

Implications of Sea Breeze Circulations on Boundary Layer Aerosols in the Southern Coastal Texas Region

Tamanna Subba¹, Michael P. Jensen¹, Min Deng¹, Scott E. Giangrande¹, Mark C. Harvey², Ashish Singh¹, Die Wang¹, Maria Zawadowicz¹, Chongai Kuang¹

¹Environmental Science and Technologies, Brookhaven National Laboratory, Upton, NY, United States

²Department of Physics, Texas Southern University, Houston, TX, United States

Correspondence: Tamanna Subba (tsubba@bnl.gov)

Abstract

The Sea Breeze Circulation (SBC) influences atmospheric processes at multiple scales in coastal regions. Understanding how SBCs impact the aerosol number budget and aerosol-cloud interaction processes is essential. This study investigates sea breeze–aerosol interactions (SAIs) during 46 summertime SBC events using data from the TRacking Aerosol Convection Interactions Experiment (TRACER) field campaign across urban (main) and rural (supplemental) coastal sites in southern Texas. Weather Research and Forecasting model coupled with Chemistry (WRF-Chem) simulations complement observations to explore spatio-temporal meteorological controls on boundary layer aerosols. During the summertime, Sea Breeze Fronts (SBF) penetrating inland transported cool, moist air over the land, introducing air masses with distinct properties compared to the preexisting continental air. These SAIs cause variability in number concentrations of up to a factor of two, with events typically lasting ~5 hours before returning to background conditions. SAI impact on aerosols varies with site proximity to water and the preceding sea breeze (SB) history, primarily affecting the marine-influenced accumulation mode. The main site, influenced by both Galveston Bay and the Gulf of Mexico, reflects a stronger marine influence. In contrast, a supplemental site, at a similar shoreline distance but exposed to the Gulf of Mexico and typically upstream of the urban core, samples SB air that has traversed land and partially regained continental characteristics. Simulations show that the regional SAIs extend ~50 km inland and reach up to the boundary layer height. SAIs further decrease cloud condensation nuclei relevant aerosol number concentrations in ~20% of events during SBF passage.

31 **1 Introduction**

32 A significant portion of the global population resides in coastal cities, including several
33 megacities (Brown et al., 2013). Nearly half of the U.S. population faces environmental
34 challenges associated with complexities tied to urban coastal atmospheres (Crossett et al.,
35 2004; Hudson et al., 2012). Houston, located along the Southern Texas coastline, is one of the
36 United States' most populated cities, while also one of its most polluted, with high aerosol
37 concentrations (Yoon et al., 1994; Kleinman et al., 2002; Banta et al., 2011). Aerosol particles
38 can negatively impact human health (Partanen et al. 2018; Mack et al., 2020), and influence
39 Earth's energy balance. They exert direct effects by scattering and absorbing the incoming solar
40 radiation, altering net radiative fluxes (Charlson et al., 1992; Bond et al., 2013; IPCC, 2021),
41 and indirect effects by acting as cloud condensation nuclei (CCN) and ice nucleating particles
42 (INP), thereby modulating cloud microphysical properties and precipitation processes
43 (Twomey, 1974; Albrecht et al., 1989; Ramanathan et al., 2001; Rosenfeld et al., 2008; Ariya
44 et al., 2009; Burkart et al., 2021).

45 In particular, the Houston region experiences highly complex aerosol processes due to
46 elevated local emissions, diverse aerosol sources, and intricate atmospheric chemistry. One
47 such process is new particle formation (NPF), which is a common aerosol microphysical
48 process that impacts the overall aerosol number concentration (Kulmala et al., 2004; Kerminen
49 et al., 2005; Kuang et al., 2008; IPCC 2013). NPF events typically include a sudden burst of
50 aerosols, i.e., the nucleation of gas molecules and formation of stable clusters of diameters
51 ' D_p ' > 2 nm, followed by subsequent growth, firstly to a size range with D_p > 50 nm and
52 possibly growing to a size where the particles can act as a CCN (D_p > 100 nm) (Yu and Luo,
53 2009; Kerminen et al., 2012; Gordon et al., 2017). In addition, mesoscale meteorological
54 phenomenon around Houston, such as sea breeze circulations (SBCs), further modulate these
55 aerosol dynamics (SBC, e.g., Miller et al., 2003; Wang et al., 2024; Deng et al., 2025;
56 Thompson et al., 2025). These SBCs develop regularly in the warm season along coastal
57 regions (Miller et al., 2003). One key challenge for aerosol process studies common to coastal
58 city environments is in determining the relative importance of aerosol microphysical versus
59 mesoscale meteorological controls such as SBCs, in governing the aerosol number budget and
60 aerosol impacts on that population center.

61 The summertime SBC is a thermally-driven feature tied to differential heating between
62 the land and sea; this results in density gradients that cause the cooler marine air to propagate

63 inland (Miller et al., 2003; di Bernardino et al., 2021). Daytime SBC formation can facilitate
64 convective cloud and precipitation onset (Comin et al., 2015), influence boundary layer
65 meteorology (Adaricheva et al., 2023), and has been associated with complex impacts on
66 overall air quality (Simpson, 1994; Masselink and Pattiaratchi, 1998; Moorthy et al., 2003;
67 Miller et al., 2003; Augustin, et al., 2020; Park et al., 2020; Parajuli et al., 2022; Wang et al.,
68 2023). These circulations also influence transport of atmospheric gases (Gangoiti et al., 2001;
69 Ahmadov et al., 2007; Hernández-Ceballos et al., 2015) and aerosol particles (Clappier et al.,
70 1999; Borge et al., 2008; Papanastasiou et al., 2010). A sea breeze front (SBF), which is the
71 boundary between that cooler, more moist marine air of the SBC flow and the warmer, drier
72 air over the land, is often a focal point that facilitates the transport and dispersal of aerosols, as
73 well as aiding in the formation of cumulus clouds (Miller et al., 2003). While low-level lapse
74 rates are often more stable on the maritime side of the SBF, the conditional instability
75 (Convective Available Potential Energy-CAPE) is often observed to be greater on the maritime
76 side due to the higher moisture content in that air mass (Hanft and Houston, 2018; Sharma et
77 al., 2024; Boyer et al., 2025). Convergence along these SBFs often results in enhanced upward
78 air motion, allowing aerosols to ascend to higher altitudes ~2 km (Iwai et al., 2011). Stronger
79 wind shear along these SBFs also generates increased turbulence, as owing to Kelvin-
80 Helmholtz instability occurring just behind this front (Linden and Simpson, 1986; Plant and
81 Keith, 2007), while the aforementioned vertical air motions are important for convective cloud
82 initiation (Rao and Fuelberg, 2000; Arrillaga et al., 2020).

83 The common conceptual model for SBCs is one where the marine air mass propagates
84 inland, bringing with it different atmospheric and aerosol characteristics compared to the
85 ambient land air mass conditions. In this study, the influence of these SBCs on regional aerosols
86 is termed as “sea breeze - aerosol interaction” (SAI). Previous studies have shown that SAIs
87 vary depending on complex interactions among emissions sources, boundary layer dynamics,
88 and the strength and/or direction of the SBC (Miller et al., 2003; Boyouk et al., 2011; di
89 Bernardino et al., 2021). For example, SBF passage has been found to trap aerosols at lower
90 elevations within the boundary layer (Miller et al., 2003). In SBC environments, competing
91 processes can yield opposite aerosol responses, as the formation of a shallow thermal boundary
92 layer can confine particles near the surface and raise aerosol concentrations, whereas inland
93 buoyant (convective) lifting within the convective boundary layer, can lift aerosols aloft
94 (Simpson, 1994; Boyouk et al., 2011; di Bernardino et al., 2021). In addition, SBCs may

95 replace the regional air mass with the cleaner marine air mass, leading to a decrease in surface
96 aerosol concentration. This now-modified coastal environment can affect the generation and
97 growth of aerosols, impacting the local aerosol number budget that further influences their
98 direct and indirect effects.

99 Although several studies have investigated the overall change in the aerosol loading
100 during SBC events, less is known about the role of SAI on the aerosol microphysical properties.
101 Moorthy et al. (1993) observed that the passage of the SBF was associated with an increase in
102 the concentration of smaller particles. Furthermore, since SBFs propagate inland, SBCs can
103 have far-reaching impacts on aerosol properties (Iwai et al., 2011; Park and van den Heever,
104 2022). As an example, previous studies conducted in the Southeastern United States indicated
105 that inland propagating SBFs are followed by air masses that often contrasted with regional air,
106 having potential influence on distances 220 km from the Gulf of Mexico (Viner et al., 2021;
107 Bao et al., 2023). In a similar case of these farther-reaching influences, Parajuli et al. (2020)
108 found that the SBC influences the aerosol vertical distribution over the eastern coast of the Red
109 Sea while lifting dust aerosols along the western slope of the Sarawat mountains, with the
110 elevated dust at a height of ~ 1.5 km over the mountains. Similarly, Talbot et al. (2007) observed
111 that enhanced turbulent activity along the SBF facilitated vertical aerosol transport above the
112 boundary layer top (~ 1.1 km a.s.l) over a flat coastal area of the North Sea.

113 Finally, high aerosol concentrations in the Houston area are linked to strong surface
114 emissions and meteorological conditions (Wert et al., 2003; Ryerson et al., 2003). This metro
115 region is also home to numerous petrochemical factories that are one of the sources of
116 anthropogenic emissions. Several studies have also shown that meteorological conditions
117 around Houston are highly susceptible to the interaction between large-scale (background)
118 geostrophic flows and mesoscale SBCs (Miller, 2003; Wang et al., 2024; Deng et al., 2025).
119 Pinto et al., (2014) observed that wind direction reversals bring aged, aerosol laden plumes
120 with high O_3 and NO_x levels back to the Houston area. They found that easterly winds,
121 originating from the Houston Ship Channel (HSC), are most strongly associated with elevated
122 levels of photochemically produced species. Similar conditions that promote O_3 and NO_x build-
123 up also drive secondary particle formation, leading to increases in aerosol number
124 concentrations. These particle-phase enhancements in total number concentration result in
125 higher aerosol concentration in the air mass transported from the east. Occasional increases in
126 aerosol concentrations around the greater Houston metropolitan area can also be associated

127 with long-range transported aerosols. At the synoptic scales, the circulation patterns modulate
128 regional meteorology over the Gulf coast. The Bermuda-Azores High helps trans-Atlantic
129 transport of North African dust to the southeast coast (Perry et al., 1997; Bozlaker et al., 2013).
130 Summertime conditions are notably influenced by episodic transboundary aerosol transport
131 (Mao et al., 2020; Das et al., 2023), including dust events from the Sahara Desert (Aldhaif et
132 al., 2020) and biomass burning events in Central America and its neighboring states. The
133 biomass burning includes prescribed agricultural fires in Central America (Wang et al., 2018)
134 and forest fires in surrounding states (Westenbarger and Morris, 2018). Central America
135 biomass burning contributes to half of the biomass burning particulate matter concentrations
136 in Houston (Das et al., 2023). The motivation of this study is to investigate the role of SAIs as
137 observed over a complex urban megacity region, and specifically document SBC influence on
138 aerosol microphysical properties. These efforts expand on previous air quality studies over
139 Houston, including Li et al. (2020) who employed a K-Means clustering algorithm to study the
140 relationship between Houston-region SBCs and the daily ozone variability during the
141 DISCOVER-AQ (Deriving Information on Surface Conditions from Column and Vertically
142 Resolved Observations Relevant to Air Quality) field campaign. While Li et al. (2020) focused
143 on gas-phase chemistry, the same emissions and meteorological processes that drive ozone
144 variability can also influence aerosol loading over the southern Texas region.

145 This study capitalizes on the TRacking Aerosol Convection Interactions ExpeRiment
146 (TRACER) field campaign conducted by the US Department of Energy (DOE) Atmospheric
147 Radiation Measurement (ARM) user facility (Mather and Voyles, 2013), which took place
148 from October 1, 2021, to September 30, 2022 (Jensen et al., 2022; 2025). The main TRACER
149 field site was placed at an urban coastal location in Houston. As in TRACER's overarching
150 motivations, the Houston region is frequented by isolated convective clouds that interact with
151 ambient aerosol conditions from the urban and industrial sources, potentially serving as a
152 natural contrast to clouds that form in surrounding areas that exhibit significantly lower
153 background aerosol concentrations (Banta et al., 2011; Parrish et al., 2009; Wang et al., 2024;
154 Thompson et al., 2025). Additional observations were made at a rural coastal site (supplemental
155 site) in southern Texas during an intensive observation period (IOP) from June 1 to September
156 30, 2022. Using these TRACER-IOP measurements, our study explores how these SBCs
157 influence the aerosol environment at multiple ground sites. In addition, the Weather Research
158 and Forecasting model coupled with Chemistry (WRF-Chem) is used to investigate the

159 regional impacts of SAI over Southern Texas. A detailed description of the TRACER sites,
160 instruments, measurements, and methodology, followed by the WRF-Chem model
161 configuration details, are presented in Section 2. Section 3 presents campaign observational
162 and simulated results. Our efforts will characterize the composite meteorological (Section 3.1)
163 and aerosol (Section 3.2) observations during the IOP at the TRACER main and supplemental
164 sites. This is followed by a composite analysis of the observed effects of the sea breeze on
165 aerosol properties at the two ARM sites (Section 3.3), as well as a detailed case study
166 examination of SAI influence for these locations (Section 3.4). The regional influence of SAI
167 is further explored using model simulations, as demonstrated for the horizontal (Section 3.5)
168 and vertical propagation of SAIs (Section 3.6), and SAI impact on cloud condensation nuclei
169 over the southern Texas region (Section 3.7). The study concludes with our key findings
170 summarized in Section 4.

171

172 **2 Data and methods**

173 2.1 Site description

174 The DOE ARM TRACER field campaign was centered on the deployment of the first ARM
175 Mobile Facility (Miller et al., 2016, herein AMF1) at the main instrument site (M1) (Fig. 1).
176 The M1 is an urban coastal site located at the La Porte, Texas (TX) airport, to the southeast of
177 Houston, TX. Given the high propensity for isolated convective cloud events during
178 summertime months (Jensen et al., 2022; 2025), the TRACER IOP was conducted from June
179 1 to September 30, 2022, with a goal towards sampling a range of aerosol-cloud interactions
180 during these convective events. Additional ARM and guest instruments were deployed to a
181 supplemental site (S3) during the IOP as documented in Jensen et al. (2022). The S3
182 supplemental site is a rural coastal site in Guy, TX, located ~70 km west from M1, upstream
183 and periphery to the highly populated and commercial sectors of the Houston-Galveston-
184 Brazoria region.

185 The southern Texas region is characterized by flat terrain with elevations < 50 m a.s.l and
186 a diversity of land cover/use, including urban, rural, grassland, and forested coastal
187 environments (see Fig. 2a). Although both the M1 and S3 sites are a similar distance from the
188 Gulf of Mexico, the M1 site is located near the western shore of Galveston Bay. This urban

189 M1 site may experience different sea-breeze timing because of its location, the added influence
190 of the Galveston Bay breeze, and urban heating that alters local circulations. The M1 site is
191 expected to be strongly influenced by anthropogenic activities due to its proximity to the
192 Houston urban core, large-scale industrial complexes and the HSC. The HSC is lined with
193 dense clusters of industrial facilities, including major petrochemical complexes (Yoon et al.,
194 2021), which can contribute to aerosol populations beyond those typically associated with an
195 urban environment. Similarly, the Texas A&M University (TAMU) TRACER measurements
196 also showed that short-lived ship emissions contributed to high aerosol concentrations (up to
197 $34,000 \text{ cm}^{-3}$) (Rapp et al., 2024; Thompson et al., 2025). The S3 site, while relatively less
198 impacted by the emissions from the Greater Houston area, is not representative of a pristine
199 rural location in terms of aerosol loading. Under typical south-southeasterly wind, this S3 site
200 is located downstream of heavy industry along the southeast Texas coastline (Freeport, TX and
201 Lake Jackson, TX) and can be influenced by upstream anthropogenic sources (Fig. 2b).

202

203 2.2 Measurements of aerosols and meteorological properties

204 This study focuses on the enhanced aerosol and complementary observations available
205 during the TRACER summertime IOP period. The key aerosol datasets available during this
206 IOP include: (1) the aerosol number size distribution and total number concentration, (2) bulk
207 aerosol chemical composition, and (3) state meteorological properties (e.g., surface
208 temperature, humidity). Campaign availability of in-situ observations at two contrasting sites
209 provided an excellent opportunity to understand the regional aspects of SAI.

210 The aerosol number size distribution with diameter ranging from 10 to 500 nm was
211 measured at M1 and S3 sites using Scanning Mobility Particle Sizer (SMPS) (Singh and Kuang,
212 2024). The aerosol number size distributions ($dN/d\log D_p$) (aerosol number concentrations in
213 different diameter bins) at different diameters (D_p) were added to calculate the total integrated
214 aerosol number concentrations. Bulk aerosol chemical compositions consisting of total
215 organics, sulfate, nitrate, ammonium, and chloride were measured at M1 and S3 sites using
216 Aerosol Chemical Speciation Monitor (ACSM) (Watson, 2017). Surface meteorological
217 variables: temperature, water vapor mixing ratio (w), wind direction and wind speed at M1 and
218 S3 sites were taken from the meteorological instruments collocated with the aerosol
219 instruments. All of these instruments are part of the ARM Aerosol Observing Systems (AOS),

220 which is the platform for in situ aerosol measurements at Earth's surface (Uin et al., 2019).
221 Missing data were excluded from this analysis. If more than 20% of the data were missing
222 during the 5 hours before and after the passing of the SBF, the dataset was not used to study
223 SAI processes. SMPS and ACSM sample data at 5-minute and ~30-minute intervals,
224 respectively. State meteorological variables were observed at one second intervals. All
225 datasets, except for the ACSM, were averaged over a 5-minute interval, centered on the time
226 of the SMPS sample.

227 To supplement the ARM observations, we use particulate matter of 2.5 micrometers or less
228 in diameter ($PM_{2.5}$) mass concentrations from the Texas Commission on Environmental
229 Quality (TCEQ) database (Shrestha et al., 2023; sfcmetradaq-tceq ARM PI product). Although
230 TCEQ operates a broad network of air quality monitoring stations throughout Texas, the
231 Seabrook Friendship Park site (C45, $-95.02^{\circ}E$, $29.58^{\circ}N$) was selected because it is the nearest
232 monitor to the M1 site (~6 km away) and provided continuous hourly $PM_{2.5}$ data during the
233 study period. $PM_{2.5}$ was chosen as a representative aerosol to directly compare with the model
234 simulations. For reference, this TCEQ C45 site location was added to the map displaying the
235 TRACER sites (Fig. 1).

236 This study draws heavily from SBC synoptic-scale regime identification performed by
237 Wang et al. (2024) to further inform on controls affecting SBC evolution and cloud formation
238 at the two sites. Every SBC day identified by Wang et al. (2024) during the IOP period is
239 considered to explore SAI during TRACER. A total of 46 SBC events at the M1 site, and 30
240 SB events at the S3 site were identified by Wang et al. (2024) during TRACER's IOP (Table
241 1). They explored Gulf breeze and bay breeze circulation characteristics using a suite of
242 datasets, including ground-based measurements, satellite observations, and reanalysis datasets,
243 using machine learning techniques, and Lagrangian cell tracking methods. Most IOP SBC
244 events were classified as occurring during large-scale anticyclonic conditions, with the
245 predominant occurrence of SBCs observed during southeasterly background surface wind
246 directions. The SBF timing at both ARM sites was determined using surface wind and w mixing
247 ratio time series.

248 Overall, Wang et al., (2024) found that the SBF typically arrived at the M1 site at 20:30
249 UTC (i.e., 15:30 LT), and at the S3 site at 20:50 UTC (i.e., 15:50 LT). The M1 site, situated
250 along the western shore of the Galveston Bay, was also influenced by bay breeze circulations,
251 frequently resulting in an earlier shift in the local meteorological state compared to that of the

252 S3 site (only influenced by the Gulf SBC). The M1 site was shown to experience an additional
253 bay breeze contribution during 22 out of 43 SBC events. Wang et al. (2024) also reported that
254 M1 experienced higher intensity changes in the meteorological conditions associated with these
255 SBFs as compared to S3, particularly when the background wind directions are southwesterly
256 or westerly. At both the sites, these SBF passages were associated with a significant increase
257 in w and wind speed, along with a decrease in surface temperature. The arrival of the fronts
258 also typically increased the vertical wind speed within the boundary layer, with a mean speed
259 of up to 2 m s^{-1} within the lowest 1 km. The enhanced updrafts associated with SBF low level
260 convergence also was shown to promote short lived-isolated convective clouds and likely
261 associated with vertical mixing of aerosols by diluting near-surface concentrations and
262 redistributing aerosols aloft.

