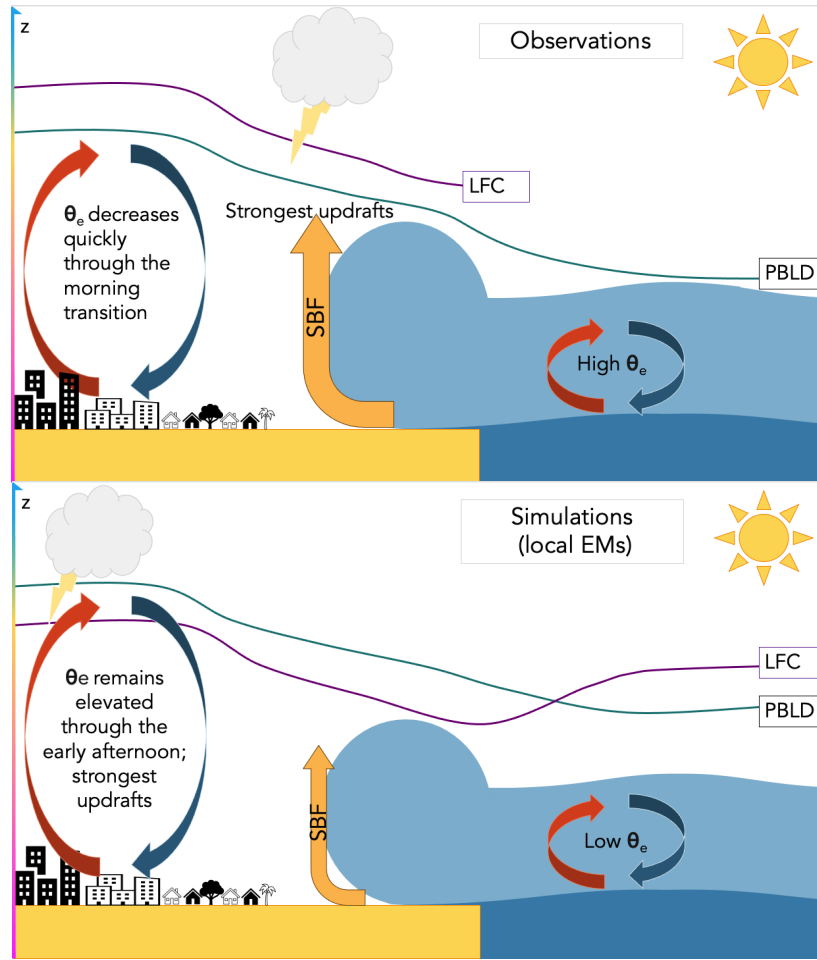


Figure 6.1: Conceptual drawing of the differences between the SB interactions with the ABL in (top) observations and (bottom) local EM simulations

It is hypothesized that decreased vertical motion within the SB inflow layer mechanically caps the  $\theta_e$  rich airmass from reaching the LFC. This theory was further investigated using NWP simulations, but the differences between observed and simulated SBs cause inherent issues. Because simulated SBs have more cooling and slower moistening rates than observations (Figs. 4.3, 4.4), the response in  $\theta_e$  is much weaker (Fig. 5.13). As a result, the SBF is no longer the optimal region for CI, except for YSU EMs. YSU EMs develop the CBL rapidly which mixes the low-level moisture and decreases  $\theta_e$  shortly after initialization, thus delaying surface-based CI until the SB

propagates inland (Figs. 4.7, 4.9). For local EMs (MYJ and MYNN) the CBL environment often had larger surface values of  $\theta_e$  than the SB inflow layer which led to frequent CI prior to the SB passage (Fig 5.20). With the CBL being more convectively unstable than the SB airmass, the region of preferential CI is ahead of the SB. Figure 6.1 illustrates the differences in observation (top) patterns and local EM simulations (bottom). YSU EMs behave similarly to observations. For observations, the region of maximum updraft along the SBF was determined by composites of vertical velocity observations from Doppler lidar in Wang et al. (2024), and LFC height increasing inland was determined using radiosondes released at multiple distances from the coastline from Sharma et al. (2024).

In addition to the region of most unstable air, the LFC/PBLD ratio causes some EMs to have broader areas that are primed for CI. The MYJ EM's LFC/PBLD ratio was much lower than other EMs, readily allowing cells to initiate across the domain without additional lifting from the SBF (Fig. 5.11). This makes the environment overly conducive to CI before the SB. The YSU EMs are less prone to erroneous convection and most CI occurs within 10 km of the SBF because the destabilization is localized to the SBF, seen by the enhancement of  $\theta_e$  and CAPE immediately following the SB (Fig. 5.13, 5.20a, d). In observations, the LFC is higher than the PBLD throughout the early and late afternoon by 300–400 m (Sharma et al. 2024). Part of the problem stems from the overestimation of PBLD for all EMs (Fig. 4.9). Behind the SB, the inflow layer causes a decline in the PBLD, which reduces the potential for surface-based parcels to reach the LFC (Fig. 5.14).

The increase in LFC height in response to the SB disagrees with findings in Boyer et al. (2025) for the LES of a lake breeze driving CI. Similar to observations, the lake breeze advects elevated  $\theta_e$  and reduces the LFC. The model used in Boyer et al. (2025) has 100 m horizontal grid spacing and 50 m vertical spacing that resolves the vertical



transport and heterogeneity of the lake breeze better than the WoFS model resolution. This is to say, that these observed  $\theta_e$  impacts can be simulated, but require finer model resolution.

## 6.2 Conclusions

Coastal breezes around the Houston area have a large impact on weather and air quality forecasts. The interactions between the PBL and coastal breezes occur on rapid timescales and induce vertical gradients that impact pollutant trapping and convection initiation. For these reasons, it is important to simulate such processes accurately in NWP models. To improve simulations, it is critical to understand the dynamic forcing that drives the ABL evolution, and how well parameterizations can replicate these in NWP models. Operationally, observations within the ABL are insufficient to resolve these processes, but the recent TRACER field campaign gathered a dense ABL dataset to explicate the dynamic interactions.

Observations from UAS were gathered throughout the TRACER-UAS campaign near the Gulf of Mexico coastline south of Houston, TX, from June to September 2022. The location of the TRACER campaign was chosen for its interactions between urban, coastal, and industrial influence. One of the goals of TRACER-UAS was to supplement the broader TRACER campaign with a vast dataset of low-level observations to capture ABL interactions with the SB and its impact on the convective cloud lifecycle. The CopterSonde UAS provides 5 m vertical resolution profiles of thermodynamic variables and 2D winds with 15–30 min resolution during the day. These observations composed a novel dataset of high temporal and vertically resolved, in-situ observations in a coastal environment over four months.

Measurements from the CopterSonde showed a range of ABL responses to coastal influences, primarily by the BB and SB on temperature and water vapor mixing ratio. Using rate of change, instantaneous alterations to the ABL could be quantified and statistically compared as a function of the SBF passage time (Fig. 3.6). The range of observed SB impacts is far broader than described in past literature, which often used observations with coarser spatiotemporal resolution. The BB can advect appreciable moisture but has a weaker influence on temperature due to the warm bay surface temperatures (Table 3.1). The SB intensity is highly variable regarding changes in temperature and moisture with frequent outliers. A two-sample Z-test was used to compare the factors influencing SB and BB intensity. Results indicate that SB intensity is dependent on SBF passage time with respect to sunset time and influence from Galveston Bay (Table 3.2). Moreover, the evolution of the moist energy in the form of  $\theta_e$  was examined and found a tendency for  $\theta_e$  to increase post-SB for 2-3 h (Fig. 3.9). Days when the SB moves into an environment with already elevated or increasing  $\theta_e$ , lead to successful CI (Fig. 3.10). The increase in  $\theta_e$  is sustained without convection, but that is not enough to trigger CI above the marine layer.

The number of small-scale influences observed by the CopterSonde motivated the work on verifying the simulation of the PBL interactions with the SB. Parameterizations have a large impact on forecast success since they represent the subgrid processes that are most often driving CI. The PBL and SW radiation parameterizations were evaluated since the SB relies on the establishment of a density gradient that develops through differential surface heat fluxes. Traditionally, verification of NWP in the PBL is done with surface observations or radiosondes which lack the necessary resolution with height and time, respectively. Thus utilizing a novel dataset, like CopterSonde UAS observations, can provide more context on biases in the surface and mixed layer.

It was found that many of the state variable’s mean biases can differ in sign and magnitude from the surface to the mixed layer, particularly the wind vector (Figs. 4.5-4.8). While the SB is fairly well represented in timing and magnitude, the BB is often too weak to propagate as far inland as observed (Fig. 4.3). Because the BB circulation is more weakly forced, it is sensitive to surface temperature over land and the rate of vertical heat transport. For this reason, the nonlocal mixing PBL scheme (YSU) had more success at simulating the BB than local schemes. The radiation scheme also plays a large role in BB formation in local schemes. For instance, Dudhia EMs tend to have higher cloud fractions over land, leading to lower surface temperatures that inhibit BB propagation inland (Fig. 4.12).

Although this is a single case, it holds value in understanding how parameterization combinations vary and how those differences can influence air quality or weather forecasts. The SW radiation scheme is important for local schemes as they are slower to adjust the PBL. Across all PBL schemes, the RRTMG scheme EMs have better SB timing and larger land-bay temperature gradients. The YSU EMs have the best kinematic representation of the PBL but are too warm and dry, consistent with previous literature (Hu et al. 2010; Milovac et al. 2016). For Houston-Galveston air-quality research, it is important to simulate the BB, for which YSU EMs have the most success. However, they produce the deepest PBLs, which dilutes pollutants. There is no perfect parameterization combination, but configurations can be optimized based on simulation priorities. As observations continue to advance, so can the way parameterizations are evaluated and tuned. In addition to data assimilation, these observations can work with NWP to gain reciprocal insights into dynamical processes and model shortcomings.