263

264 2.3 Model simulation setup

265 The WRF-Chem model (Grell et al., 2005; Skamarock et al., 2008) was used to simulate
266 the multiscale interactions between aerosols and meteorology over the coastal region of
267 southeast Texas. Fig. 2 shows the model domain centered on the M1 site and extended from
268 26 to 33 °N (~770 km) in latitude and from -98.5 to -91.5 °E (~770 km) in longitude. The model
269 simulations were performed for the period from 1 July to 30 August 2022, using a 5x5 km
270 horizontal grid spacing with 45 vertical layers. A model spin-up time of 3 days was used, and
271 the restart files were used for the remainder of the simulations. Initial and boundary conditions
272 for meteorology were provided by the North American Mesoscale (NAM) model every 6 hours.
273 The model configuration was successfully set-up and is considered sufficient to resolve the key
274 meteorological processes relevant to the aerosol chemistry examined in this study. To validate
275 this assumption, simulated meteorological fields and aerosol variabilities are compared against
276 observations. Similar model setups have been successfully applied in previous WRF-Chem
277 studies over the continental US (e.g., Berg et al., 2015; Wang et al., 2021; Subba et al., 2023;
278 Shrivastava et al., 2024), which demonstrate their suitability for representing aerosol-cloud
279 interactions. The details of the configurations are shown in Table 2.

280 The model simulations were performed with (with aerosol-WA condition) and without (no
281 aerosol-NA condition) full aerosol-gas chemistry, and land-atmosphere interactions enabled.
282 Boundary conditions for gas-phase species and aerosols were provided by the Whole

283 Atmosphere Community Climate Model (WACCM) (Gettelman et al., 2019). The WACCM
284 output datasets, available on a horizontal grid resolution of $1^{\circ}\times 1^{\circ}$ were spatially interpolated
285 to our model domain every 6 hours. Biogenic emissions were generated online by WRF-Chem
286 model based on meteorology and land use data, using the Model of Emissions of Gases and
287 Aerosols from Nature version 2.1 (MEGAN2.1) by Guenther et al. (2012). The U.S.
288 Environmental Protection Agency National Emission Inventories (NEI, Ma and Tong, 2022)
289 was used to provide anthropogenic emissions of trace gases and aerosols from diverse sources,
290 including point, area, on-road mobile, non-road mobile, and other sectors. These emissions are
291 incorporated to WRF-Chem at hourly intervals. The area surrounding the M1 site is
292 characterized by urban infrastructure and cropland, whereas the S3 site is largely a mix of
293 cropland, natural mosaic, and barren or sparsely vegetated land type. Both sites have cropland
294 and grassland to the west and north, as well as evergreen, deciduous, and mixed forests from
295 the north to east directions. The selected domain included both anthropogenic and biogenic
296 aerosol sources, as indicated by NEI and MEGAN datasets (Fig. 2b). The M1 site is anticipated
297 to be more influenced by anthropogenic sources due to its proximity to the Houston urban core,
298 local industry and the HSC. The S3 site is expected to be more influenced by biogenic sources.

299 The role for these simulations is to provide a physically-reasonable spatial approximation
300 for the meteorological and aerosol environments across the southern Texas region that are not
301 captured by the point measurements during TRACER. Comparing the meteorological variables
302 between the two sites helps identify the underlying factors that may influence the aerosol
303 transport and transformation processes. The simulated meteorological time series show
304 adequate agreement for the purposes of this study at both sites (Fig. S1). We assessed model
305 performance using metrics: mean bias (MBE), root mean square error (RMSE), and correlation
306 coefficient (R) for the quantities of temperature, wind speed, and wind direction. In addition,
307 we also considered Modern-Era Retrospective analysis for Research and Applications
308 (MERRA-2) reanalysis products to further evaluate the model performance (Geralo et al.,
309 2017). Our model reproduces the measured temperature diurnal cycle at both sites with high
310 correlation (r up to 0.87) and low MBE ($< \pm 1$ °C). Wind speed and wind directions show
311 weaker correlation (r up to 0.65) and MBE of 0.76 m s^{-1} and 12.5° , respectively. Individual
312 SBF events are further analysed to compare the measured and modeled variables in later
313 sections.

314 We find a reasonable behavior in the heterogeneous spatial distribution of PM_{2.5}, with
315 higher values in the urban areas around the M1 site and lower values in the rural areas around
316 the S3 site (Fig. 3b). The simulated hourly PM_{2.5} has been compared with the TCEQ measured
317 values (Fig. 3a). The model reasonably captures the timings and magnitude of high and low
318 aerosol concentrations. The model (mean ~ 10.8 μg m⁻³, median ~8.5 μg m⁻³) overestimates the
319 observations (mean ~8.2 μg m⁻³, median ~7.0 μg m⁻³), with a correlation of $r \sim 0.6$,
320 corresponding to differences of ~30% in the mean and ~ 23% in the median. These model-
321 measurement discrepancies are consistent with previously reported WRF-Chem biases. For
322 example, Soni et al. (2022) reported that during dust storm events over the Indian sub-
323 continent, WRF-Chem captured spatial aerosol patterns but underestimated concentrations in
324 regions of high aerosol loading. Similarly, Tuccella et al. (2012) reported that WRF-Chem
325 underestimated peak aerosol concentrations by 7.3%. More recently, Georgiou et al. (2022)
326 reported underestimation of background PM_{2.5} by 16% and of industrial by ~20%.

327

328 **3 Results and discussion**

329 **3.1 Composite IOP Meteorological Observations**

330 Comparisons between the background summertime meteorology around the TRACER
331 sites help to identify the underlying factors that may influence the aerosol transport and
332 transformation processes. Fig. 4. shows composite averaged diurnal variations of
333 meteorological properties during the IOP period. When comparing meteorological variables
334 between M1 and S3 sites, paired t-test results calculated a very low p-value (<0.0001) and a
335 large negative or positive t-statistic, indicating a statistically significant difference. M1 exhibits
336 higher temperatures during the cooler parts of the day (early morning) and slightly lower
337 temperatures during the warmest parts of the day (early afternoon). w at M1 is lower during
338 the warmer periods and higher during the cooler periods of the day. At both sites the value
339 stays near 17-18 g kg⁻¹ for most of the day, with a common moistening pulse around 13:00-
340 15:00 UTC that coincides with increased wind speed. At similar hours, the wind directions are
341 similar at both the sites. Except in the morning, winds at M1 are typically 1-2 m s⁻¹ stronger
342 than at S3. The M1 site shows an increase in w near 20:00 UTC, likely tied to the SBC. S3
343 exhibits a larger shift in the wind directions compared to that of M1. The two sites have similar

344 directions during the late night (00:00- 05:00 UTC) and early morning (13:00-15:00 UTC)
345 hours. During the dominant afternoon SBC period (around 20:00 UTC), winds are
346 predominantly from the southeast at M1 and from the southwest at S3.

347 Although these sites are geographically close, their different proximities to water bodies
348 and varying land cover types may account for the observed meteorological variations, such as
349 differences in temperature modulation, humidity, and breeze development. M1 lies adjacent to
350 both Galveston Bay and Gulf of Mexico, thus nearby water moderates temperature and
351 promotes higher humidity, favoring sea- or bay- breeze circulations. In contrast, although S3
352 is at a similar distance from the Gulf as M1, it is more inland, separated from the shoreline by
353 an intervening expanse of land, so it experiences stronger daytime heating and a weaker, more
354 modified marine influence than M1. It has a land surface covered predominantly with
355 vegetation and soil that cools faster at night than urban landscapes. However, urban landscapes
356 retain heat, remaining warmer into the nighttime and potentially moderating temperatures
357 during the subsequent daytime (Maria et al., 2013). These behaviors are consistent with the
358 prior studies showing the coastal sites experienced moderate temperature and enhanced
359 humidity (Hu, 2021; Subramanian et al., 2023), and that land-use influenced local temperature
360 and boundary layer dynamics via evapotranspiration and surface heating (Fang et al., 2025).

361

362 3.2 Composite IOP Aerosol Observations

363 The southern Texas region is influenced by locally-generated (e.g., vehicular, industrial,
364 construction and road dust, and sea spray) and long range transported aerosols (e.g., biomass
365 burning, mineral dust, and sea spray) from anthropogenic and natural sources (Brown et al.,
366 2002; Barrett and Sheesley, 2014; Karnae and John, 2019; Song et al., 2021; Das et al., 2023;
367 Shrestha et al., 2023). In Fig. 5a, aerosol number concentration peaks around 17:00 UTC at M1
368 and around 20:00 UTC at S3. Both sites exhibit a tri-modal aerosol size distribution (Fig. 5b.).
369 Throughout the day, the aerosol concentrations are consistently higher at the M1 site when
370 compared to those observed at the S3 site. At the M1 site, we observe a distinct nucleation
371 mode that appears at diameter <20 nm, and two additional modes at larger diameters ~ 80 nm
372 and ~ 150 nm. This nucleation mode is less prominent at the S3 site, which more commonly
373 exhibits similar modes at diameters ~ 80 nm and ~ 150 nm.

374 The ACSM observations suggest a similar percentage contribution from various species,
375 with organics having the highest concentration (59.2% at M1 and 53.0% at S3), followed by
376 sulfate (23.3% at M1 and 30.6% at S3), ammonium (11.4% at M1 and 10.8% at S3), nitrate
377 (5.2% at M1 and 5.0% at S3) and chloride (less than 0.9% at M1, and less than 0.6% at S3).
378 Higher percentages of organics and sulfate were also measured at other urban (Minguillón et
379 al., 2015; Huang et al., 2010; Qi et al., 2020) and rural locations (Crippa et al., 2014; Atabakhsh
380 et al., 2023).

381 The NPF events are identified by analyzing the aerosol size distribution measured by the
382 SMPS (Kuang et al., 2008; Dal Maso et al., 2002; Mikkonen et al., 2011). This is accomplished
383 by designating characteristic features for NPF found in the size distribution behaviors in time,
384 including the appearance of the nucleation mode at a diameter (D_p) < 25 nm, followed by
385 distinct growth pattern (where the particles increase in size over several hours) forming the
386 characteristic “banana-shaped” pattern in the aerosol number size distribution. NPF events
387 were common at both the M1 and S3 sites. During summertime, NPF events were identified at
388 both the M1 and S3 sites, finding 23 and 17 events, respectively. In approximately 35% of
389 cases, NPF events were observed simultaneously at the sites, implying a regional-scale
390 behavior. These regional NPF nucleation modes appear at D_p < 25 nm and grow consistently
391 across a broader region, covering a minimum radius of tens of kilometers. However, these
392 simultaneously-occurring NPF events displayed different characteristics in terms of their
393 duration and growth, hinting at the possible influence of mesoscale to larger-scale
394 meteorological controls on these processes (such as SBCs), the background aerosol
395 concentration and/or the availability of necessary precursors.

396

397 3.3 Observed Sea Breeze aerosol interaction at the surface

398 Coastal regions have a mixture of urban, terrestrial, and marine aerosol regimes. The
399 inland-penetrating SBF can have a complex influence on the aerosol populations over Houston
400 and its surroundings depending on several coexisting factors including: (i) the pre-existing
401 aerosol regime over the location, (ii) the aerosol regime of the air mass preceded by the SBF,
402 (iii) the local to synoptic thermodynamic conditions resulting from convective boundary layer
403 features such as horizontal convective rolls, and (iv) the characteristics of the SBF itself,
404 including the lifting and mixing of the onshore flow with the ambient air, and wind anomalies

405 near the surface. Three scenarios for the influence of an inland-penetrating SBF on aerosols
406 within the region of influence are considered.

407 First, we consider a potential “reduction influence” that may occur when an air mass with
408 higher aerosol concentration over a location is replaced by an air mass with lower aerosol
409 concentration. In contrast, an “enhancement influence” may occur when an air mass with lower
410 aerosol concentration over a location is replaced by an air mass with higher aerosol
411 concentration. Otherwise, a “neutral influence” implies minimal change associated with the
412 SBF, defined as a change in the aerosol concentration is less than 5% in the pre-existing aerosol
413 regime. This scenario indicates that the air mass following the SBF is similar to the existing
414 conditions.

415 For example, these enhancement influence scenarios may be anticipated when long-range
416 transported aerosols are present in the air mass downwind of the SBF, or when the SBF first
417 advects over areas (marine or continental) with high local emissions. Similarly, neutral
418 influence scenarios are anticipated when the entire region has relatively homogeneous (i.e.,
419 similar aerosol concentrations also belonging to the same aerosol regime) distribution of
420 aerosols. Nevertheless, aerosol exchanges are complex, and TRACER also provided several
421 examples of marine aerosols carried by the SBF that were associated with negligible influences
422 on the ambient marine aerosol mode. Finally, TRACER site measurements may not always be
423 representative of a broader air mass or regional conditions (e.g., intermittent local source
424 interactions with smaller-scale SBC features). WRF-Chem modeling may help to bridge these
425 spatial representativeness gaps and provide reference for the regional context of the potential
426 impact of the SBC on aerosol distributions.

427 To investigate the influence of SAI, one approach employed in this study is to normalize
428 the surface aerosol concentration at time T by the value measured immediately before the
429 passing of the SBF ($T_{\text{SBF}}=0$ hour). The timing of the SBF for each event is explicitly
430 considered, using the passage times provided in Table A1 on Wang et al. (2024). The SBF
431 passage at a site is defined as $T_{\text{SBF}}=0$. This approach allowed evaluation of aerosol number
432 concentrations before and after the SBF passage while retaining the diurnal cycle context. Here,
433 “just before” refers to the five minutes prior to the SBF passage, as previously identified by
434 Wang et al. (2024). Figs. S2 and S3 show the temporal variation of this normalized aerosol
435 number concentration for all the SB events. At both the M1 and S3 sites, before-SBF aerosol
436 concentrations can vary by up to a factor of two.

437 Example days with an “enhancement influence” in the aerosol concentration after T_{SBF} are
438 shown in Fig. 6, highlighting the 18 July event at the M1 site, and a 10 August event at the S3
439 site. In contrast, the 17 June (M1 site) and 10 July (S3 site) events in the same figure help
440 illustrate a “reduction influence” in aerosol concentration after T_{SBF} . While these example
441 events are instructive, there is not a clear trend for TRACER events given the high level of
442 variability in the duration or influence of SAIs. For example, the sharp increase we observe in
443 aerosol concentration on the 10 August “enhancement” event quickly dissipates within an hour
444 after T_{SBF} at the S3 site. In contrast, the increase in the number concentration we observed on
445 18 July persisted for over an hour after T_{SBF} . Considering all the SBF passages we collected
446 (Figs. S2 and S3), we suggest $\Delta T = T_{\text{SBF}} \pm 1$ hour often best represents the “before” ($\Delta T = T_{\text{SBF}}$
447 - 1 hour) and “after”- SBF ($\Delta T = T_{\text{SBF}} + 1$ hour) times over a location. The enhancement or
448 reduction effects are most pronounced during the first hour following the passing of the SBF.
449 Beyond this period, the observed changes may be influenced by additional factors, such as the
450 secondary effects resulting from meteorological transitions induced by the SBF. Additionally,
451 the intensity of the SBF’s impact may begin to weaken or become less pronounced after the
452 first hour. With that assumption, a percentage change of the aerosol number concentration
453 $[(\text{after}-\text{before})/\text{before} \times 100\%]$ can be further calculated. ‘Neutral influence’ days with the
454 change in aerosol concentration $<10\%$ are not considered in this analysis.

455 Table 1 summarizes the total number of SBC events, along with number and percentage of
456 days showing enhancement, reduction, or neutral influence on the aerosol number
457 concentration at the M1 and S3 sites. Neutral days were excluded from the overall averages to
458 focus solely on the cases with a clear aerosol response. Out of 46 SBC events at the M1 site,
459 29 events ($\sim 63\%$) showed an enhancement or reduction influence on total aerosol number
460 concentration, while the remaining 17 events ($\sim 37\%$) were classified as having a neutral
461 influence. In contrast to M1, at the S3 site, out of 30 SBC events, only 12 events ($\sim 40\%$)
462 exhibited a detectable change in aerosol number concentration, with the remaining 18 days
463 ($\sim 60\%$) considered neutral. At the M1 site, reduction events (16 events) slightly outnumbered
464 enhancement events (13 events). In contrast, at S3, enhancements (8 events) were twice as
465 common as reductions (4 events). This opposite pattern underscores the site-dependent nature
466 of the sea-breeze influence.

467 During enhancement days, the M1 site shows an average increase in aerosol number
468 concentration of $\sim 55\%$, rising from $3.8 \times 10^3 \text{ cm}^{-3}$ during $\Delta T-$ to $5.9 \times 10^3 \text{ cm}^{-3}$ during $\Delta T+$. In

469 contrast, during the reduction days, the concentration decreases by $\sim 42\%$, dropping from $13.2 \times 10^3 \text{ cm}^{-3}$
470 10^3 cm^{-3} during ΔT^- to $7.6 \times 10^3 \text{ cm}^{-3}$ during ΔT^+ . At the S3 site, the average changes are $\sim 64\%$
471 (from $2.4 \times 10^3 \text{ cm}^{-3}$ during ΔT^- to $3.9 \times 10^3 \text{ cm}^{-3}$ during ΔT^+) enhancement and $\sim 45\%$ (from
472 $4.9 \times 10^3 \text{ cm}^{-3}$ during ΔT^- to $2.7 \times 10^3 \text{ cm}^{-3}$ during ΔT^+) reduction. When averaged across all
473 events, the aerosol number concentration at M1 shows a net decrease of $\sim 23\%$, from 8.9×10^3
474 cm^{-3} during ΔT^- to $6.8 \times 10^3 \text{ cm}^{-3}$ during ΔT^+ , while S3 exhibits a net increase of $\sim 9\%$, from
475 $3.2 \times 10^3 \text{ cm}^{-3}$ during ΔT^- to $3.5 \times 10^3 \text{ cm}^{-3}$. These contrasting trends underscore the regional
476 variability in aerosol responses associated with SAI events.

477 As previously mentioned, the geographical positioning of M1 and S3 sites could be one of
478 the reasons for such variabilities. M1 is more influenced by the bay breeze coming from
479 Galveston Bay and S3 is more likely influenced by Gulf breeze from Gulf of Mexico. Even if
480 the air mass associated with the SBF contains lower aerosol concentration, the longer distance
481 the SBF travels to reach the S3 site allows the marine air mass to mix with the continental air
482 mass, potentially resulting in higher aerosol concentrations, and vice versa. The M1 site is
483 influenced by the air masses and SBCs from both sources, whereas the S3 site is affected
484 predominantly by those originating from the Gulf of Mexico. As discussed in detail by previous
485 studies (Sharma et al., 2024; Wang et al., 2024), the SBFs originating from Galveston Bay and
486 the Gulf of Mexico are often distinct at onset but tend to merge later in the afternoon or evening.
487 Due to the M1 site's proximity to Galveston Bay, it is more directly influenced by maritime air
488 masses that are heavily modified by Galveston Bay as the SBF originating from the Gulf of
489 Mexico traverses the Bay. On the other hand, the Gulf-originating SBF must cross land before
490 reaching S3. The difference in SBF pathways can lead to notable meteorological and aerosol
491 contrasts between the two sites. In addition, as observed by Thompson et al. (2025), the
492 maritime air masses near Galveston can deviate significantly from typical clean maritime
493 conditions. As a result, bay breeze passages may not always lead to cleaner air but can, in fact,
494 be more polluted. The consequences of this increased aerosol concentration in the modified
495 maritime air mass are reflected in the enhancement aerosol response observed at the M1 site.