In continuing the research on how parameterizations influence the simulation of SBs, the consequential effects on CI are evaluated. Through two case analyses, the

performance of simulating storms in the WoFS model is compared against MRMS reflectivity using object-based identification and verification. The 25 July case shows a strong performance dependence on the PBL parameterization, with an overproduction of storm objects by local EMs, especially MYJ, and an underestimation by YSU EMs. This is caused by thermodynamic factors and variable mixing lengths. Local EMs have the largest  $\theta_e$  values in the CBL ahead of the SB, while YSU EMs have greater  $\theta_e$  values within the SB inflow layer. (Figs. 5.13, 5.20). The LFC/PBLD ratio for MYJ is much lower than the other schemes, allowing parcels to easily reach free convection without additional forcing (Fig. 5.11). As a result, the regional preference for CI with local EMs is ahead of the SB, and for nonlocal EMs CI tends to stay close to the SBF (Fig. 5.8). For 13 July, the spread in performance is more narrow across EMs, with a tendency to overestimate the number of cells. While the PBL schemes have similar differences as on 25 July, the convective instability in the CBL is significantly higher for all EMs than on 13 July (Figs. 5.15, 5.16). Thus, these results suggest that CI and convective evolution are more dependent on the initialization of the CBL than the simulation of the SB characteristics. Future work should evaluate the sensitivity of CI to the initial conditions and the lag correlation of  $\theta_e$  anomalies to CI. Additionally, an observational analysis of the LFC/PBLD ratio evolution in pre-convective environments would provide context to mitigating its underestimation.

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# 1 Appendix A

Table A.1: TRACER-UAS CopterSonde dataset description including SB and BB passage times. Convection time refers to the period with ongoing convection  $> 30$  dBZ within 35 km of the profiling site based on KHGX radar base reflectivity. All times are in UTC. For reference, average sunset time was at 0045 UTC and sunrise at 1145 UTC from June-September.

| Date  | Location | # of Flights | SBF Time     | BBF Time | Convection Time | Operation Time |
|-------|----------|--------------|--------------|----------|-----------------|----------------|
| 13/06 | UHCC     | 17           |              |          |                 | 1400-2200      |
| 15/06 | UHCC     | 16           |              |          |                 | 1430-2200      |
| 16/06 | UHCC     | 18           | 2030         | 1730     |                 | 1500-2230      |
| 17/06 | UHCC     | 18           | 1945         | 1830     |                 | 1500-2230      |
| 19/06 | UHCC     | 10           | 2115         |          |                 | 2000-0000      |
| 20/06 | UHCC     | 19           |              |          |                 | 1400-2130      |
| 21/06 | BRZ      | 18           | 1730         |          |                 | 1500-2230      |
| 22/06 | BRZ      | 18           | 1917         |          | 1730-2000       | 1500-2230      |
| 23/06 | BRZ      | 18           | 1830         |          |                 | 1400-2130      |
| 11/07 | BRZ      | 16           | 2100         |          |                 | 1600-2300      |
| 12/07 | BRZ      | 14           | 1930         |          | 1900-2100       | 1700-0030      |
| 13/07 | BRZ      | 17           | 1830         |          | 1930-2100       | 1730-0030      |
| 16/07 | BRZ      | 18           | 1930         |          | 1630-1900       | 1600-2330      |
| 17/07 | BRZ      | 20           | 1930         |          |                 | 1600-2300      |
| 18/07 | BRZ      | 16           | 1830         |          |                 | 1500-2230      |
| 20/07 | BRZ      | 20           |              |          |                 | 1500-2230      |
| 22/08 | UHCC     | 15           |              |          | 1500-2000       | 1430-2200      |
| 23/08 | UHCC     | 12           |              |          |                 | 1500-2130      |
| 25/08 | BRZ      | 16           |              |          | 1630-2045       | 1500-2100      |
| 26/08 | BRZ      | 16           | 1730         |          | 1730-2100       | 1500-2230      |
| 27/08 | BRZ      | 15           |              |          | 1400-2130       | 1400-2130      |
| 28/08 | BRZ      | 17           |              |          |                 | 1400-2000      |
| 30/08 | UHCC     | 17           |              |          |                 | 1500-2200      |
| 31/08 | UHCC     | 12           |              |          |                 | 1500-2000      |
| 14/09 | UHCC     | 19           | 2115         | 1930     |                 | 1500-2230      |
| 15/09 | UHCC     | 16           |              |          | 1900-2200       | 1430-2200      |
| 16/09 | UHCC     | 15           |              |          | 1530-2030       | 1400-2200      |
| 18/09 | UHCC     | 20           | 2000         | 1730     | 1915-2030       | 1400-2130      |
| 19/09 | UHCC     | 12           |              |          |                 | 1400-1930      |
| 20/09 | UHCC     | 16           |              |          |                 | 1400-2130      |
| 21/09 | UHCC     | 20           |              |          |                 | 1400-2130      |
| 22/09 | UHCC     | 22           | 0007 (23/09) |          |                 | 1600-0030      |
| 24/09 | UHCC     | 13           | 2130         |          |                 | 1900-2300      |



## 2 Appendix B

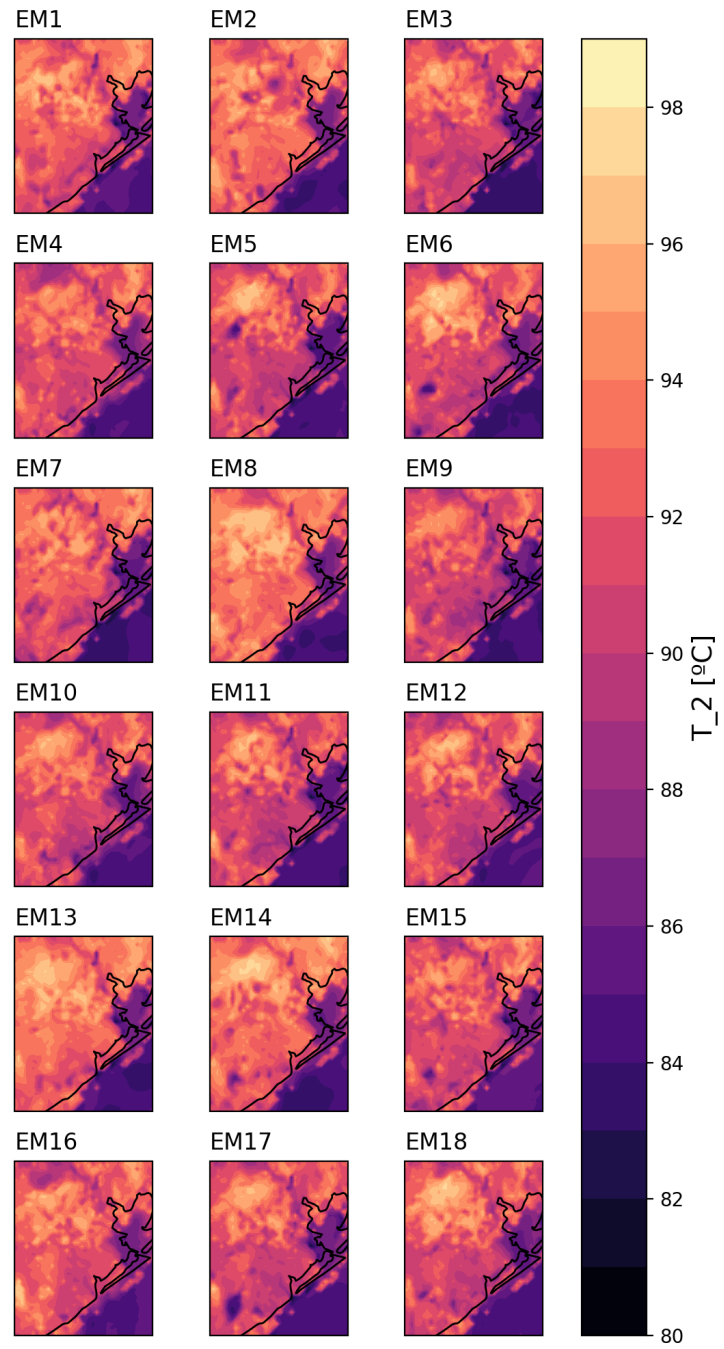


Figure A.1: Temperature (°F) at 1700 UTC on 25 July 2022 across all EMs

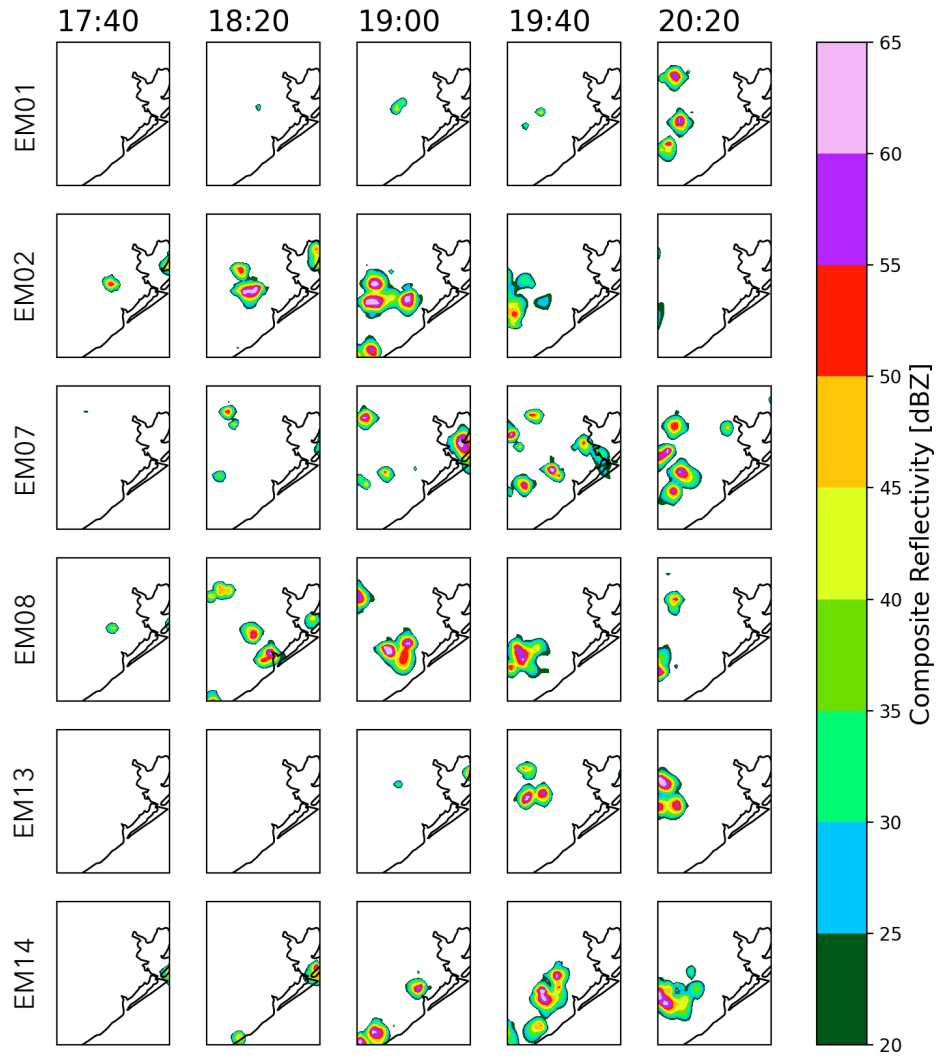


Figure A.2: WoFS simulated composite reflectivity (dBZ) on 13 July 2022 with each column representing a valid time (UTC) and each row is an ensemble member (EM). The EMs all use the YSU PBL parameterization