496 SAIs can also interfere with NPF events. On SB days, a total of 7 NPF events were observed
497 at the M1 site and 4 at the S3 site, with 3 occurring simultaneously at both sites. Among these,
498 45% (5 out of 11) events showed distinct changes in NPF characteristics during the SBF
499 passage. For example, on 16 July an NPF event was observed at M1 prior to the SBF (Fig. S4).
500 With the arrival of the SBF, particle growth abruptly ceased, and the elevated particle

501 concentration ($\sim 14 \text{ e}^3 \text{ particles cm}^{-3}$) rapidly decreased to $\sim 5 \text{ e}^3 \text{ particles cm}^{-3}$ (Fig. S4). The
502 normalized aerosol size distribution further shows that the NPF activity evident in the hours
503 before the SBF period ($\Delta T = T_{\text{SBF}} - 1 \text{ hour}$) disappeared in the hour following the SBF
504 ($\Delta T = T_{\text{SBF}} + 1 \text{ hour}$). The low aerosol concentration air mass trailing the SBF passage thus led
505 to a sharp reduction in the aerosol number concentrations in the after-SBF period.

506 The open-air polar plots summarize the relationship between aerosol number concentration,
507 wind speed and wind direction within $\Delta T = T_{\text{SBF}} \pm 1 \text{ hour}$ during enhancement and reduction
508 events (Fig. 7). At M1, enhancement events reveal elevated aerosol concentrations when the
509 prevailing winds emanate from the east and southeast, where the air mass is influenced by
510 industry and shipping along Galveston Bay. During the reduction influence the pre-SBF aerosol
511 loading is higher compared to that of the reduction events. These high concentrations are
512 associated with the influence from the Houston urban core in the northwest and the other
513 influences from the east as mentioned above. These are also apparent in the monthly plots
514 shown in Fig. S5. After-SBF winds, particularly from the southeast and south, are associated
515 with markedly lower aerosol loads, indicative of cleaner marine air intrusion.

516 Meanwhile at S3, enhancement scenarios also manifest somewhat higher concentrations
517 when winds shift southeastward, though to a lesser extent, reflecting rural aerosol dynamics.
518 In reduction scenarios at S3, aerosol levels decrease most notably under southerly and
519 southwest flow, reinforcing the interpretation that sea breeze incursions generally replace
520 continental aerosol-laden air with cleaner marine air at both sites, albeit with stronger source
521 influence at M1. This wind-direction-dependent concentration pattern aligns with previous
522 findings: northwesterly to easterly winds bring continental aerosols, while southerly to
523 southwesterly flows usher in marine-influenced clean air that modulates aerosol number
524 concentrations (Levy et al., 2013; Pinto et al., 2014). However, as shown in Figs. S2 and S3,
525 each SB event is unique in terms of the change in the aerosol concentrations.

526 3.4. Examples of sea breeze aerosol interaction at the TRACER sites

527 In Fig. 8, we provide an example of an aerosol reduction influence of SAI. Since M1 and
528 S3 both experienced the passage of a SBF on 10 July, this day serves as a good example to
529 investigate how SAIs evolve when simultaneously viewed at multiple sites. The SBF reached
530 the M1 site in the afternoon at around 21:30 UTC, and the S3 site at around 23:45 UTC. In Fig.
531 S6, we supplement these discussions with displays for the temporal variation of measured and

532 model-simulated meteorological properties for this event. Both sites suggest the typical
533 temperature decreases and surface wind speed increase associated with the SBF reaching the
534 site. The wind direction changes from east to south at the M1 site and from southwest to south
535 at the S3 site.

536 The changes in aerosol size distribution, reduction in the bulk chemical composition, and
537 simulated $PM_{2.5}$ all suggest that the air mass following SBF passage contains lower aerosol
538 concentration (Fig. 8.). This likely indicates that during the after-SBF period, the air mass is
539 arriving from directions less influenced by the aerosol sources. The SBF acts as a leading edge
540 of this cleaner marine air mass. The aerosol number concentration decreases by $\sim 5\%$ (5.2 e^2
541 cm^{-3}) at the M1 site. At the M1 site, there was no significant change in the mean D_p ($\sim 100 \text{ nm}$)
542 during the first 45 min after T_{SBF} , which is followed by a sharp decrease in the mean D_p (~ 25
543 nm). This change in the aerosol number concentration is synchronous with the changes in wind
544 directions. During the after-SBF period, the winds shift predominantly from the southeast and
545 south, bringing in a more marine-influenced air mass.

546 Immediately after the passing of the SBF at the S3 site, the SAI also indicates a
547 reduction of the aerosol number concentration by $\sim 62\%$ ($3.3 \text{ e}^3 \text{ cm}^{-3}$) (Fig. 8b). However, the
548 background aerosol mode persists at diameters ~ 60 and 150 nm (aerosol size distribution plot
549 in Fig. 8b). Note, we did not observe a profound change in the wind directions after the passing
550 of the SBF at the S3 site. However, we suggest that the higher wind speed associated with the
551 SBF dilutes the existing air mass with marine air with lower aerosol concentration. Higher
552 wind speeds enhance near-surface shear, mechanically generate turbulence, deepen the
553 boundary layer, and strengthen vertical transport, thereby accelerating dispersion and diluting
554 aerosol and water-vapor concentrations (Kgabi and Mokgwetisi, 2009; Dueker et al., 2017; Liu
555 et al., 2025). Conversely, low winds with a shallow boundary layer and weak turbulence
556 promote accumulation and often worsen air quality due to limited dilution (Seinfeld and Pandis,
557 2006). The modified near-surface air mass at S3 persists overnight until convective mixing
558 begins the following day. Under stable stratification, buoyant turbulence is suppressed, and
559 shear-driven mixing becomes the primary dilution mechanism; although weaker than
560 convective mixing, it can still substantially mitigate concentration build-up (Rodier et al.,
561 2017).

562 The aerosol bulk chemical mass concentration at the M1 site shows a steady buildup
563 through the day, peaking just before the passing of the SBF. Organics were the dominant

564 species throughout, with sulfate and nitrate also contributing. After the passage of the SBF,
565 concentrations dropped rapidly by about 1 to 3 $\mu\text{g m}^{-3}$, with the drop being more apparent in
566 sulfate and ammonium. Within a few hours, concentrations returned to the background levels.
567 These concentrations remained higher than those at the rural S3 site. However, the more
568 pronounced changes in aerosol properties were observed at the S3 site. The concentrations of
569 all species, including organic, decreased by 2 to 3 $\mu\text{g m}^{-3}$. This is consistent with the earlier
570 discussion that the maritime air mass near Galveston Bay exhibits higher aerosol
571 concentrations compared to the more pristine maritime air mass originating directly from the
572 Gulf of Mexico.

573 In Figs. S7 and S8, we provide additional examples from TRACER SAI events. The first
574 example is from the 17 July event where we observed an increased influence in the aerosol
575 concentration that followed SBF passage. In Fig. S7, we present an example of an aerosol
576 enhancement case associated with an SAI event on 17 July. The SBF reached the M1 site in
577 the early afternoon ($\sim 18:12$ UTC), and at around 21:42 UTC at the S3 site. The aerosol size
578 distribution displayed an enhancement of particles in the diameter range of 15-100 nm. Total
579 organics, sulfate, and simulated $\text{PM}_{2.5}$ also increased, suggesting that the post-SBF air mass
580 contained higher aerosol concentrations, likely due to transport from more polluted source
581 regions. Similar to the 10 July case, the SBF acted as the leading edge, but here it marked a
582 more polluted marine-influenced air mass.

583 At M1, the aerosol number concentration also doubled ($\sim 2.2 \times 10^3 \text{ cm}^{-3}$), accompanied by a
584 significant shift in mean particle diameter (within 15-100 nm) during the first hour after SBF
585 passage, with weaker changes thereafter. These responses were synchronous with shifts in wind
586 direction from southwest to east. The easterly winds, influenced by emissions from the HSC,
587 contributed to the observed increase. In contrast, at S3 the SAI did not produce distinct changes
588 in aerosol size distribution or mass concentrations, and except for the increase in the wind
589 speed, no substantial wind direction change occurred after SBF passage. The modified near-
590 surface air mass at both sites persisted for only ~ 2 hours, after which background conditions
591 returned. Notably, background aerosol modes at ~ 60 nm and ~ 150 nm persisted throughout
592 (Fig. S7).

593 Fig. S8 shows an example of a neutral SAI influence on 16 August. The SBF reached M1
594 at $\sim 17:05$ UTC and S3 at $\sim 20:10$ UTC. At M1, winds shifted from east to south, while no
595 distinct directional change was observed at S3. Unlike the 10 and 17 July cases, M1 was already

596 under high aerosol conditions, with particle concentrations consistently elevated at diameters
597 <80 nm. In contrast, S3 remained under low aerosol conditions for most of the day, except for
598 a brief increase just prior to the SBF passage. The SAI did not produce notable changes in
599 aerosol size distribution, bulk chemical composition, or simulated PM_{2.5}, indicating that pre-
600 and post-SBF aerosol concentrations were comparable at both sites. Although wind direction
601 changed at M1, the marine-influenced air mass was also burdened by high aerosol loading,
602 limiting its impact on conditions at the site. Similarly, S3 showed no discernible change, with
603 concentrations remaining low before and after the SBF passage. Detailed discussions on these
604 example events will be continued in the next section that expands this discussion to include
605 regional removal and transport influences on these SAI events.

606

607 3.5. Regional influence of sea-breeze aerosol interaction

608 In Fig. 9, we provide the spatial distribution of modeled w , planetary boundary layer height
609 (PBLH), surface-level wind vectors, PM_{2.5}, and integrated aerosol number concentration
610 (nucleation-nu0 + accumulation-ac0 mode) using WRF-Chem. Together, nu0 and ac0
611 concentrations reveal size-dependent aerosol changes that bulk PM_{2.5} mass or total number
612 obscure, allowing SBF-driven redistribution to be attributed to specific aerosol modes and
613 clarifying implications for microphysics, CCN/INP, and radiative effects. On 10 July, the
614 observed SBF reached the M1 site at 21:30 UTC and reached the S3 site at 23:45 UTC. The
615 simulation for this event accurately represents this timing for the SBF passage. The output for
616 the time 20:00 UTC on 10 July corresponds to an example point in the simulation and daytime
617 observations when the SBF had not reached either site. The 22:00 UTC examples correspond
618 to a time when the modeled and observed SBF has recently passed the M1 site but not reached
619 the S3 site. The 00:00 UTC examples (next day) correspond to a timing when the SBF has
620 passed both TRACER field sites.

621 Behind the SBF in our simulations, south or southeast winds prevail, passing through from
622 the Gulf of Mexico and blowing onshore at an average speed of 5 m s⁻¹. There is an increase in
623 w associated with the SBF passage. This transition in the air mass is also observed around the
624 M1 site at timestep 22:00 UTC. A similar pattern in the w is observed at the S3 site at the
625 timestep 00:00 UTC. This change at S3 is also accompanied by a decrease in the modeled
626 PBLH.

627 The 10 July simulations help illustrate that while changes in aerosol and meteorological
628 properties are more pronounced near the SBF, SBF influences may extend >50 km inland
629 associated with the path and extent of this feature. Along the convergence zone associated with
630 the SBF, particle concentrations are higher ahead of the SBF and lower behind it, due to
631 intrusion of cleaner marine air into the convergence zone. Consequently, SBF passage in the
632 model creates a swath of reduced aerosol concentration (up to 50%) parallel to the Galveston
633 Bay or Gulf of Mexico coastline. Over time, a well-defined dipole pattern emerges,
634 characterized by reduced concentrations over the coastal zone and enhanced concentrations
635 farther inland, consistent with the inland penetration of the maritime air mass and displacement
636 of pre-existing polluted air.

637 The additional example on 17 July (Fig. 10) is suggestive of an enhancement in aerosol
638 concentration associated with the SBF event, while the 16 August event (Fig. 11) is indicative
639 of a neutral influence from the SBF passage. Similar to 10 July, both days exhibit an increase
640 in w associated with passage of the SBF, relative to inland areas not influenced by the front
641 (Figs. 10a, 11a). The SBF passage was also accompanied by a decrease in modeled PBLH
642 (Figs. 10b, 11b). On 17 July, the SBF had reached M1 and S3 by ~19:00 and 21:00 UTC,
643 respectively; winds were predominantly from southwest to east, with easterlies likely advecting
644 emissions from the HSC and contributing to the observed enhancements.

645 Notably, the 17 July event occurred in a different ambient aerosol environment than the 10
646 July event. MERRA-2 column dust mass concentrations (Fig. S9) indicate Saharan dust
647 transport on this day, yielding elevated dust loading over the Gulf of Mexico and resulting in
648 marine aerosol mass concentrations that exceeded those over land. The high concentrations are
649 also observed to be more prominent to the southwest of the M1 site (Fig. 10c). Hence, as the
650 SBF moves inland on 17 July, it transports this higher aerosol containing air mass, replacing
651 the lower aerosol containing air over the site and causing an increased aerosol concentration at
652 the M1 site. The onshore winds carry an air mass influenced by both local and long-range
653 transport, originating from both land and sea. In contrast to the other two events, the 16 August
654 event occurred under a transitional regime and likely influenced by the bay breeze. The aerosol
655 environment was notably uniform over the wider regional air masses, thus SBF passage
656 resulted in minimal changes to the aerosol distribution (Fig. 11c, d, f).

657 Overall, one implication from these simulations is that the effect of the inland-
658 penetrating SBF on the aerosol environment appears highly dependent on the pre-existing

659 aerosol condition over the location, as well as the air mass characteristics trailing the SBF. The
660 wind anomaly associated with the Gulf breeze front can transport more (less) polluted, particle-
661 laden air mass, leading to increased (decreased) aerosol concentration as it passes the site
662 during the subsequent ~5 hours after the front passes. A study by Deng et al., (2025) using
663 scanning radar data collected during TRACER reported similar findings during one of the SB
664 events on 10 September 2022. They reported a reduced influence on the aerosol concentration
665 immediately after the passing of the bay breeze front for the next few hours, due to the
666 dominance of onshore flow consistent with the findings from this study (Fig. S2).

667

668 3.6 Sea breeze effects on the vertical distribution of aerosols

669 Fig. 12 shows the modeled normalized $PM_{2.5}$ at different elevations before and after the
670 passage of the SBF. On 10 July, the cleaner marine air mass that follows the SBF led to a
671 decrease in aerosol concentration below 1 km at the ARM sites. The model indicates surface
672 convergence along the SBF (Fig. S10.). The aerosol concentrations are redistributed
673 horizontally and vertically. Two hours later, the SBF reaches the S3 site where its passage
674 causes a similar change in the aerosol concentration. The varying extent of this air mass and its
675 inland propagation redistributes the vertical $PM_{2.5}$ profiles from urban to suburban regions as
676 this SBF moves northwest from Houston. Similar to the changes in the aerosol mass
677 concentrations, the changes in the vertical distributions of nu_0 (Fig. 12b) and ac_0 number
678 concentration (Fig. 12c) are not homogeneous within these layers. The cleaner air mass
679 following the SBF replaces the more polluted continental air, lowering aerosol number
680 concentrations. The response is vertically inhomogeneous, reductions are most prominent
681 around M1 and are strongest below ~500 m. Within the 1.5 km, nu_0 shows the largest negative
682 anomalies (often > 80%) immediately behind the SBF, consistent with marine air being
683 relatively depleted in the smallest particles. A thin narrow yellow/orange area (~+70%
684 normalized changes) behind the front (within 1 to 1.5 km) reflects lifting, which can
685 momentarily concentrate or mix in small particles. The ac_0 exhibits a similar pattern but weaker
686 signal. This reflects that accumulation-mode particles are less sensitive to the front, so the
687 reductions are smaller and less uniform, with occasional localized decreases along the front.
688 Overall, the inland-propagating SBF drives an exchange between cleaner marine and more
689 polluted continental air masses, redistributing aerosols both horizontally and vertically.

690 These results compliment those shown in SB simulations by Lu and Turco (1994),
691 Verma et al., (2006), Igel et al., (2018), and Parajuli et al., (2022). Parajuli et al., (2022)
692 observed that the SB pushes dust inland and upward along the mountain slopes, reaching
693 heights of up to 1.5 km. During TRACER, the vertical influence of SAI extended up to ~1.5
694 km (~PBLH). The region of SBC influence is shown to extend inland up to 50 km and vertically
695 up to 2 km over a period of up to 5 hours following the passage of the SBF. The model
696 simulations supplement the observations by filling observational gaps and enabling the
697 extrapolation of findings across a broader regional scale, an endeavor that would be challenging
698 to achieve with limited in-situ observational sites or standalone models.

699

700 3.7 Impacts of sea breeze aerosol interaction on cloud condensation nuclei

701 Fig. 13 shows the time series of the normalized aerosol number concentration with $D_p >$
702 100 nm, N_{100} for the 10 July event. Due to the unavailability of measured CCN data at both M1
703 and S3, N_{100} serves as our proxy for the CCN (CCN_{proxy}) concentration (Ahlm et al., 2013).
704 Hence, the current analysis is limited to observational evidence of N_{100} variability. Similar to
705 the changes in the overall aerosol number budget, the SBF passage and the air mass that follows
706 induces simultaneous changes in the CCN budget. During this event, the CCN_{proxy}
707 concentration decreases by ~35% at the M1 site and ~60% at the S3 site, with these changes
708 observed within an hour of the SBF passage.

709 Simulations performed for this event also suggest similar changes in aerosol budget,
710 indicating that the SBF brings in a cleaner air mass from directions consistent with a more
711 marine environment. Model results suggest that the CCN concentration at the surface decreases
712 by up to 60%, consistent with the observations. In our supplemental Figs. S11. and S12., we
713 include the temporal variation of the normalized N_{100} during all the other SB events during the
714 TRACER IOP. The preexisting N_{100} is less frequently impacted by the SAI than previous
715 examples we provided for SBF changes to the total number concentration, and these events
716 show a decrease in N_{100} for ~25% of the SB events at both M1 and S3 site. This suggests that
717 the influence of SAI is lesser over the marine influenced regional background aerosol larger
718 than 100 nm in diameter.

719

720 4 Summary and conclusions

721 Sea breezes influence multi-scale processes across the land-ocean-atmosphere interface
722 within the region of influence of the SBC. The TRACER field campaign provided a unique
723 opportunity to understand how aerosol and meteorological processes impact weather and
724 climate in the urban and rural coastal environment of Houston, Texas. A total of 46 (M1) and
725 30 (S3) instances of SB passages were identified during the summertime TRACER IOP period.
726 Summertime measurements from the ARM sites coupled with WRF-Chem model simulations
727 (July and August 2022) help to quantify aerosol changes resulting from onshore transport of
728 marine boundary layer air masses due to SBF passage and the associated atmospheric SBC
729 impacts.

730 Understanding the spatial extent and duration of SAIs is crucial for assessing their
731 environmental and meteorological impacts. For inland-penetrating SBFs, aerosol responses fall
732 into one of the three types: reduction (clean marine air replacing more polluted continental air);
733 enhancement (import of more polluted air), or neutral (similar air masses). The sign and
734 magnitude of changes depend on coastal proximity to the coast and the upwind air mass history
735 prior to SBF arrival.

736 TRACER measurements indicate that the urban M1 site, closer to both Galveston Bay
737 and the Gulf of Mexico, experiences more frequent aerosol concentration changes (increase or
738 decrease during 63% of SB events) than the rural S3 site (increase or decrease during 40% of
739 SB days), which is primarily Gulf-breeze influenced and farther from urban/industrial sources.
740 During IOP events, surface aerosol number changed by up to a factor of two. On average, SBF
741 passages were associated with a decrease of ~23% at M1 and increase of ~4% at S3. SBF
742 passages produce distinct aerosol responses depending on the type of SAI event. At M1,
743 enhancement days (28% of SB events) are associated with an average increase of aerosol
744 concentration by ~55%, while reduction days (35% of SB events) show an average decrease of
745 ~42%. At S3, enhancement days (27% of SB events) exhibit an average increase of ~64%,
746 whereas reduction days (13% of SB events) show a decrease of ~45%.