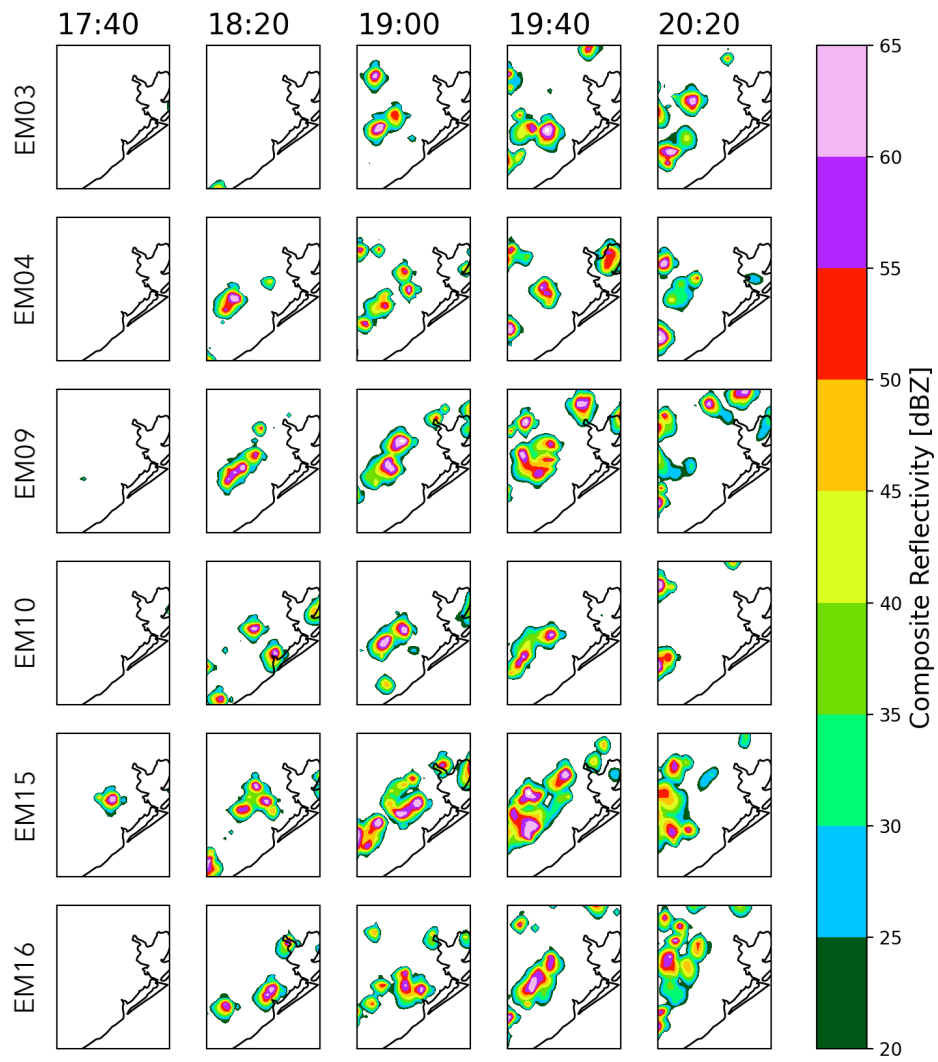


Figure A.3: Same as Fig. A.2 but for MYJ EMs

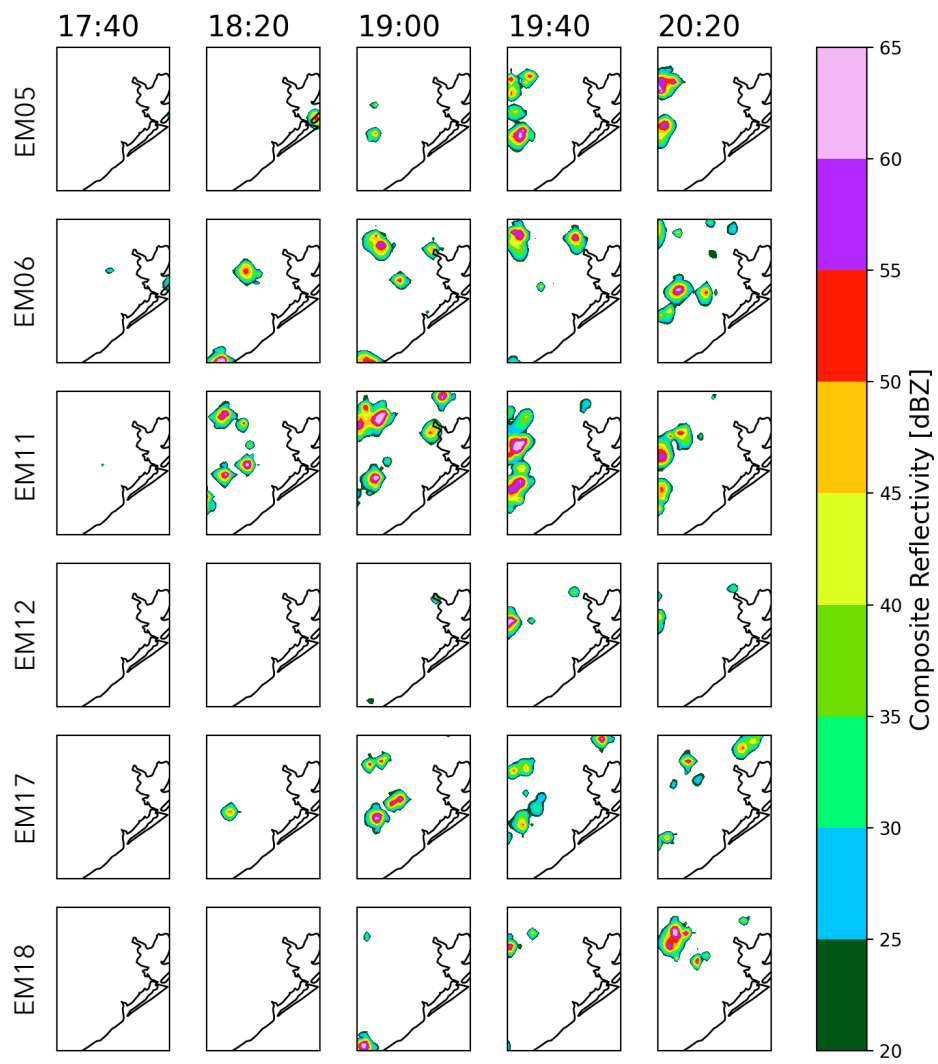


Figure A.4: Same as Fig. A.2 but for MYNN EMs

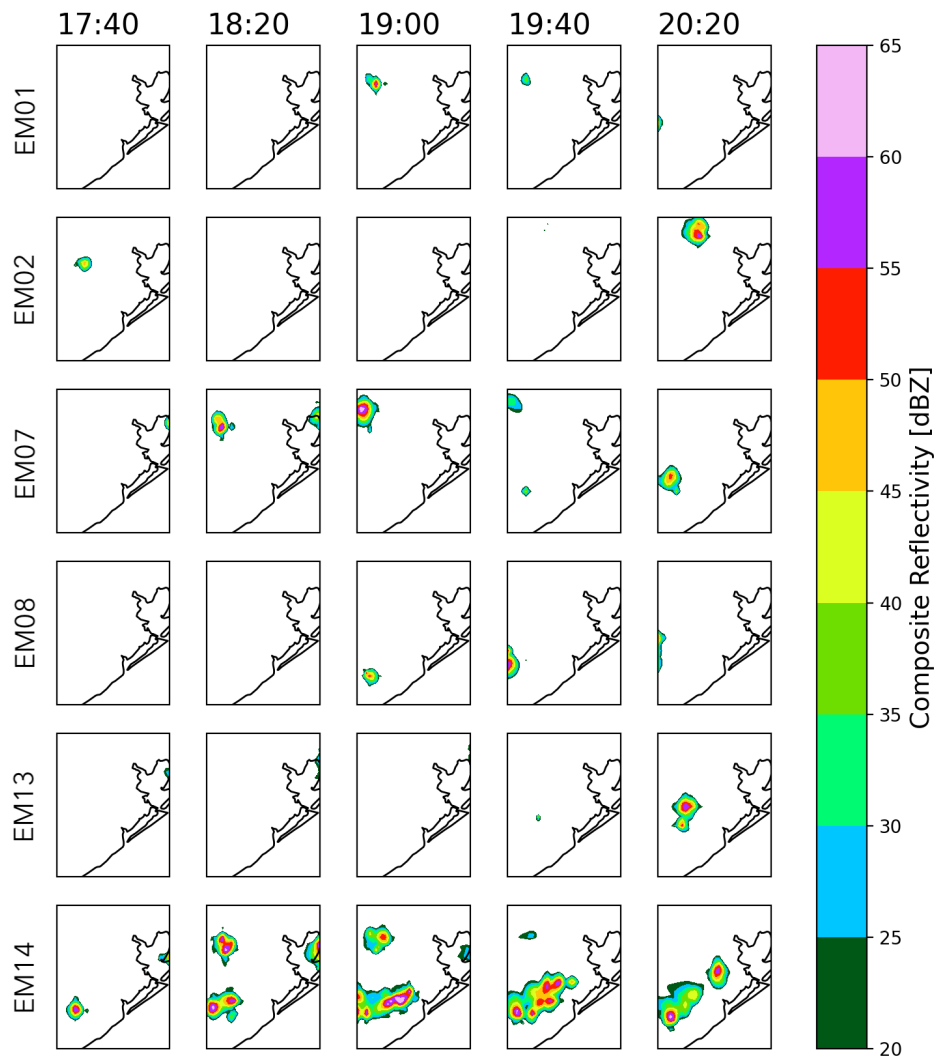