747 This study also provides support for how SAIs may interfere with aerosol microphysical
748 processes, including NPF events, a key driver of the overall aerosol number budget. These
749 changes occur with sharp meteorological shifts, including RH (+30%) and wind speed (+4 m
750 s⁻¹) increases, and backing to southeasterly flow (Figs. 7. and 8.). The relationship between
751 wind and aerosol number concentrations showed that aerosol concentrations at the M1 site are
752 higher when prevailing winds originate from the direction of the Houston urban core

753 (northwest) to north, compared to the winds coming from the sea (south) (Fig. S5). Recently,
754 Rapp et al. (2024) emphasized using targeted mobile sampling that collecting measurements
755 on both sides of SB boundaries are critical for disentangling aerosol from meteorological
756 controls. These findings are complementary to the results in this study that boundary timing
757 and air mass origin drive the different responses at M1 and S3.

758 WRF Chem simulations extend the site perspective regionally, indicating
759 heterogeneous SAI footprints (Figs. 9, 10, 11, and 12). Across 18 simulated events, near surface
760 $PM_{2.5}$ tends to decrease by $\sim 15\%$ around the M1 site and increase by $\sim 3\%$ near the S3 site (Fig.
761 S13). However, these responses vary with altitude (Fig. 12). The SBF may alter the vertical
762 aerosol distribution in the boundary layer up to 2 km. Beyond thermodynamics, SB fronts also
763 reshape convective environments (Wang et al., 2024). The storm characteristics across
764 maritime vs. continental sides of these fronts drive the air mass contrasts produced by SBCs
765 (Sharma et al., 2024), which can further influence the aerosol environment.

766 With respect to cloud-relevant particles, both observations and simulations indicate that
767 the surface CCNproxy concentrations decrease by up to 60% following SBF passage (Fig. 13),
768 although such changes are infrequent ($\sim 25\%$ of the SB events at both M1 and S3 site), implying
769 a weaker impact of SAI on marine influenced regional background accumulation mode. This
770 aligns with Thompson et al. (2025), which showed that aerosol cloud-forming properties differ
771 between polluted marine and continental air masses, with variability in size, hygroscopicity,
772 and CCN efficiency across sites. Given the complex mix of marine, terrestrial, and urban
773 sources, and the strong spatial heterogeneity revealed by both our analysis and prior TRACER
774 studies, future studies should include direct CCN and INP measurements and size-resolved
775 aerosol properties to better capture the role of SAI in aerosol–cloud interactions. It is important
776 to remember that these effects are localized, occurring only during shorter timescales (~ 5
777 hours) associated with daily SBC cycles over these locations. But these SAI timings align with
778 periods of peak solar radiation and elevated aerosol concentrations, potentially leading to
779 significant impacts on the radiation budget over the coastal regions. During times in close
780 proximity to SBF passage, changes in solar radiation and cloud formation may influence the
781 aerosol formation and distribution, modify atmospheric chemical reactions, and affect cloud
782 formation and properties, thereby impacting various atmospheric processes and interactions.
783 Because many coastal cities have high aerosol loading with frequent SBCs, accounting for SAI

784 when estimating direct aerosol radiative forcing is crucial. However, quantifying these changes
785 is challenging, underscoring the need for detailed future studies across diverse coastal regions.

786

787 **Code and data availability.** DOE-ARM datasets can be downloaded from the ARM data
788 discovery (https://adc.arm.gov//discovery/#/results/instrument_class_code::#). The TCEQ
789 data can be downloaded from <https://www.tceq.texas.gov/agency/data> and sfcmetradaq-tceq
790 ARM PI product (<https://doi.org/10.5439/2587278>) The Weather Research and Forecasting
791 Model with Chemistry model code is available from
792 www2.mmm.ucar.edu/wrf/users/download/. WRF-Chem preprocessors are available on the
793 website (www.aom.ucar.edu/wrf-chem). The model output data is made available upon
794 request. The primary tools to analyze the model output and generate figures are CDO
795 (code.mpimet.mpg.de/projects/cdo/), MATLAB (www.mathworks.com/products/), and
796 Jupyter Notebook platform (<https://jupyter.org>).

797

798 **Supplement.** The supplementary document contains supplementary figures referred to in the
799 main manuscript.

800

801 **Author contribution.** TS and CK planned the study; TS conducted the analysis and wrote the
802 manuscript; MH provided the aerosol data; MJ, MD, SG, MH, AS, DW, MZ and CK reviewed
803 and edited the manuscript.

804

805 **Competing interests.** The authors declare that they have no conflict of interest.

806

807 **Acknowledgments.** We would like to acknowledge support from the Atmospheric System
808 Research (ASR) program, the Atmospheric Radiation Measurement (ARM) user facility, and
809 the ARM TRACER operation and science teams. This research was supported in part by
810 resources provided by the National Energy Research Scientific Computing Center (NERSC),
811 a DOE Office of Science User Facility under Contract No. DE-AC02-05CH11231, through
812 NERSC award BER-ERCAP0026649. Additionally, the NE Linux Cluster (nlc) at Brookhaven
813 National Laboratory was utilized for model simulations and output storage.

814

815 **Financial support.** This paper has been authored by employees of Brookhaven Science
816 Associates, LLC, under Contract DE-SC0012704 with the U.S. Department of Energy (DOE).

817

818

819 **References**

820 Ackermann, I. J., Hass, H., Memmesheimer, M., Ebel, A., Binkowski, F. S., & Shankar, U.:
821 Modal aerosol dynamics model for Europe: Development and first applications.
822 Atmospheric Environment, 32(17), 2981–2999. [https://doi.org/10.1016/S1352-](https://doi.org/10.1016/S1352-2310(98)00006-5)
823 2310(98)00006-5, 1998.

824 Adaricheva, K., Bernhardt, J. E., Liu, W., & Schmidt, B.: Importance of overnight parameters
825 to predict Sea Breeze on Long Island. <http://arxiv.org/abs/2309.01803>, 2023.

826 Ahlm, L., Julin, J., Fountoukis, C., Pandis, S. N., & Riipinen, I. (2013). Particle number
827 concentrations over Europe in 2030: The role of emissions and new particle formation.
828 Atmospheric Chemistry and Physics, 13(20), 10271–10283.
829 <https://doi.org/10.5194/acp-13-10271-2013>

830 Ahmadov, R., Gerbig, C., Kretschmer, R., Koerner, S., Neininger, B., Dolman, A. J., & Sarrat,
831 C.: Mesoscale covariance of transport and CO₂ fluxes: Evidence from observations and
832 simulations using the WRF-VPRM coupled atmosphere-biosphere model. Journal of
833 Geophysical Research Atmospheres, 112(22). <https://doi.org/10.1029/2007JD008552>,
834 2007.

835 Albrecht, B. A.: Aerosols, cloud microphysics, and fractional cloudiness. Science, 245, 1227–
836 1230, 1989.

837 Aldhaif, A. M., Lopez, D. H., Dadashazar, H., & Sorooshian, A.: Sources, frequency, and
838 chemical nature of dust events impacting the United States East Coast. Atmospheric
839 Environment, 231. <https://doi.org/10.1016/j.atmosenv.2020.117456>, 2020.

840 Ariya, P., Sun, J., Eltouny, N., Hudson, E. D., Hayes, C. T., & Kos, G.: Physical and chemical
841 characterization of bioaerosols—Implications for nucleation processes. International

842 Reviews in Physical Chemistry, 28(1), 1–32.
843 <https://doi.org/10.1080/01442350802597438>, 2009.

844 Arrillaga, J. A., Jiménez, P., de Arellano, J. V.-G., Jiménez, M. A., Román-Cascón, C., Sastre,
845 M., and Yagüe, C.: Analyzing the synoptic-, meso- and local-scale involved in sea
846 breeze formation and frontal characteristics. *J. Geophys. Res. Atmos.*, 125,
847 e2019JD031302, <https://doi.org/10.1029/2019JD031302>, 2020.

848 Atabakhsh, S., Poulain, L., Bigi, A., Coen, M. C., Pöhlker, M., & Herrmann, H.: Trends of
849 PM1 aerosol chemical composition, carbonaceous aerosol, and source over the last 10
850 years at Melpitz (Germany). *Atmospheric Environment*, 346.
851 <https://doi.org/10.1016/j.atmosenv.2025.121075>, 2025.

852 Augustin, P., Billet, S., Crumeyrolle, S., Deboudt, K., Dieudonné, E., Flament, P., Fourmentin,
853 M., Guilbaud, S., Hanoune, B., Landkocz, Y., Méausoone, C., Roy, S., Schmitt, F. G.,
854 Sentchev, A., & Sokolov, A.: Impact of sea breeze dynamics on atmospheric pollutants
855 and their toxicity in industrial and urban coastal environments. *Remote Sensing*, 12(4).
856 <https://doi.org/10.3390/rs12040648>, 2020.

857 Banta, R. M., Senff, C. J., Alvarez, R. J., Langford, A. O., Parrish, D. D., Trainer, M. K., Darby,
858 L. S., Michael Hardesty, R., Lambeth, B., Andrew Neuman, J., Angevine, W. M.,
859 Nielsen-Gammon, J., Sandberg, S. P., & White, A. B.: Dependence of daily peak O₃
860 concentrations near Houston, Texas on environmental factors: Wind speed,
861 temperature, and boundary-layer depth. *Atmospheric Environment*, 45(1), 162–173.
862 <https://doi.org/10.1016/j.atmosenv.2010.09.030>, 2011.

863 Bao, S., Pietrafesa, L., Gayes, P., Noble, S., Viner, B., Qian, J. H., Werth, D., Mitchell, G., &
864 Burdette, S.: Mapping the Spatial Footprint of Sea Breeze Winds in the Southeastern
865 United States. *Journal of Geophysical Research: Atmospheres*, 128(7).
866 <https://doi.org/10.1029/2022JD037524>, 2023.

867 Barrett, T. E., & Sheesley, R. J.: Urban impacts on regional carbonaceous aerosols: Case study
868 in central Texas. *Journal of the Air and Waste Management Association*, 64(8), 917–
869 926. <https://doi.org/10.1080/10962247.2014.904252>, 2014.

870 Bauman, W. H.: Verify MesoNAM Performance. NASA Contractor Report CR-2010-216-287,
871 Kennedy Space Center, FL, 31 pp. [Available from ENSCO, Inc., 1980 N. Atlantic

872 Ave., Suite 830, Cocoa Beach, FL, 32931 and online at
873 <http://science.ksc.nasa.gov/amu/final-reports/mesoNAMverify.pdf>], 2010.

874 Bond, T. C., Doherty, S. J., Fahey, D. W., Forster, P. M., Berntsen, T., Deangelo, B. J., Flanner,
875 M. G., Ghan, S., Kärcher, B., Koch, D., Kinne, S., Kondo, Y., Quinn, P. K., Sarofim,
876 M. C., Schultz, M. G., Schulz, M., Venkataraman, C., Zhang, H., Zhang, S., ... Zender,
877 C. S.: Bounding the role of black carbon in the climate system: A scientific assessment.
878 *Journal of Geophysical Research Atmospheres*, 118(11), 5380–5552.
879 <https://doi.org/10.1002/jgrd.50171>, 2013.

880 Borge, R., Alexandrov, V., José del Vas, J., Lumberras, J., & Rodríguez, E.: A comprehensive
881 sensitivity analysis of the WRF model for air quality applications over the Iberian
882 Peninsula. *Atmospheric Environment*, 42(37), 8560–8574.
883 <https://doi.org/10.1016/j.atmosenv.2008.08.032>, 2008.

884 Boyer, C. H., Keeler, J. M., & Rakoczy, B. C. (2025). An Idealized Parameter Study of
885 Destabilization and Convection Initiation in Coastal Regions. Part I: Calm or Offshore
886 Synoptic-Scale Flow. *Journal of the Atmospheric Sciences*, 82(3), 519–539.
887 <https://doi.org/10.1175/JAS-D-23-0180.1>

888 Boyouk, N., Léon, J. F., Delbarre, H., Augustin, P., & Fourmentin, M.: Impact of sea breeze
889 on vertical structure of aerosol optical properties in Dunkerque, France. *Atmospheric*
890 *Research*, 101(4), 902–910. <https://doi.org/10.1016/j.atmosres.2011.05.016>, 2011.

891 Bozlaker, A., Prospero, J. M., Fraser, M. P., & Chellam, S.: Quantifying the contribution of
892 long-range saharan dust transport on particulate matter concentrations in Houston,
893 Texas, using detailed elemental analysis. *Environmental Science and Technology*,
894 47(18), 10179–10187. <https://doi.org/10.1021/es4015663>, 2013.

895 Brown, S., Nicholls, R. J., Woodroffe, C. D., Hanson, S., Hinkel, J., Kebede, A. S., Neumann,
896 B. and Vafeidis, A. T.: “Sea-Level Rise Impacts and Responses: A Global Perspective.”
897 In *Coastal Hazards*, edited by Charles W. Finkl, 117–49. Dordrecht: Springer
898 Netherlands. https://doi.org/10.1007/978-94-007-5234-4_5, 2013.

899 Burkart, J., Gratzl, J., Seifried, T. M., Bieber, P., & Grothe, H.: Subpollen particles (SPP) of
900 birch as carriers of ice nucleating macromolecules. *Biogeosciences Discussions*, 1–15,
901 2021.

- 902 Charlson, R. J., Schwartz, S. E., Hales, J. M., Cess, R. D., Coakley, J. A. Jr, Hansen, J. E., and
903 Hofmann, D. J.: Climate forcing by anthropogenic aerosols. *Science* 255, 423—430,
904 1992.
- 905 Chen, F., & Dudhia, J.: Coupling an advanced land surface-hydrology model with the Penn
906 State-NCAR MM5 modeling system. Part I: Model implementation and sensitivity.
907 *Monthly Weather Review*, 129(4), 569–585. [https://doi.org/10.1175/1520-
908 0493\(2001\)129<0569:caalsh>2.0.co;2](https://doi.org/10.1175/1520-0493(2001)129<0569:caalsh>2.0.co;2), 2001.
- 909 Chou, M., Suarez, M. J., Ho, C., Yan, M. M., & Lee, K.: Parameterizations for cloud
910 overlapping and shortwave single-scattering properties for use in general circulation
911 and cloud ensemble models. *Journal of Climate*, 11(2), 202–214. [https://doi.
912 org/10.1175/1520-0442\(1998\)011<0202:PFCOAS>2.0.CO;2](https://doi.org/10.1175/1520-0442(1998)011<0202:PFCOAS>2.0.CO;2), 1998.
- 913 Clappier, A., Martilli, A., Grossi, P., Thunis, P., Pasi, F., Krueger, B. C., Calpini, B., &
914 Graziani, G., Bergh, H.V.D.: Effect of Sea Breeze on Air Pollution in the Greater
915 Athens Area. Part I: Numerical Simulations and Field Observations. *J. of Applied
916 meteorology*, (39). [https://doi.org/10.1175/1520-
917 0450\(2000\)039<0546:EOSBOA>2.0.CO;2](https://doi.org/10.1175/1520-0450(2000)039<0546:EOSBOA>2.0.CO;2), 1999.
- 918 Comin, A. N., Miglietta, M. M., Rizza, U., Acevedo, O. C., & Degrazia, G. A.: Investigation
919 of sea-breeze convergence in Salento Peninsula (southeastern Italy). *Atmospheric
920 Research*, 160, 68–79. <https://doi.org/10.1016/j.atmosres.2015.03.010>, 2015.
- 921 Crippa, M., Canonaco, F., Lanz, V. A., Äijälä, M., Allan, J. D., Carbone, S., Capes, G.,
922 Ceburnis, D., Dall’Osto, M., Day, D. A., DeCarlo, P. F., Ehn, M., Eriksson, A., Freney,
923 E., Hildebrandt Ruiz, L., Hillamo, R., Jimenez, J. L., Junninen, H., KiendlerScharr, A.,
924 Kortelainen, A. M., Kulmala, M., Laaksonen, A., Mensah, A. A., Mohr, C., Nemitz, E.,
925 O’Dowd, C., Ovadnevaite, J., Pandis, S. N., Petäjä, T., Poulain, L., Saarikoski, S.,
926 Sellegri, K., Swietlicki, E., Tiitta, P., Worsnop, D. R., Baltensperger, U., Prévôt, A. S.
927 H.: Organic aerosol components derived from 25 AMS data sets across Europe using a
928 consistent ME-2 based source apportionment approach. *Atmos. Chem. Phys.* 14 (12),
929 6159–6176. <https://doi.org/10.5194/acp-14-6159>, 2014.
- 930 Crossett, K., Culliton, T., Wiley, P., & Goodspeed, T.: Population trends along the coastal
931 United States, 1980–2008. Silver Spring, National Oceanic and Atmospheric
932 Administration, 2004.

933 Das, S., Prospero, J. M., & Chellam, S.: Quantifying international and interstate contributions
934 to primary ambient PM_{2.5} and PM₁₀ in a complex metropolitan atmosphere.
935 Atmospheric Environment, 292. <https://doi.org/10.1016/j.atmosenv.2022.119415>,
936 2023.

937 Deng, Min, et al.: A Closed Bay-Breeze Circulation and Its Lifecycle from TRACER with a
938 New Orienteering Tape Recorder Diagram, Journal of Geophysical Research:
939 Atmospheres (under revision), 2025.

940 di Bernardino, A., Iannarelli, A. M., Casadio, S., Mevi, G., Campanelli, M., Casasanta, G.,
941 Cede, A., Tiefengraber, M., Siani, A. M., Spinei, E., & Cacciani, M.: On the effect of
942 sea breeze regime on aerosols and gases properties in the urban area of Rome, Italy.
943 Urban Climate, 37. <https://doi.org/10.1016/j.uclim.2021.100842>, 2021.

944 Emmons, L. K., Walters, S., Hess, P. G., Lamarque, J. F., Pfister, G. G., Fillmore, D., et al.:
945 Description and evaluation of the model for ozone and related chemical tracers, version
946 4 (MOZART-4). Geoscientific Model Development, 3(1), 43–67.
947 <https://doi.org/10.5194/gmd-3-43-2010>, 2010.

948 Dueker, M. E., O'Mullan, G. D., Martínez, J. M., Juhl, A. R., & Weathers, K. C.: Onshore
949 wind speed modulates microbial aerosols along an urban waterfront. Atmosphere,
950 8(11). <https://doi.org/10.3390/atmos8110215>, 2017.

951 Fang, C., Li, X., Li, J., Tian, J., & Wang, J. (2025). Research on the impact of land use and
952 land cover changes on local meteorological conditions and surface ozone in the north
953 China plain from 2001 to 2020. Scientific Reports, 15(1).
954 <https://doi.org/10.1038/s41598-025-85940-0>

955 Gangoiti, G., Millán, M. M., Salvador, R., & Mantilla, E.: Long-range transport and re-
956 circulation of pollutants in the western Mediterranean during the project Regional
957 Cycles of Air Pollution in the West-Central Mediterranean Area. Atmospheric
958 Environment, 35(36), 6267–6276. [https://doi.org/10.1016/S1352-2310\(01\)00440-X](https://doi.org/10.1016/S1352-2310(01)00440-X),
959 2001.

960 Gelaro, R., and Coauthors: The Modern-Era Retrospective Analysis for Research and
961 Applications, version 2 (MERRA-2). J. Climate, 30, 5419–5454,
962 <https://doi.org/10.1175/JCLI-D-16-0758.1>, 2017.

963 Georgiou, G. K., Christoudias, T., Proestos, Y., Kushta, J., Pikridas, M., Sciare, J., Savvides,
964 C., & Lelieveld, J.: Evaluation of WRF-Chem model (v3.9.1.1) real-Time air quality
965 forecasts over the Eastern Mediterranean. *Geoscientific Model Development*, 15(10),
966 4129–4146. <https://doi.org/10.5194/gmd-15-4129-2022>, 2022.

967 Gettelman, A., Mills, M. J., Kinnison, D. E., Garcia, R. R., Smith, A. K., Marsh, D. R., et al.:
968 The whole atmosphere community climate model version 6 (WACCM6). *Journal of*
969 *Geophysical Research: Atmospheres*, 124, <https://doi.org/10.1029/2019JD030943>,
970 2019.