Figure A.5: Same as Fig. A.2 but on 25 July 2022

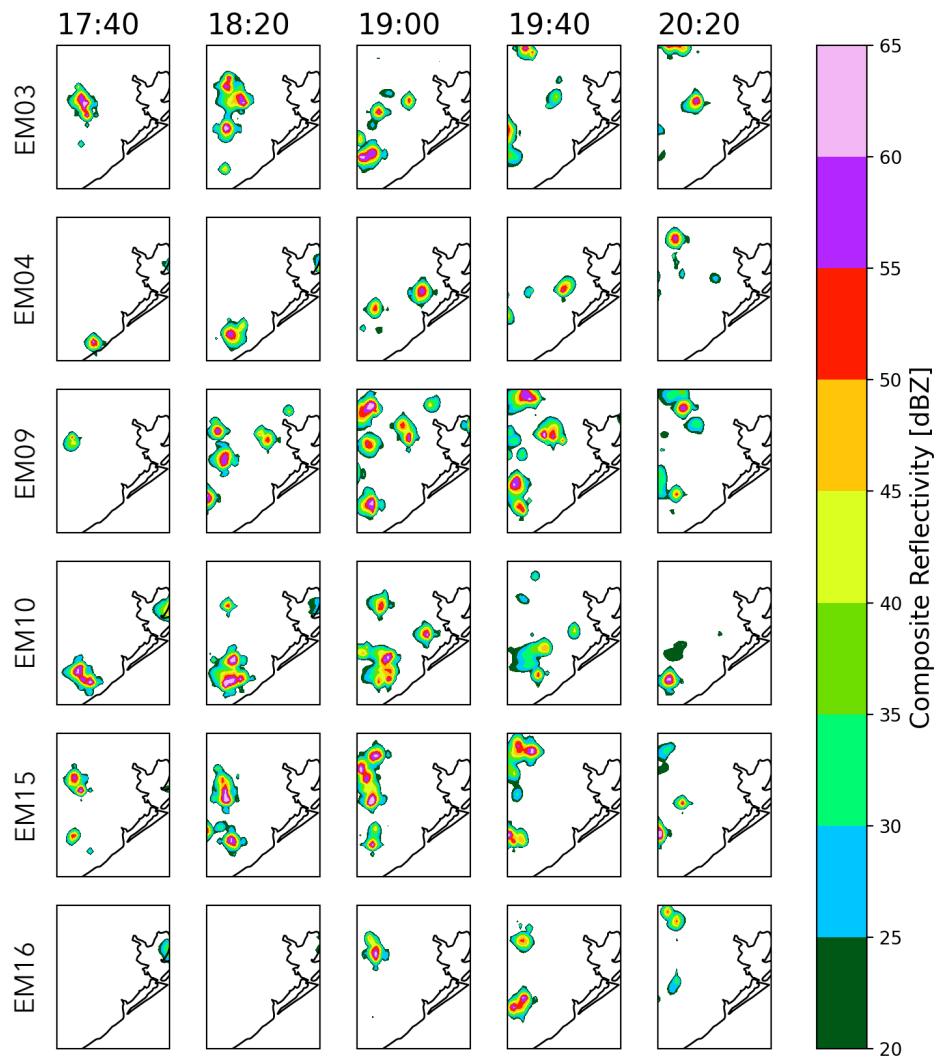


Figure A.6: Same as Fig. A.5 but for MYJ EMs

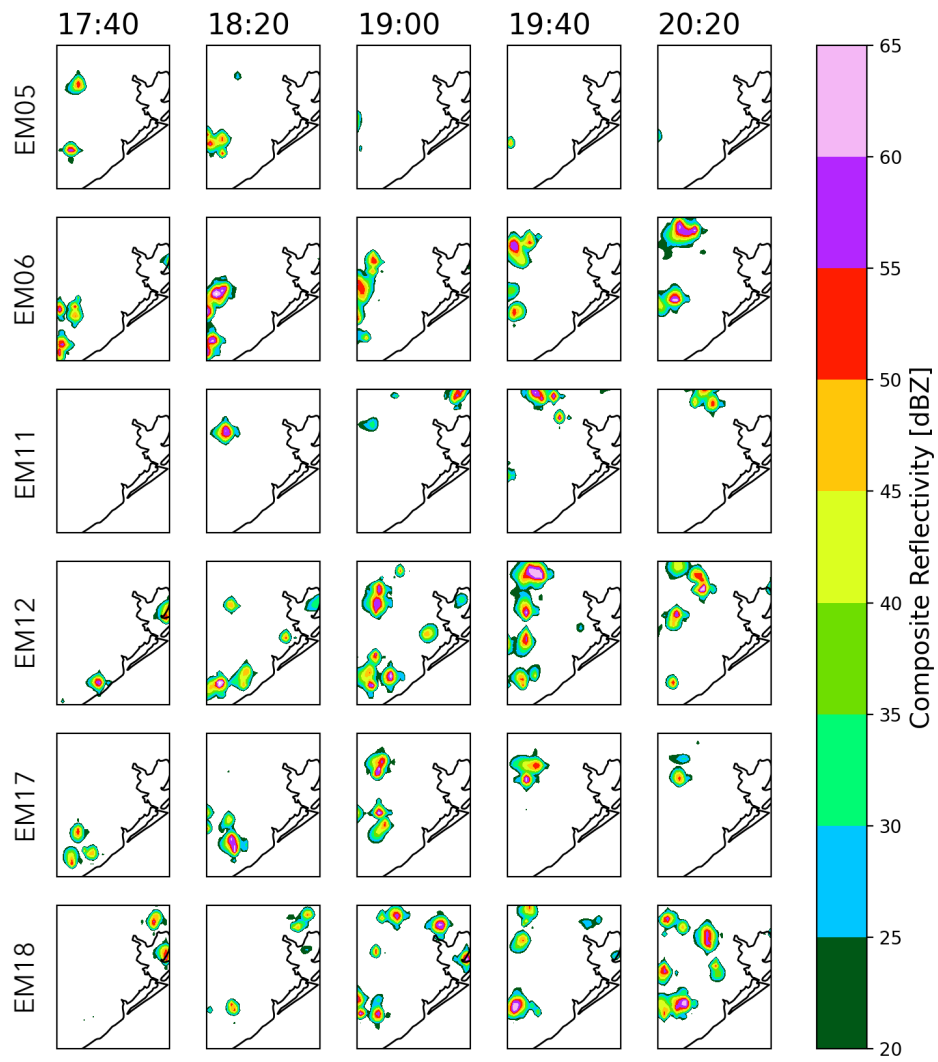


Figure A.7: Same as Fig. A.5 but for MYNN EMs