971 Glantz, P., Nilsson, D. E., & von Hoyningen-Huene, W. (2006). Estimating a relationship
972 between aerosol optical thickness and surface wind speed over the ocean. In *Atmos.*
973 *Chem. Phys. Discuss* (Vol. 6). www.atmos-chem-phys-discuss.net/6/11621/2006/

974 Grell, G. A., & Devenyi, D.: A generalized approach to parameterizing convection combining
975 ensemble and data assimilation techniques. *Geophysical Research Letters*, 29(4), 38-1–
976 38-4. <https://doi.org/10.1029/2002GL015311>, 2002.

977 Grell, G. A., Peckham, S. E., Schmitz, R., McKeen, S. A., Frost, G., Skamarock, W. C., &
978 Eder, B.: Fully coupled “online” chemistry within the WRF model. *Atmospheric*
979 *Environment*, 39(37), 6957–6975. <https://doi.org/10.1016/j.atmosenv.2005.04.027>,
980 2005.

981 Guenther, A. B., Jiang, X., Heald, C. L., Sakulyanontvittaya, T., Duhl, T., Emmons, L. K., &
982 Wang, X.: The model of emissions of gases and aerosols from nature version 2.1
983 (MEGAN2.1): An extended and updated framework for modeling biogenic emissions.
984 *Geoscientific Model Development*, 5(6), 1471–1492. [https://doi.org/10.5194/gmd-5-](https://doi.org/10.5194/gmd-5-1471-2012)
985 1471-2012, 2012.

986 Hanft, W., & Houston, A. L.: An Observational and Modeling Study of Mesoscale Air Masses
987 with High Theta-E. <https://doi.org/10.1175/MWR-D-17>, 2018.

988 Hernández-Ceballos, M. A., Sorribas, M., San Miguel, E. G., Cinelli, G., Adame, J. A., &
989 Bolívar, J. P.: Impact of sea-land breezes on 210Pb in southern Iberian Peninsula–
990 Feasibility study on using submicron-sized aerosol particles to analyze 210Pb hourly
991 patterns. *Atmospheric Pollution Research*, 7(1), 1–8.
992 <https://doi.org/10.1016/j.apr.2015.06.011>, 2016.

- 993 Hong, S. Y., Noh, Y., & Dudhia, J.: A new vertical diffusion package with an explicit treatment
994 of entrainment processes. *Monthly Weather Review*, 134(9), 2318–2341.
995 <https://doi.org/10.1175/MWR3199.1>, 2006.
- 996 Hu, L. (2021). A Global Assessment of Coastal Marine Heatwaves and Their Relation With
997 Coastal Urban Thermal Changes. *Geophysical Research Letters*, 48(9).
998 <https://doi.org/10.1029/2021GL093260>
- 999 Huang, X. F., He, L. Y., Hu, M., Canagaratna, M. R., Sun, Y., Zhang, Q., Zhu, T., Xue, L.,
1000 Zeng, L. W., Liu, X. G., Zhang, Y. H., Jayne, J. T., Ng, N. L., Worsnop, D. R.: Highly
1001 time-resolved chemical characterization of atmospheric submicron particles during
1002 2008 Beijing Olympic Games using an Aerodyne High-Resolution Aerosol Mass
1003 Spectrometer. *Atmos. Chem. Phys.* 2010, 10, 8933– 8945, DOI: 10.5194/acp-10-8933-
1004 2010.
- 1005 Hudson, B.: Coastal Land Loss and the Mitigation-Adaptation Dilemma: Between Scylla and
1006 Charybdis Repository Citation Coastal Land Loss and the Mitigation-Adaptation
1007 Dilemma: Between Scylla and Charybdis. In *Louisiana Law Review* (Vol. 73).
1008 <https://digitalcommons.law.lsu.edu/lalrev/vol73/iss1/3>, 2012.
- 1009 Igel, A. L., van den Heever, S. C., & Johnson, J. S.: Meteorological and Land Surface
1010 Properties Impacting Sea Breeze Extent and Aerosol Distribution in a Dry
1011 Environment. *Journal of Geophysical Research: Atmospheres*, 123(1), 22–37.
1012 <https://doi.org/10.1002/2017JD027339>, 2018.
- 1013 IPCC, Intergovernmental Panel on Climate Change: In V. Masson-Delmotte, P. Zhai, A.
1014 Pirani, S. L. Connors, C. P. an, S. Berger, et al. (Eds.), *The Physical Science Basis.*
1015 *Contribution of Working Group I to the Sixth Assessment Report of the*
1016 *Intergovernmental Panel on Climate Change.* Cambridge University Press.
1017 <https://doi.org/10.1017/9781009157896>, 2021.
- 1018 Iwai, H., Murayama, Y., Ishii, S., Mizutani, K., Ohno, Y., & Hashiguchi, T.: Strong Updraft at
1019 a Sea-Breeze Front and Associated Vertical Transport of Near-Surface Dense Aerosol
1020 Observed by Doppler Lidar and Ceilometer. *Boundary-Layer Meteorology*, 141(1),
1021 117–142. <https://doi.org/10.1007/s10546-011-9635-z>, 2011.
- 1022 Janjic, Z. I.: Nonsingular implementation of the Mellor–Yamada level 2.5 scheme in the NCEP
1023 Meso model. *NCEP Office Note*, 437, 61, 2002.

- 1024 Jensen, M. P., and Coauthors, (2022): A Succession of Cloud, Precipitation, Aerosol, and Air
1025 Quality Field Experiments in the Coastal Urban Environment. *Bull. Amer. Meteor.*
1026 *Soc.*, 103, 103–105, <https://doi.org/10.1175/BAMS-D-21-0104.1>, 2022.
- 1027 Jensen, M. P., Flynn, J. H., Gonzalez-Cruz, J. E., Judd, L. M., Kollias, P., Kuang, C.,
1028 McFarquhar, G. M., Powers, H., Ramamurthy, P., Sullivan, J., Aiken, A. C., Alvarez,
1029 S. L., Argay, P., Argrow, B., Bell, T. M., Boyer, D., Brooks, S. D., Bruning, E. C.,
1030 Brunner, K., ... Zhu, Z. (2025). Studying Aerosol, Clouds, and Air Quality in the
1031 Coastal Urban Environment of Southeastern Texas. *Bulletin of the American*
1032 *Meteorological Society*. <https://doi.org/10.1175/bams-d-23-0331.1>
- 1033 Karnae, S., & John, K.: Source apportionment of PM_{2.5} measured in South Texas near U.S.A.
1034 – Mexico border. *Atmospheric Pollution Research*, 10(5), 1663–1676.
1035 <https://doi.org/10.1016/j.apr.2019.06.007>
- 1036 Kerminen, V. M., Chen, X., Vakkari, V., Petäjä, T., Kulmala, M., & Bianchi, F. : Atmospheric
1037 new particle formation and growth: Review of field observations. In *Environmental*
1038 *Research Letters* (Vol. 13, Issue 10). Institute of Physics Publishing.
1039 <https://doi.org/10.1088/1748-9326/aadf3c>, 2018.
- 1040 Kgabi, N. A., & Mokgwetsi, T. (2009). Dilution and dispersion of inhalable particulate matter.
1041 *WIT Transactions on Ecology and the Environment*, 127, 229–238.
1042 <https://doi.org/10.2495/RAV090201>
- 1043 Kleinman, L. I., Daum, P. H., Imre, D. G., Lee, Y.-N., Nunnermacker, L. J., Springston, S. R.,
1044 Weinstein-Lloyd, J., and Rudolph, J.: Ozone production rate and hydrocarbon reactivity
1045 in 5 urban areas: A cause of high ozone concentration in Houston, *Geophys. Res. Lett.*,
1046 29(10), 1467, doi:10.1029/2001GL014569, 2002.
- 1047 Kuang, C., Chen, M., Zhao, J., Smith, J., McMurry, P. H., & Wang, J.: Size and time-resolved
1048 growth rate measurements of 1 to 5 nm freshly formed atmospheric nuclei. *Atmospheric*
1049 *Chemistry and Physics*, 12(7), 3573–3589. <https://doi.org/10.5194/acp-12-3573-2012>,
1050 2012.
- 1051 Kuang, C., McMurry, P. H., and McCormick, A. V.: Determination of cloud condensation
1052 nuclei production from measured new particle formation events, *Geophys. Res. Lett.*,
1053 36, L09822, doi:10.1029/2009GL037584, 2009.

1054 Kulmala, M., Laakso, L., Lehtinen, K. E. J., Riipinen, I., Dal Maso, M., Anttila, T., Kerminen,
1055 V.-M., Horrak, U., Vana, M., and Tammet, H.: Initial steps of aerosol growth, *Atmos.*
1056 *Chem. Phys.*, 4, 2553–2560, doi:10.5194/acp-4-2553-2004, 2004.

1057 Kulmala, M., Petäjä, T., Ehn, M., Thornton, J., Sipilä, M., Worsnop, D. R., & Kerminen, V.
1058 M.: Chemistry of atmospheric nucleation: On the recent advances on precursor
1059 characterization and atmospheric cluster composition in connection with atmospheric
1060 new particle formation. *Annual Review of Physical Chemistry*, 65, 21–37.
1061 <https://doi.org/10.1146/annurev-physchem-040412-110014>, 2014.

1062 Levy, M. E., Zhang, R., Khalizov, A. F., Zheng, J., Collins, D. R., Glen, C. R., Wang, Y., Yu,
1063 X. Y., Luke, W., Jayne, J. T., & Olaguer, E.: Measurements of submicron aerosols in
1064 Houston, Texas during the 2009 SHARP field campaign. *Journal of Geophysical*
1065 *Research Atmospheres*, 118(18), 10,518-10,534. <https://doi.org/10.1002/jgrd.50785>,
1066 2013.

1067 Li, W., Wang, Y., Bernier, C., & Estes, M.: Identification of Sea Breeze Recirculation and Its
1068 Effects on Ozone in Houston, TX, During DISCOVER-AQ 2013. *Journal of*
1069 *Geophysical Research: Atmospheres*, 125(22). <https://doi.org/10.1029/2020JD033165>,
1070 2020.

1071 Linden, P.F., Simpson, J.E., Gravity-driven flows in a turbulent fluid. *Journal of Fluid*
1072 *Mechanics*, 172, 481-497. doi:10.1017/S0022112086001829, 1986.

1073 Liu, H., Zhang, B., Moore, R. H., Ziemba, L. D., Ferrare, R. A., Choi, H., Sorooshian, A.,
1074 Painemal, D., Wang, H., Shook, M. A., Scarino, A. J., Hair, J. W., Crosbie, E. C., Fenn,
1075 M. A., Shingler, T. J., Hostetler, C. A., Chen, G., Kleb, M. M., Luo, G., ... Johnson,
1076 M. S.: Tropospheric aerosols over the western North Atlantic Ocean during the winter
1077 and summer deployments of ACTIVATE 2020: Life cycle, transport, and distribution.
1078 *Atmospheric Chemistry and Physics*, 25(4), 2087–2121. [https://doi.org/10.5194/acp-](https://doi.org/10.5194/acp-25-2087-2025)
1079 [25-2087-2025](https://doi.org/10.5194/acp-25-2087-2025), 2025.

1080 Lu, R., & Turco, R. P.: Air pollutant transport in a coastal environment.1. 2-dimensional
1081 simulations of sea-breeze and mountain effects. *Journal of the Atmospheric Sciences*,
1082 51(15), 2285–2308. [https://doi.org/10.1175/1520-](https://doi.org/10.1175/1520-0469(1994)051<2285:APTIAC>2.0.CO;2)
1083 [0469\(1994\)051<2285:APTIAC>2.0.CO;2](https://doi.org/10.1175/1520-0469(1994)051<2285:APTIAC>2.0.CO;2), 1994.

- 1084 Ma, S., & Tong, D. Q.: Neighborhood Emission Mapping Operation (NEMO): A 1-km
1085 anthropogenic emission dataset in the United States. *Scientific Data*, 9(1).
1086 <https://doi.org/10.1038/s41597-022-01790-9>, 2022.
- 1087 Mack, S. M., Madl, A. K., & Pinkerton, K. E.: Respiratory health effects of exposure to ambient
1088 particulate matter and bioaerosols. *Comprehensive Physiology*, 10(1), 1–20.
1089 <https://doi.org/10.1002/cphy.c180040>, 2020.
- 1090 Mao, F., Zang, L., Wang, Z., Pan, Z., Zhu, B., & Gong, W.: Dominant synoptic patterns during
1091 wintertime and their impacts on aerosol pollution in Central China. *Atmospheric*
1092 *Research*, 232. <https://doi.org/10.1016/j.atmosres.2019.104701>, 2020.
- 1093 Maria, V. D., Rahman, M., Collins, P., Dondi, G., & Sangiorgi, C. (2013). Urban Heat Island
1094 Effect: Thermal Response from Different Types of Exposed Paved Surfaces.
1095 *International Journal of Pavement Research and Technology*, 6(4), 414-422.
1096 [https://doi.org/10.6135/ijprt.org.tw/2013.6\(4\).414](https://doi.org/10.6135/ijprt.org.tw/2013.6(4).414)
- 1097 Masselink, G., and Pattiaratchi, C. B.: The effect of sea breeze on beach morphology, surf zone
1098 hydrodynamics and sediment resuspension, *Mar. Geol.*, 146, 115–135, 1998.
- 1099 Mather, J. H., and Voyles, J. W.: The Arm Climate Research Facility: A Review of Structure
1100 and Capabilities. *Bull. Amer. Meteor. Soc.*, 94, 377–392,
1101 <https://doi.org/10.1175/BAMS-D-11-00218.1>, 2013.
- 1102 Miller, S. T. K., Keim, B. D., Talbot, R. W., & Mao, H.: Sea breeze: Structure, forecasting,
1103 and impacts. *Reviews of Geophysics*, 41(3). <https://doi.org/10.1029/2003RG000124>,
1104 2003.
- 1105 Minguillón, M. C., Ripoll, A., Pérez, N., Prévôt, A. S. H., Canonaco, F., Querol, X., and
1106 Alastuey, A.: Chemical characterization of submicron regional background aerosols in
1107 the western Mediterranean using an Aerosol Chemical Speciation Monitor, *Atmos.*
1108 *Chem. Phys.*, 15, 6379–6391, <https://doi.org/10.5194/acp-15-6379-2015>, 2015.
- 1109 Mlawer, E. J., Taubman, S. J., Brown, P. D., Iacono, M., & Clough, S. A.: Radiative transfer
1110 for inhomogeneous atmospheres: RRTM, a validated correlated-k model for the
1111 longwave. *Journal of Geophysical Research*, 102(D14), 16663–16682.
1112 <https://doi.org/10.1029/97JD00237>, 1997.

- 1113 Monin, A. S., & Obukhov, A. M.: Basic laws of turbulent mixing in the surface layer of the
1114 atmosphere. Contributions of the Geophysical Institute of the Slovak Academy of
1115 Science, USSR, 151, 163–187, 1954.
- 1116 Moorthy, K. K., Murthy, B. V. K., and Nair, P. R.: Sea-breeze front effects on boundary layer
1117 aerosols at a tropical station, *J. Appl. Meteorol.*, 32, 1196–1205. 1993.
- 1118 Moorthy, K. K., Pillai, P. S., & Suresh Babu, S.: Influence of changes in the prevailing synoptic
1119 conditions on the response of aerosol characteristics to land-and sea-breeze circulations
1120 at a coastal station. In *Boundary-Layer Meteorology* (Vol. 108), 2003.
- 1121 Morrison, H., Curry, J. A., and Khvorostyanov, V. I.: A new double-moment microphysics
1122 parameterization for application in cloud and climate models. Part I: Description.
1123 *Journal of the Atmospheric Sciences*, 62(6), 1665–1677.
1124 <https://doi.org/10.1175/jas3446.1>, 2005.
- 1125 Papanastasiou, D. K., Melas, D., Bartzanas, T., & Kittas, C.: Temperature, comfort and
1126 pollution levels during heat waves and the role of sea breeze. *International Journal of*
1127 *Biometeorology*, 54(3), 307–317. <https://doi.org/10.1007/s00484-009-0281-9>, 2010.
- 1128 Parajuli, S. P., Stenchikov, G. L., Ukhov, A., Mostamandi, S., Kucera, P. A., Axisa, D.,
1129 Gustafson, W. I., & Zhu, Y.: Effect of dust on rainfall over the Red Sea coast based on
1130 WRF-Chem model simulations. *Atmospheric Chemistry and Physics*, 22(13), 8659–
1131 8682. <https://doi.org/10.5194/acp-22-8659-2022>, 2022.
- 1132 Parajuli, S., Stenchikov, G. G., Ukhov, A., Shevchenko, I., Dubovik, O., & Lopatin, A.:
1133 Aerosol vertical distribution and interactions with land/sea breezes over the eastern
1134 coast of the Red Sea from lidar data and high-resolution WRF-Chem simulations.
1135 *Atmospheric Chemistry and Physics*, 20(24), 16089–16116.
1136 <https://doi.org/10.5194/acp-20-16089-2020>, 2020.
- 1137 Park, J. M., van den Heever, S. C., Igel, A. L., Grant, L. D., Johnson, J. S., Saleeby, S. M.,
1138 Miller, S. D., & Reid, J. S. (2020). Environmental Controls on Tropical Sea Breeze
1139 Convection and Resulting Aerosol Redistribution. *Journal of Geophysical Research:*
1140 *Atmospheres*, 125(6). <https://doi.org/10.1029/2019JD031699>, 2020.

- 1141 Park, M. J., and van den Heever, S. C.: Weakening of tropical sea breeze convective systems
1142 through interactions of aerosol, radiation, and soil moisture. *Atmospheric Chemistry*
1143 *and Physics*, 22(16), 10527–10549. <https://doi.org/10.5194/acp-22-10527-2022>, 2022.
- 1144 Parrish, D. D., Allen, D. T., Bates, T. S., Estes, M., Fehsenfeld, F. C., Feingold, G., Ferrare,
1145 R., Hardesty, R. M., Meagher, J. F., Nielsen-Gammon, J. W., Pierce, R. B., Ryerson,
1146 T. B., Seinfeld, J. H., & Williams, E. J.: Overview of the second texas air quality study
1147 (TexAQS II) and the Gulf of Mexico atmospheric composition and climate study
1148 (GoMACCS). *Journal of Geophysical Research Atmospheres*, 114(13).
1149 <https://doi.org/10.1029/2009JD011842>, 2009.
- 1150 Partanen, A. I., Landry, J. S., and Matthews, H. D.: Climate and health implications of future
1151 aerosol emission scenarios. *Environmental Research Letters*, 13(2).
1152 <https://doi.org/10.1088/1748-9326/aaa511>, 2018.
- 1153 Perry, K. D., Cahill, T. A., Eldred, R. A., Dutcher, D. D., and Gill, T. E.: Long-range transport
1154 of North African dust to the eastern United States. *Journal of Geophysical Research*
1155 *Atmospheres*, 102(10), 11225–11238. <https://doi.org/10.1029/97jd00260>, 1997.
- 1156 Pinto, J. P., Dibb, J., Lee, B. H., Rappenglück, B., Wood, E. C., Levy, M., Zhang, R. Y., Lefer,
1157 B., Ren, X. R., Stutz, J., Tsai, C., Ackermann, L., Golovko, J., Herndon, S. C., Oakes,
1158 M., Meng, Q. Y., Munger, J. W., Zahniser, M., & Zheng, J.: Intercomparison of field
1159 measurements of nitrous acid (HONO) during the SHARP campaign. *Journal of*
1160 *Geophysical Research*, 119(9), 5583–5601. <https://doi.org/10.1002/2013JD020287>,
1161 2014.
- 1162 Plant, R. S., & Keith, G. J.: Occurrence of Kelvin-Helmholtz billows in sea-breeze circulations.
1163 *Boundary-Layer Meteorology*, 122(1), 1–15. [https://doi.org/10.1007/s10546-006-](https://doi.org/10.1007/s10546-006-9089-x)
1164 [9089-x](https://doi.org/10.1007/s10546-006-9089-x), 2007.
- 1165 Qi, L., Vogel, A. L., Esmailirad, S., Cao, L., Zheng, J., Jaffrezo, J. L., Fermo, P., Kasper-
1166 Giebl, A., Daellenbach, K. R., Chen, M., Ge, X., Baltensperger, U., Prévôt, A. S. H., &
1167 Slowik, J. G.: A 1-year characterization of organic aerosol composition and sources
1168 using an extractive electrospray ionization time-of-flight mass spectrometer (EESI-
1169 TOF). *Atmospheric Chemistry and Physics*, 20(13), 7875–7893.
1170 <https://doi.org/10.5194/acp-20-7875-2020>, 2020.

1171 Ramanathan, V., Crutzen, P. J., Kiehl, J. T., & Rosenfeld, D.: Aerosols, Climate, and the
1172 Hydrological Cycle. *Science*, 294, 5549, DOI: 10.1126/science.1064034, 2001.

1173 Rao, P. A., & Fuelberg, H. E.: An Investigation of Convection behind the Cape Canaveral Sea-
1174 Breeze Front, 2000.

1175 Rapp, A. D., Brooks, S. D., Nowotarski, C. J., Sharma, M., Thompson, S. A., Chen, B., et al.
1176 (2024). TAMU TRACER: Targeted mobile measurements to isolate the impacts of
1177 aerosols and meteorology on deep convection. *Bulletin of the American Meteorological*
1178 *Society*, 105(9), E1685–E1702. <https://doi.org/10.1175/BAMS-D-23-0218.1>

1179 Rodier, Q., Masson, V., Couvreux, F., & Paci, A. (2017). Evaluation of a buoyancy and shear
1180 based mixing length for a turbulence scheme. *Frontiers in Earth Science*, 5.
1181 <https://doi.org/10.3389/feart.2017.00065>

1182 Rosenfeld, D., et al.: Flood or drought: How do aerosols affect precipitation? *Science*, 321,
1183 1309–1313, 2008.

1184 Ryerson, T. B., Trainer, M., Angevine, W. M., Brock, C. A., Dissly, R. W., Fehsenfeld, F. C.,
1185 Frost, G. J., Goldan, P. D., Holloway, J. S., Hübler, G., Jakoubek, R. O., Kuster, W. C.,
1186 Neuman, J. A., Nicks, D. K., Parrish, D. D., Roberts, J. M., Sueper, D. T., Atlas, E. L.,
1187 Donnelly, S. G., et al.: Effect of petrochemical industrial emissions of reactive alkenes
1188 and NO_x on tropospheric ozone formation in Houston, Texas. *Journal of Geophysical*
1189 *Research: Atmospheres*, 108(8). <https://doi.org/10.1029/2002jd003070>, 2003.

1190 Schell, B., Ackerman, I. J., Hass, H., Binkowski, F. S., & Ebel, A.: Modelling the formation
1191 of secondary organic aerosol within a comprehensive air quality model system. *Journal*
1192 *of Geophysical Research*, 106(D22), 28275–28293.
1193 <https://doi.org/10.1029/2001JD000384>, 2001.

1194 Seinfeld, J.H.; Pandis, S.N. *Atmospheric Chemistry and Physics: From Air Pollution to*
1195 *Climate Change*, 2nd ed.; Wiley: Hoboken, NJ, USA, 2006.

1196 Sharma, M., Rapp, A. D., Nowotarski, C. J., & Brooks, S. D. (2024). Observed Variability in
1197 Convective Cell Characteristics and Near-Storm Environments across the Sea- and
1198 Bay-Breeze Fronts in Southeast Texas. *Monthly Weather Review*, 152(11), 2419–2441.
1199 <https://doi.org/10.1175/MWR-D-23-0243.1>

1200 Shrestha, S., Zhou, S., Mehra, M., Guagenti, M., Yoon, S., Alvarez, S. L., Guo, F., Chao, C.
1201 Y., Flynn, J. H., Wang, Y., Griffin, R. J., Usenko, S., & Sheesley, R. J.: Evaluation of
1202 aerosol- and gas-phase tracers for identification of transported biomass burning
1203 emissions in an industrially influenced location in Texas, USA. *Atmospheric Chemistry
1204 and Physics*, 23(19), 10845–10867. <https://doi.org/10.5194/acp-23-10845-2023>, 2023.

1205 Shrivastava, M., Zhang, J., Zaveri, R. A., Zhao, B., Pierce, J. R., O'Donnell, S. E., et al.:
1206 Anthropogenic extremely low volatility organics (ELVOCs) govern the growth of
1207 molecular clusters over the Southern Great Plains during the springtime. *Journal of
1208 Geophysical Research: Atmospheres*, 129, e2024JD041212,
1209 <https://doi.org/10.1029/2024JD041212>, 2024.

1210 Simpson, J. E.: *Sea Breeze and Local Wind*, 234 pp., Cambridge Univ. Press, New York, 1994.

1211 Singh, A. and Kuang, C.: *Scanning Mobility Particle Sizer (SMPS) Instrument Handbook*. U.S.
1212 Department of Energy, Atmospheric Radiation Measurement user facility, Richland,
1213 Washington. DOE/SC-ARM-TR-147, 2024.

1214 Skamarock, W. C., Klemp, J. B., Dudhia, J., Gill, D. O., Barker, D., Wang, W., Powers, J. G.:
1215 A description of the Advanced Research WRF version 3. NCAR Tech. Note
1216 NCAR/TN-475+STR, 113 pp., doi:10.5065/D68S4MVH, 2008.

1217 Song, S. K., Choi, Y. N., Choi, Y., Flynn, J., & Sadeghi, B.: Characteristics of aerosol chemical
1218 components and their impacts on direct radiative forcing at urban and suburban
1219 locations in Southeast Texas. *Atmospheric Environment*, 246.
1220 <https://doi.org/10.1016/j.atmosenv.2020.118151>, 2021. Maria, V. D., Rahman, M.,
1221 Collins, P., Dondi, G., & Sangiorgi, C. (2013). Urban Heat Island Effect: Thermal
1222 Response from Different Types of Exposed Paved Surfaces. *International Journal of
1223 Pavement Research and Technology*, 6(4), 414-422.
1224 [https://doi.org/10.6135/ijprt.org.tw/2013.6\(4\).414](https://doi.org/10.6135/ijprt.org.tw/2013.6(4).414)

1225 Soni, M., Verma, S., Mishra, M. K., Mall, R. K., and Payra, S.: Estimation of particulate matter
1226 pollution using WRF-Chem during dust storm event over India. *Urban Climate*, 44.
1227 <https://doi.org/10.1016/j.uclim.2022.101202>, 2022.

1228 Stockwell, W. R., Middleton, P., Chang, J. S., and Tang, X.: The second generation regional
1229 acid deposition model chemical mechanism for regional air quality modeling. *Journal*

1230 of Geophysical Research, 95(D10), 16343–16367.
1231 <https://doi.org/10.1029/JD095iD10p16343>, 1990.

1232 Subba, T., Zhang, Y., & Steiner, A. L.: Simulating the transport and rupture of pollen in the
1233 atmosphere. *Journal of Advances in Modeling Earth Systems*, 15, e2022MS003329.
1234 <https://doi.org/10.1029/2022MS003329>, 2023.

1235 Subramanian, A., Nagarajan, A. M., Vinod, S., Chakraborty, S., Sivagami, K., Theodore, T.,
1236 Sathyanarayanan, S. S., Tamizhdurai, P., & Mangesh, V. L. (2023). Long-term impacts
1237 of climate change on coastal and transitional eco-systems in India: an overview of its
1238 current status, future projections, solutions, and policies. In *RSC Advances* (Vol. 13,
1239 Issue 18, pp. 12204–12228). Royal Society of Chemistry.
1240 <https://doi.org/10.1039/d2ra07448f>

1241 Talbot, C., Augustin, P., Leroy, C., Willart, V., Delbarre, H., Khomenko, G.: Impact of a sea
1242 breeze on the boundary-layer dynamics and the atmospheric stratification in a coastal
1243 area of the North Sea. *BoundaryLayer Meteorology*, 125, 133–154, 2007.

1244 Thompson, S. A., Chen, B., Matthews, B.H., Li, R., Nowotarski, C. J., Rapp, A. D., & Brooks,
1245 S. D. (2025). Characterizing Greater Houston's aerosol by air mass during TRACER.
1246 *Journal of Geophysical Research: Atmospheres*, 130, e2025JD043353.
1247 <https://doi.org/10.1029/2025JD043353>.

1248 Tuccella, P., Curci, G., Visconti, G., Bessagnet, B., Menut, L., & Park, R. J.: Modeling of gas
1249 and aerosol with WRF/Chem over Europe: Evaluation and sensitivity study. *Journal of*
1250 *Geophysical Research Atmospheres*, 117(3). <https://doi.org/10.1029/2011JD016302>,
1251 2012.

1252 Twomey, S.: Pollution and the planetary albedo. *Atmos. Environ.*, 8, 1251–1256, 1974.

1253 Uin, J., Aiken, A. C., Dubey, M. K., Kuang, C., Pekour, M., Salwen, C., Sedlacek, A. J.,
1254 Senum, G., Smith, S., Wang, J., Watson, T. B., & Springston, S. R.: Atmospheric
1255 radiation measurement (ARM) aerosol observing systems (AOS) for surface-based in
1256 situ atmospheric aerosol and trace gas measurements. *Journal of Atmospheric and*
1257 *Oceanic Technology*, 36(12), 2429–2447. [https://doi.org/10.1175/JTECH-D-19-](https://doi.org/10.1175/JTECH-D-19-0077.1)
1258 [0077.1](https://doi.org/10.1175/JTECH-D-19-0077.1), 2019.

- 1259 Verma, S., Boucher, O., Venkataraman, C., Reddy, M. S., Müller, D., Chazette, P., &
1260 Crouzille, B.: Aerosol lofting from sea breeze during the Indian Ocean Experiment.
1261 *Journal of Geophysical Research*, 111, 07208. <https://doi.org/10.1029/2005JD005953> ,
1262 2006.
- 1263 Viner, B., Noble, S., Qian, J. H., Werth, D., Gayes, P., Pietrafesa, L., and Bao, S.: Frequency
1264 and characteristics of inland advecting sea breezes in the Southeast United States.
1265 *Atmosphere*, 12(8). <https://doi.org/10.3390/atmos12080950>, 2021.
- 1266 Wang, B., Geddes, J. A., Adams, T. J., Lind, E. S., McDonald, B. C., He, J., Harkins, C., Li,
1267 D., and Pfister, G. G.: Implications of Sea Breezes on Air Quality Monitoring in a
1268 Coastal Urban Environment: Evidence From High Resolution Modeling of NO₂ and
1269 O₃. *Journal of Geophysical Research: Atmospheres*, 128(11).
1270 <https://doi.org/10.1029/2022jd037860>, 2023.
- 1271 Wang, D., Jensen, M. P., Taylor, D., Kowalski, G., Hogan, M., Wittemann, B. M.,
1272 Rakotoarivony, A., Giangrande, S. E., & Park, J. M.: Linking Synoptic Patterns to
1273 Cloud Properties and Local Circulations Over Southeastern Texas. *Journal of*
1274 *Geophysical Research: Atmospheres*, 127(5). <https://doi.org/10.1029/2021JD035920>,
1275 2022.
- 1276 Wang, D., Melvin, E. C., Smith, N., Jensen, M. P., Gupta, S., Abdullah-Smoot, A., Pszeniczny,
1277 N., & Hahn, T.: TRACER Perspectives on Gulf-Breeze and Bay-Breeze Circulations
1278 and Coastal Convection. *Monthly Weather Review*, 152(10), 2207–2228.
1279 <https://doi.org/10.1175/MWR-D-23-0292.1>, 2024.
- 1280 Wang, K., Zhang, Y., Yahya, K.: Decadal application of WRF/Chem over the continental U.S.:
1281 Simulation design, sensitivity simulations, and climatological model evaluation.
1282 *Atmospheric Environment*, 253, 118331,
1283 <https://doi.org/10.1016/j.atmosenv.2021.118331>, 2021.
- 1284 Wang, S. C., Wang, Y., Estes, M., Lei, R., Talbot, R., Zhu, L., & Hou, P.: Transport of Central
1285 American Fire Emissions to the U.S. Gulf Coast: Climatological Pathways and Impacts
1286 on Ozone and PM_{2.5}. *Journal of Geophysical Research: Atmospheres*, 123(15), 8344–
1287 8361. <https://doi.org/10.1029/2018JD028684>, 2018.

1288 Watson, TB.: Aerosol Chemical Speciation Monitor (ACSM) Instrument Handbook. U.S.
1289 Department of Energy, Atmospheric Radiation Measurement user facility, Richland,
1290 Washington.DOE/SC-ARM-TR-196, 2024.

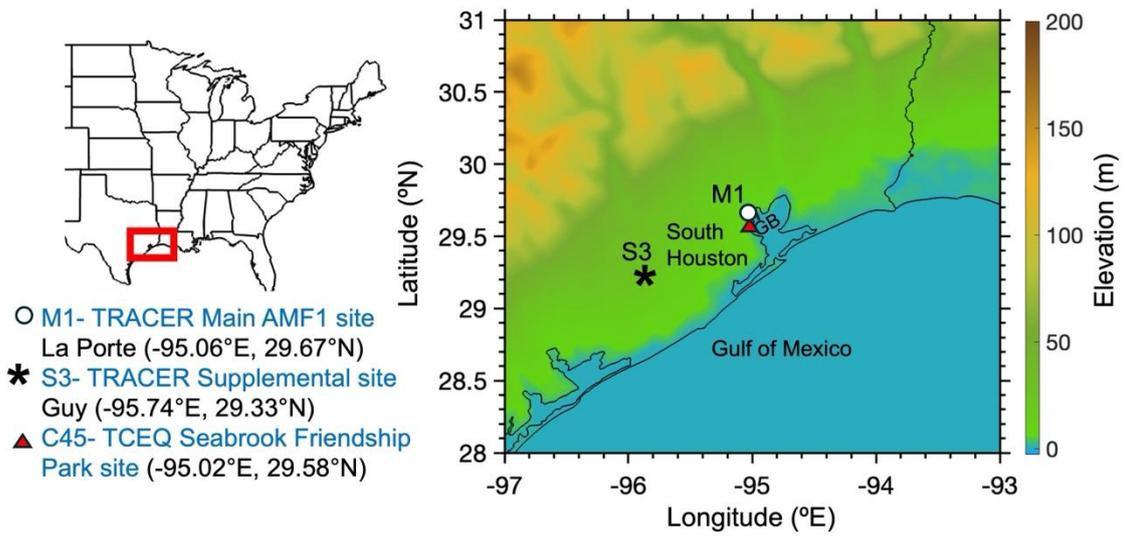
1291 Wert, B. P., Trainer, M., Fried, A., Ryerson, T. B., Henry, B., Potter, W., Angevine, W. M.,
1292 Atlas, E., Donnelly, S. G., Fehsenfeld, F. C., Frost, G. J., Goldan, P. D., Hansel, A.,
1293 Holloway, J. S., Hubler, G., Kuster, W. C., Nicks, D. K., Neuman, J. A., Parrish, D. D.,
1294 ... Wisthaler, A.: Signatures of terminal alkene oxidation in airborne formaldehyde
1295 measurements during TexAQS 2000. *Journal of Geophysical Research D:*
1296 *Atmospheres*, 108(3). <https://doi.org/10.1029/2002jd002502>, 2003.

1297 Westenbarger, D. A., & Morris, G. A.: Identifying biomass burning impacts on air quality in
1298 Southeast Texas 26–29 August 2011 using satellites, models and surface data.
1299 <https://doi.org/10.5194/acp-2017-1234>, 2018.

1300 Yoon, S., Ortiz, S. M., Clark, A. E., Barrett, T. E., Usenko, S., Duvall, R. M., Ruiz, L. H.,
1301 Bean, J. K., Faxon, C. B., Flynn, J. H., Lefer, B. L., Leong, Y. J., Griffin, R. J., &
1302 Sheesley, R. J.: Apportioned primary and secondary organic aerosol during pollution
1303 events of DISCOVER-AQ Houston. *Atmospheric Environment*, 244.
1304 <https://doi.org/10.1016/j.atmosenv.2020.117954>, 2021.

1305
1306
1307

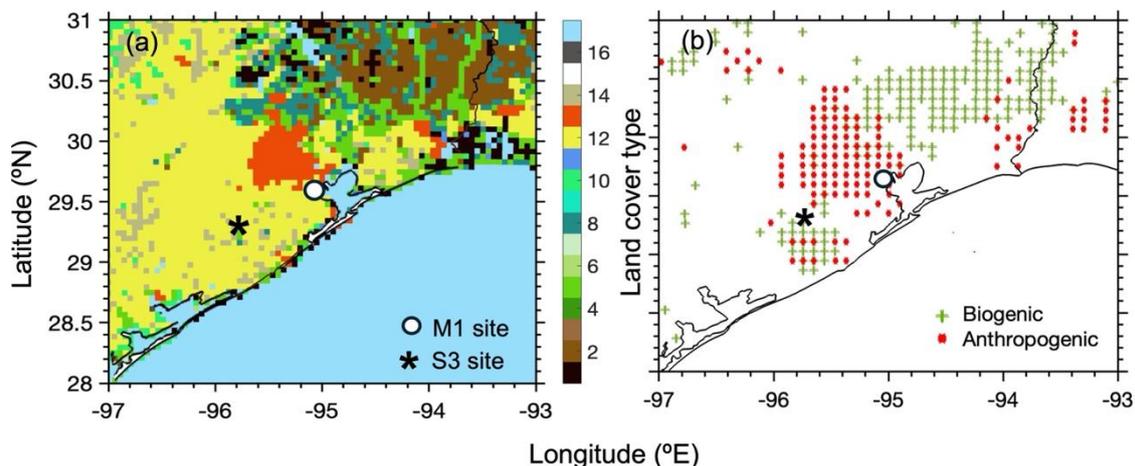
1308
1309
1310



1311
1312
1313
1314
1315
1316
1317
1318
1319
1320
1321
1322
1323
1324
1325

Figure 1. Map showing the TRACER field campaign main site (M1) and supplemental site (S3), and the TCEQ Seabrook Friendship Park site (C45). Terrain elevation is shown in color. Here, “GB” corresponds to the Galveston Bay.

1326
1327
1328
1329



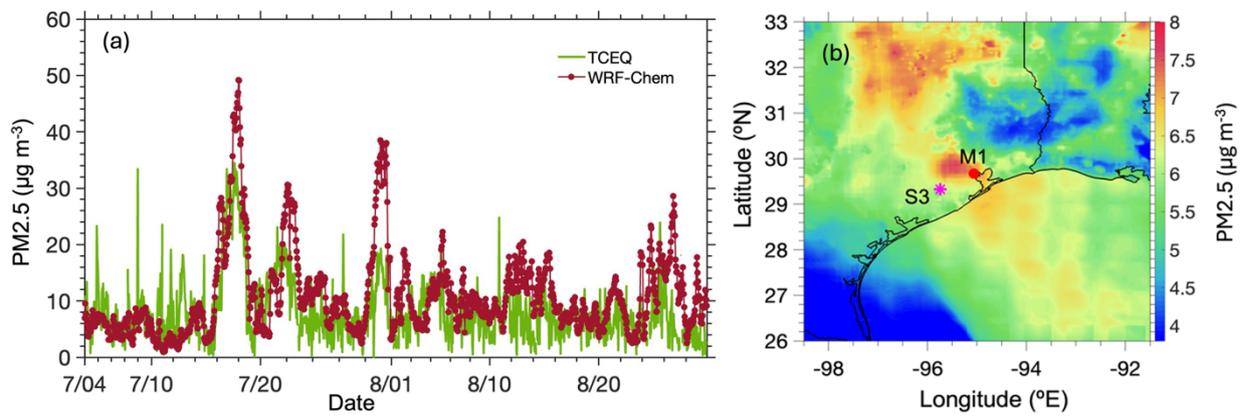
1330

1331 **Figure 2.** Weather Research and Forecasting model coupled with Chemistry (WRF-Chem)
1332 simulation domain with (a) primary land cover types comprising of (1) Evergreen Needleleaf
1333 Forest, (2) Evergreen Broadleaf Forest, (3) Deciduous Needleleaf Forest, (4) Deciduous
1334 Broadleaf Forest, (5) Mixed Forest, (6) Closed Shrubland, (7) Open Shrubland, (8) Woody
1335 Savanna, (9) Savanna, (10) Grassland, (11) Permanent Wetlands, (12) Cropland, (13) Urban
1336 and Build-up, (14) Cropland/Natural Mosaic, (15) Snow and Ice, (16) Barren or Sparsely
1337 Vegetated, and (17) Water; (b) Anthropogenic (red dots) and biogenic (green dots) aerosol
1338 emission source points obtained using the National Emissions Inventory (NEI) data and Model
1339 of Emissions of Gases and Aerosols from Nature (MEGAN) modeling system, respectively.

1340
1341
1342
1343
1344
1345
1346

1347

1348



1349

1350 **Figure 3.** (a) Comparison of daily averaged PM_{2.5} observed (green) at the TCEQ site, and
1351 WRF-Chem simulated (red) at the M1 site. (b) Spatial distribution of averaged PM_{2.5} simulated
1352 with WRF-chem (color-filled contour).

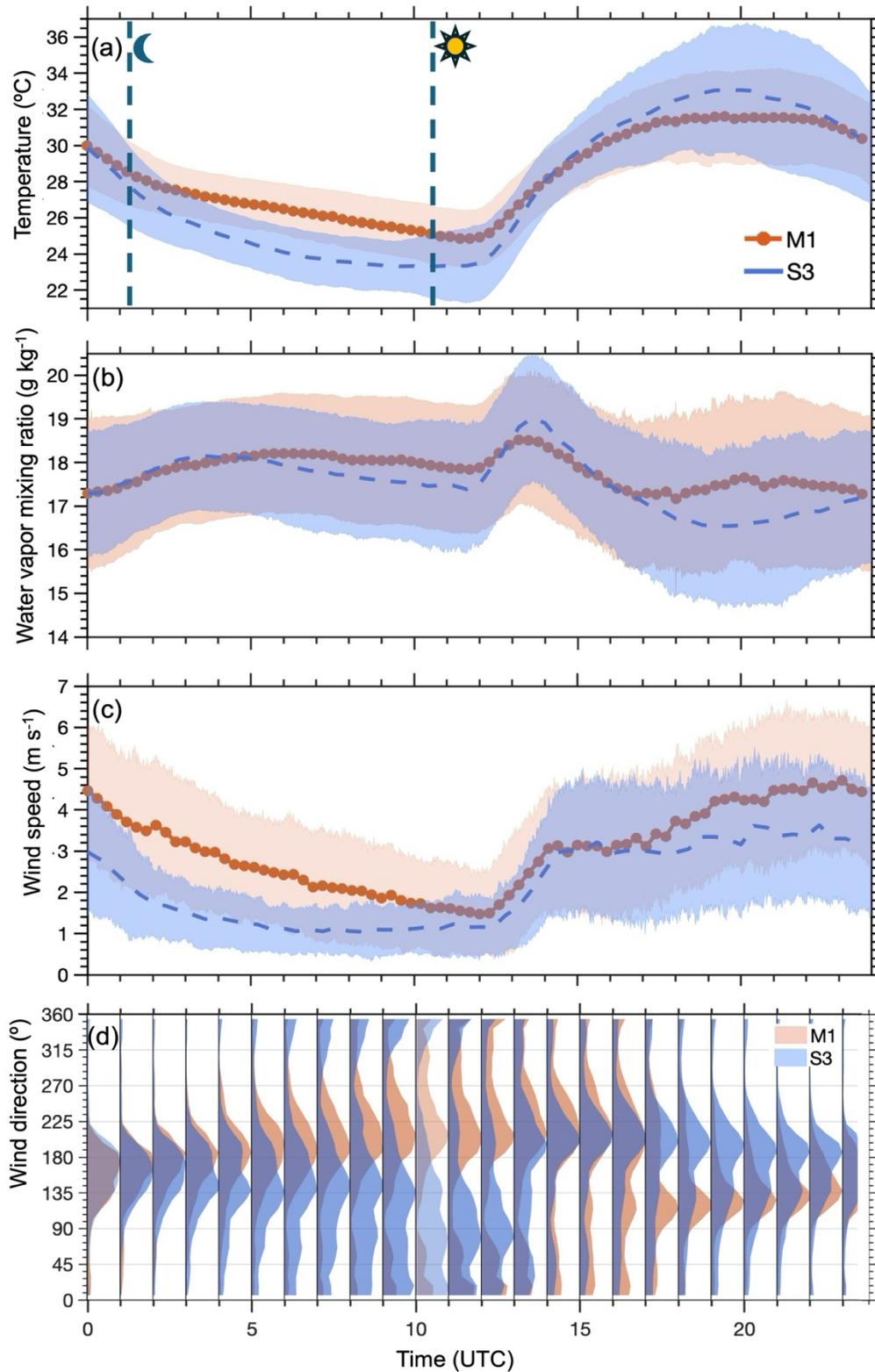
1353

1354

1355

1356

1357



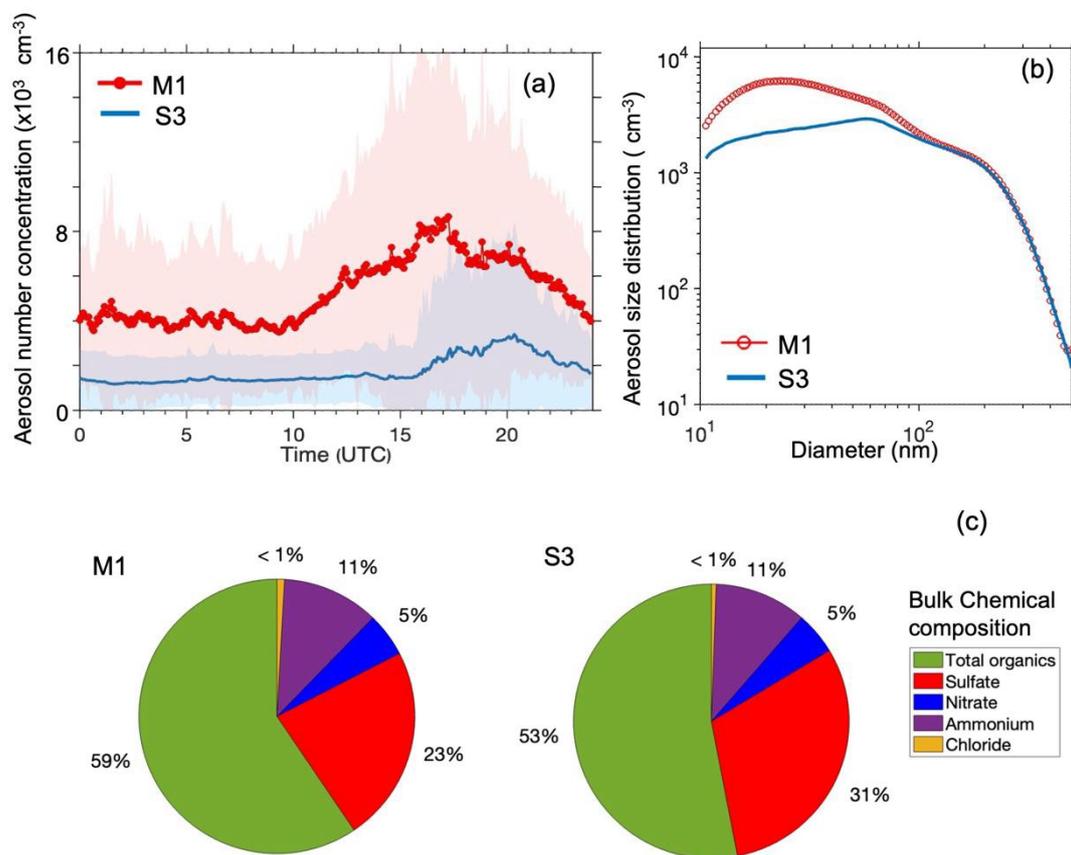
1358

1359 **Figure 4.** Diurnal variation of meteorological variables (a) Temperature at 2 m, (b) water vapor
 1360 mixing ratio (w) (c) wind speed at 10 m, and (d) wind direction waterfall diagram at 10 m
 1361 measured at M1 (in orange) and S3 (in blue) sites averaged during IOP. The shaded color
 1362 represents the standard deviation from the mean.

1363

1364

1365



1366

1367 **Figure 5.** Measured (a) diurnal distribution of aerosol number concentration, (b) aerosol size
1368 distribution, and (c) percentage contribution of bulk chemical composition at M1 and S3 sites
1369 averaged from June to September 2022.

1370

1371

1372

1373

1374

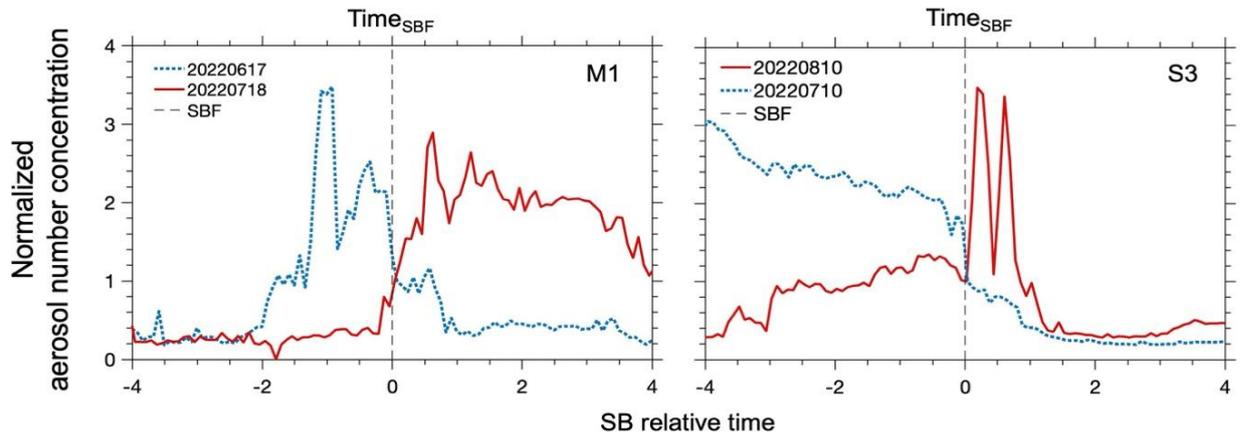
1375

1376

1377

1378

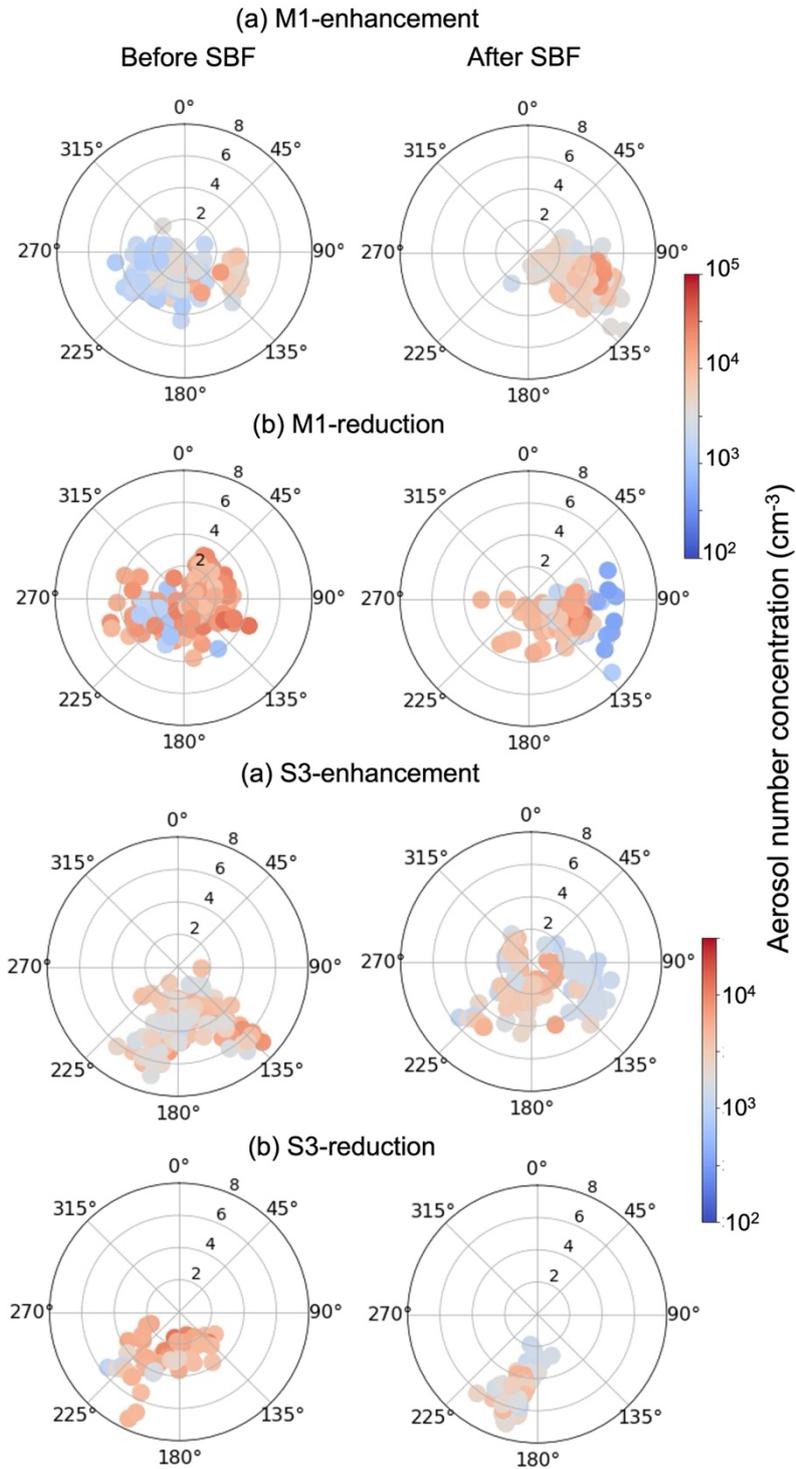
1379



1380

1381 **Figure 6.** Time series of the normalized aerosol number concentration, with the time centered
1382 at the time of the passing of the SBF ($T_{\text{SBF}}=0$) at the M1 site (1st column) and the S3 site (2nd
1383 column) during the individual SB event days.

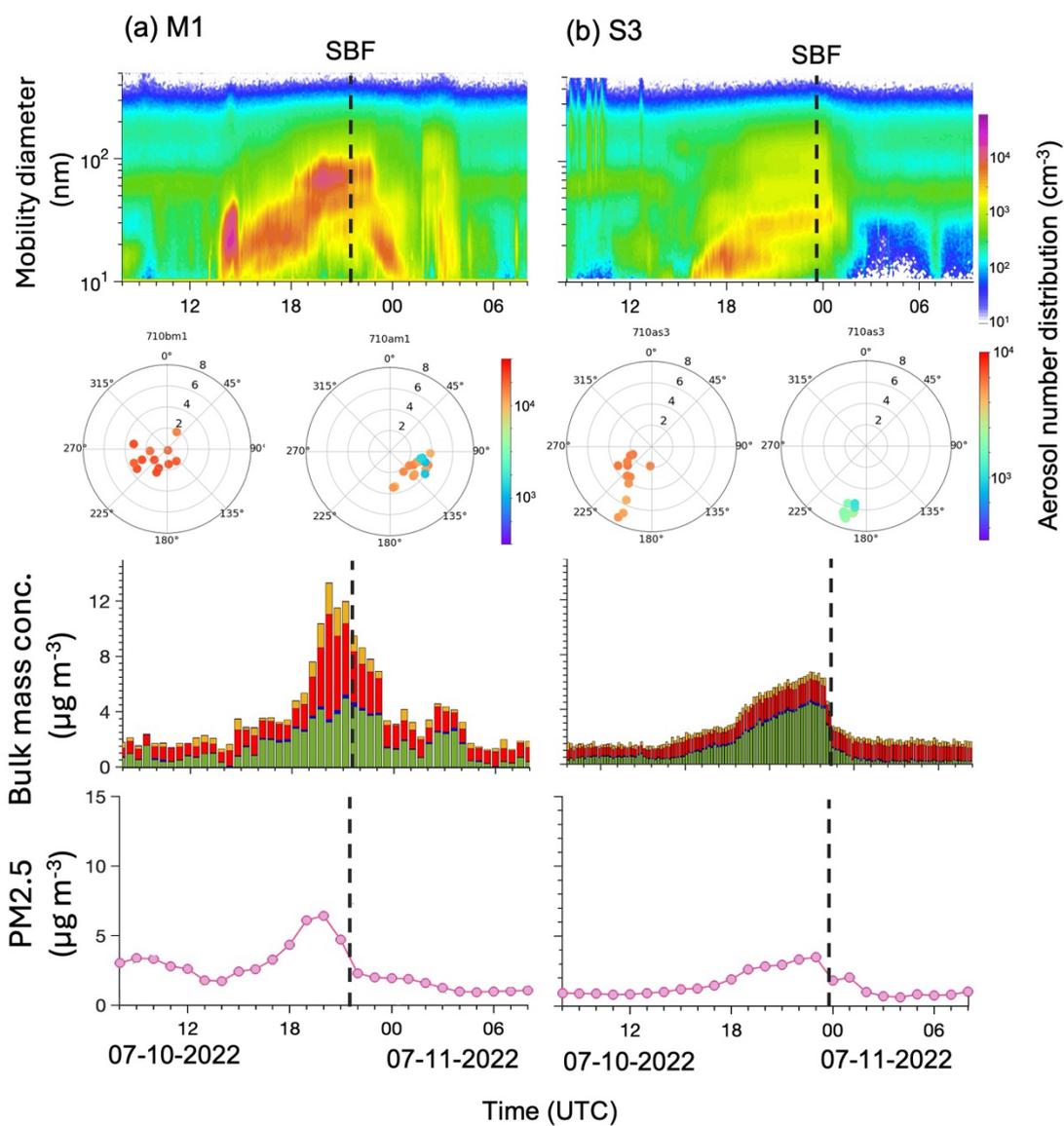
1384



1385

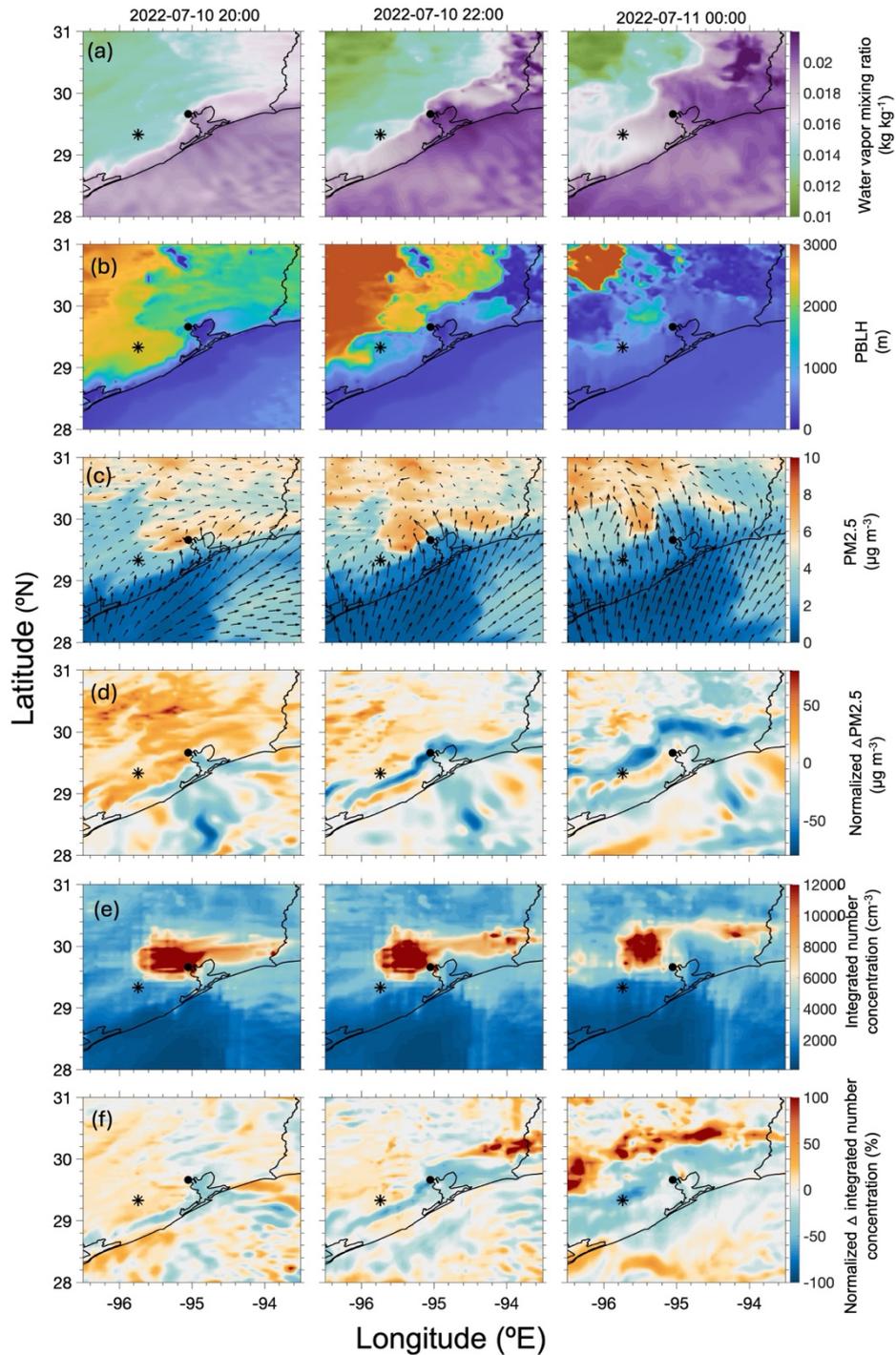
1386 **Figure 7.** Open-air polar plots for aerosol number concentration before and after the passing
 1387 of the SBF ($\Delta T = T_{\text{SBF} \pm 1}$) during (a) enhancement and (b) reduction events at M1 and S3 sites.
 1388 The wind speed (in m s^{-1}) grid lines are presented with black circles; the color scales represent
 1389 the concentrations observed with each wind speed and direction combinations.

1390
1391
1392
1393



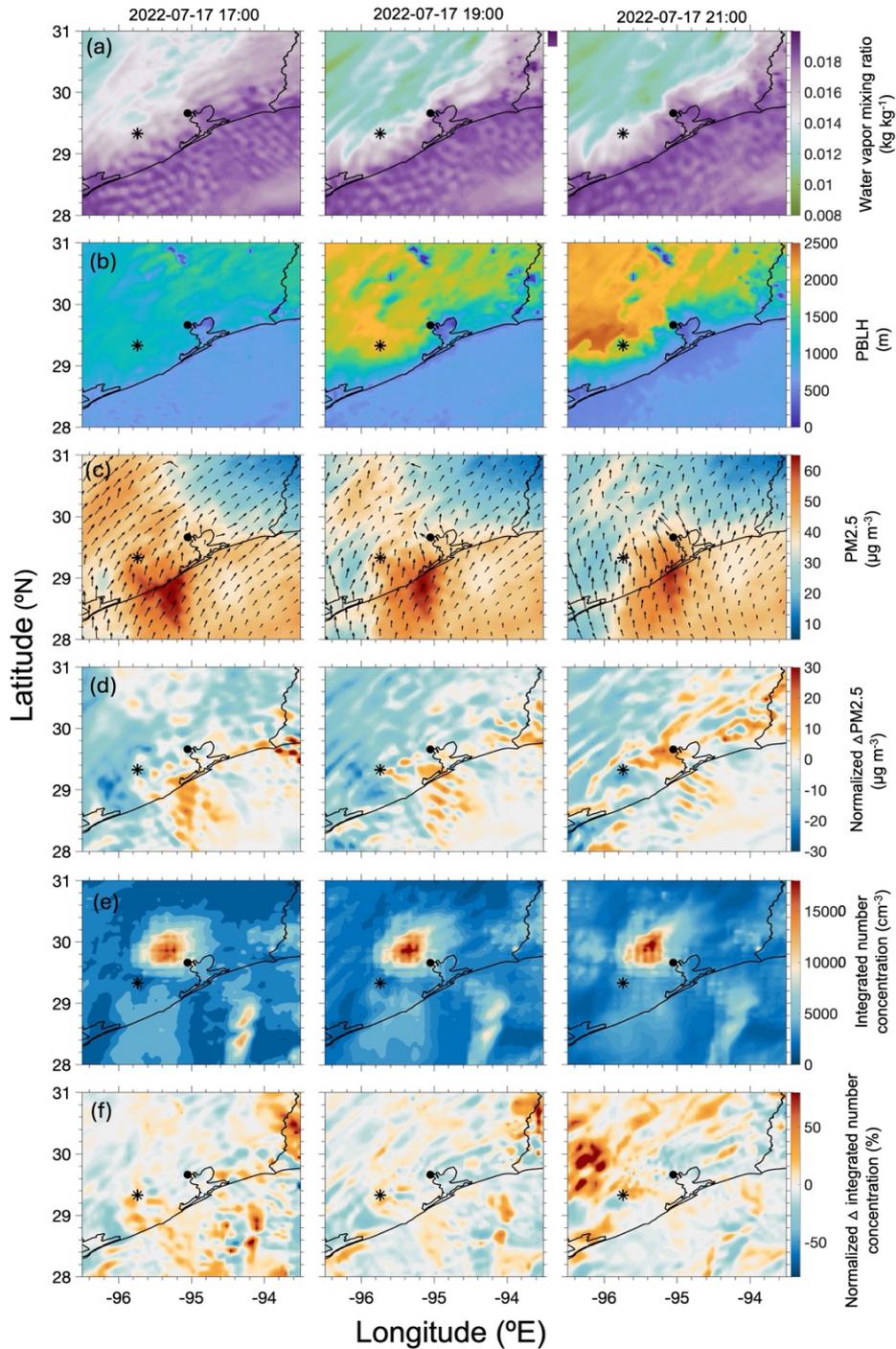
1394
1395
1396
1397
1398
1399

Figure 8. Time series of measured aerosol size distribution (1st row), measured bulk chemical composition (3rd row), and modeled and TCEQ measured PM_{2.5} mass concentration (4th row) at (a) M1 and (b) S3 on 10 July 2022. Polar plot showing the measured integrated aerosol number concentration during one hour before and after the passing of the SBF (2nd row). The black dashed line represents the time of the passing of the SBF (T_{SBF}) at the respective sites.



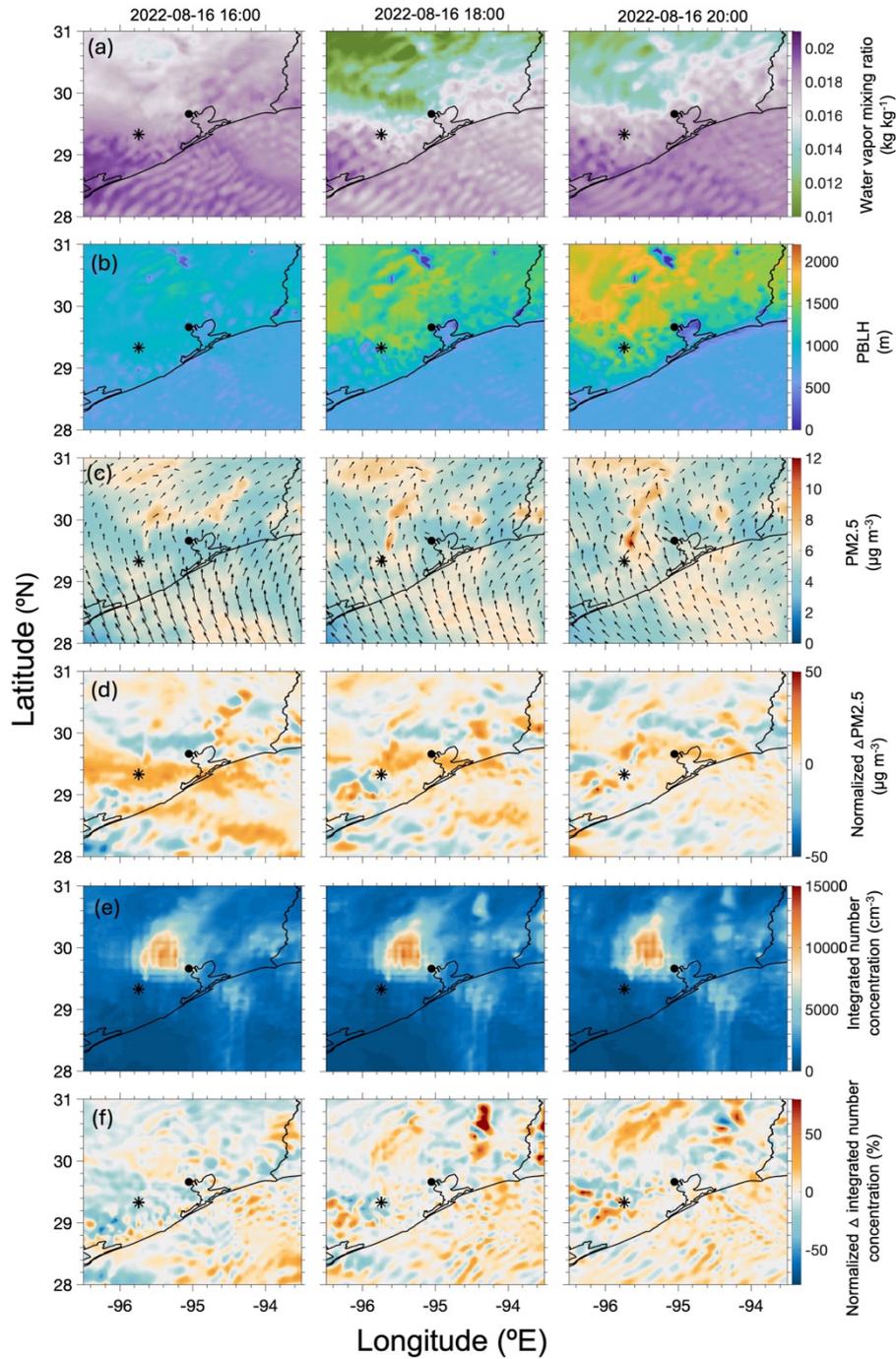
1400

1401 **Figure 9.** Modeled surface distribution of (a) water vapor mixing ratio (w), (b) PBLH, (c)
 1402 $PM_{2.5}$, and wind vector (black arrows, at the surface), and (e) integrated aerosol number
 1403 concentration (nucleation + accumulation mode) at three-time steps: 20:00 and 22:00 UTC on
 1404 10 July, and 00:00 UTC on 11 July. Sub-panels (d) and (f) show the normalized changes, where
 1405 Δ is the change from the previous time step. The filled-circle marker in the panels represent the
 1406 M1 site, while the star represents the S3 site.



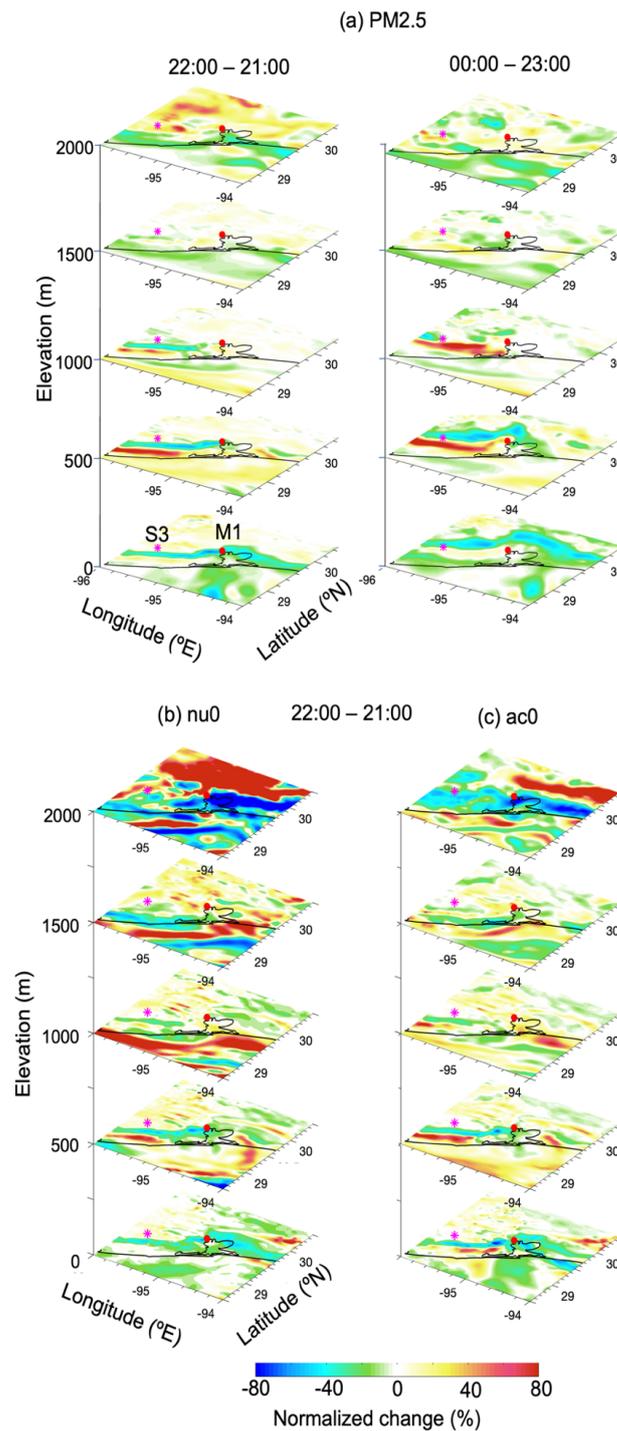
1407

1408 **Figure 10.** Modeled surface distribution of (a) water vapor mixing ratio (w), (b) PBLH, (c)
 1409 $PM_{2.5}$, and wind vector (black arrows, at the surface), and (e) integrated aerosol number
 1410 concentration (nucleation + accumulation mode) at three-time steps: 17:00, 19:00 and 21:00
 1411 UTC on 17 July. Sub-panels (d) and (f) show the normalized changes, where Δ is the change
 1412 from the previous time step. The filled-circle marker in the panels represent the M1 site, while
 1413 the star represents the S3 site.



1414

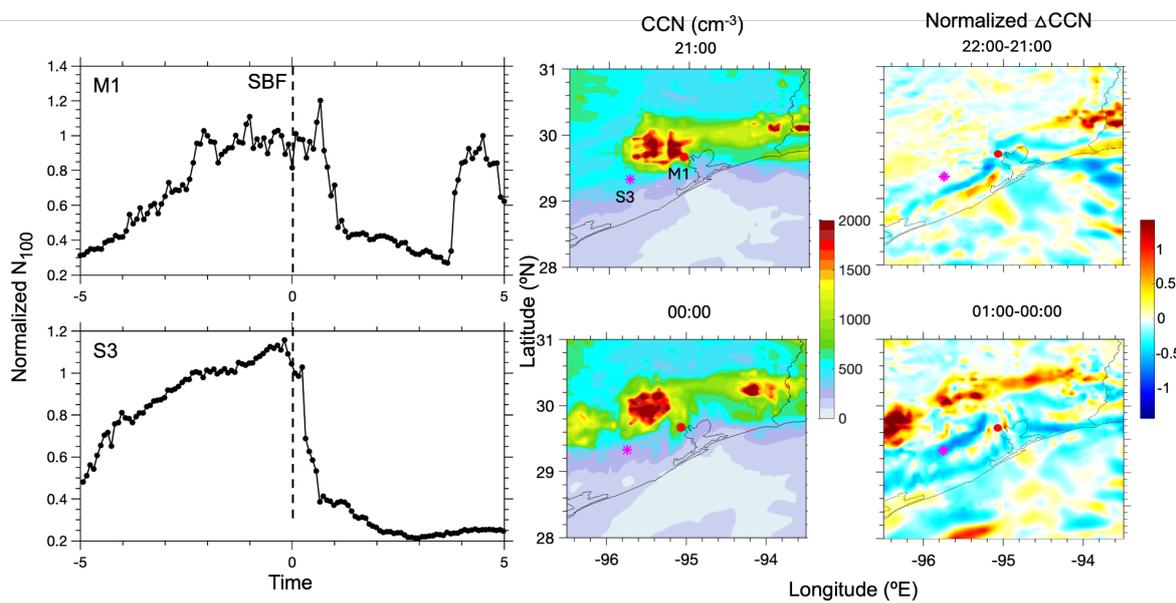
1415 **Figure 11.** Modeled surface distribution of (a) water vapor mixing ratio (w), (b) PBLH, (c)
 1416 $PM_{2.5}$, and wind vector (black arrows, at the surface), and (e) integrated aerosol number
 1417 concentration (nucleation + accumulation mode) at three-time steps: 16:00, 18:00 and 20:00
 1418 UTC on 16 August. Sub-panels (d) and (f) show the normalized changes, where Δ is the change
 1419 from the previous time step. The filled-circle marker in the panels represent the M1 site, while
 1420 the star represents the S3 site.



1422

1423 **Figure 12.** First row: the spatial distribution of normalized $\Delta\text{PM}_{2.5}$ at different elevations at
 1424 timesteps (a) 21:00 and 22:00 UTC on 10 July, and 23:00 UTC on 10 July and 00:00 UTC on
 1425 11 July. Second row: the spatial distribution of normalized (b) Δ nucleation mode (nu0) and (c)
 1426 Δ accumulation mode (ac0) aerosol number concentration at timesteps 21:00 and 22:00 UTC
 1427 on 10 July.

1428
1429
1430
1431
1432
1433
1434



1435
1436
1437
1438
1439
1440
1441
1442
1443
1444
1445

Figure 13. Time series of the normalized measured N_{100} along the time of the SBF's passing through the M1 site (first row) and the S3 site (second row) on 10 July 2022 (1st column). Spatial distribution of the modeled hourly averaged (2nd column) and normalized ΔCCN (3rd column).

1446

1447 **Table 1:** Summary of SBC influence on aerosol number concentration at the M1 and S3 sites.
 1448 Events are classified into enhancement, reduction, and neutral categories.

1449

Site	Description	Combined	Enhancement	Reduction	Neutral
M1	Days (fraction of the total events %)	46 (total SB events)	13 (28 %)	16 (35 %)	17 (37 %)
	Concentration change (after - before) %	-23 (all enhancement + reduction events)	+55	-42	-11
		-7 (total number of events)			
S3	Days	30 (total SB events)	8 (27 %)	4 (13 %)	18 (60 %)
	Concentration change (after - before) %	+9 (all enhancement + reduction events)	+64	-45	-10
		+3 (total number of events)			

1450

1451

1452

1453

1454

1455

1456

1457

1458

1459

1461 **Table 2.** Model configuration

Simulation period	1 July - 30 August 2022
Domain	26 to 33 °N and -98 to -92 °E
Horizontal resolution (dx)	5 x 5 km
Vertical resolution	45 layers from 1000-50 mb
Meteorological initial and boundary conditions	North America mesoscale (NAM) forecast output at T221 (32-km) resolution, 28 vertical levels (Bauman, 2010)
Shortwave radiation	Goddard shortwave radiation scheme (Chou et al., 1998)
Longwave radiation	The rapid radiative transfer mode (RRTM) (Mlawer et al., 1997)
Land surface	Community National Center for Environmental Prediction (NCEP), Oregon State University, Air Force, and Hydrologic Research Lab-NWS Land Surface Model (NOAH) (Chen and Dudhia, 2001)
Surface Layer	Monin-Obukhov (Monin and Obukhov, 1954; Janjic, 2002)
PBL	Yonsei University Scheme (YSU) (Hong et al., 2006)
Cumulus	The Grell scheme (Grell and Devenyi 2002)
Microphysics	Morrison 2-moment scheme (Morrison, 2005)
Chemical mechanism	RACM Chemistry with MADE/VBS aerosols using KPP library along with the volatility basis set (VBS) used for Secondary Organic Aerosols (Stockwell et al., 1990; Ackerman et al., 1998; Schell et al., 2001)
Chemical initial and boundary conditions	MOZBC from the Model for Ozone and Related chemical Tracers (MOZART) model (Emmons et al., 2010)
Anthropogenic emissions	National Emissions Inventory (NEI), U.S. Environmental Protection Agency (EPA)
Biogenic emissions	The Model of Emissions of Gases and Aerosols from Nature version MEGAN v2.1 biogenic emissions (Guenther et al., 2012)