TITLE: Forecasting for ESCAPE: A multi-institution hybrid forecasting and nowcasting operation for sea-breeze convection supporting a ground-based and airborne field campaign

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Abstract:

The Experiment of Sea Breeze Convection, Aerosols, Precipitation and Environment (ESCAPE) field project deployed two aircraft and ground-based assets in the vicinity of Houston, TX, between 27 May 2022 and 2 July 2022, examining how meteorological conditions, dynamics, and aerosols control the initiation, early growth stage, and evolution of coastal convective clouds. To ensure that airborne and ground-based assets were deployed appropriately, a Forecasting and Nowcasting Team was formed. Daily forecasts guided real-time decision making by assessing synoptic weather conditions, environmental aerosol, and a variety of atmospheric modeling data to assign a probability for meeting specific ESCAPE campaign objectives. During the research flights, a small team of forecasters provided "nowcasting" support by analyzing radar, satellite, and new model data in real time. The nowcasting team proved invaluable to the campaign operation, as sometimes changing environmental conditions affected, for example, the timing of convective initiation. In addition to the success of the forecasting and nowcasting teams, the ESCAPE campaign offered a unique "testbed" opportunity where in-person and virtual support both contributed to campaign objectives. The forecasting and nowcasting teams were each composed of new and experienced forecasters alike, where new forecasters were given invaluable experience that would otherwise be difficult to attain. Both teams received training on forecast models, map analysis, HYbrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) modeling and thermodynamic sounding analysis before the beginning of the campaign. In this article, the ESCAPE forecasting and nowcasting teams reflects on these experiences, providing potentially useful advice for future field campaigns requiring forecasting and nowcasting support in a hybrid virtual/in-person framework.

Significance Statement

To support the Experiment of Sea Breeze Convection, Aerosols, Precipitation and Environment (ESCAPE) field project, a forecasting and nowcasting team was assembled. Prior to the campaign, new and experienced forecasters alike reviewed fundamental processes leading

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to sea-breeze driven convection and optimized the forecasting and nowcasting processes to ensure both ground- and airborne-based measurement systems were deployed appropriately. The process for forecasting sea-breeze convection and supporting the aircraft during active field operations is highlighted. Many new forecasters contributed to the success of the ESCAPE Forecasting and Nowcasting teams and were given invaluable experience that would have been difficult to attain in other settings. Members of the Forecasting and Nowcasting team reflected on their experiences, providing valuable insight for future field campaigns requiring a coordinated, hybrid forecasting and nowcasting effort to guide field operations.

1. Introduction

A sea-breeze, or a wind that blows from water onto land due to a diurnal temperature gradient created between the warmer land mass and cooler water surface, affects nearly every coastal city and habitat in warm climates. The sea-breeze often occurs as part of a sea-breeze circulation, where during the day onshore-moving air is lifted upward and advected back over the open water aloft before subsiding (Miller et al., 2003), and vice versa at night. Sea-breezes are of key meteorological and climatological importance for their role in initiating deep convective thunderstorms (e.g., Zhang and Wang, 2021). In cities such as Houston, TX with a large, sprawling urban center, the urban heat island effect is thought to amplify the strength of the sea breeze (Yosikado 1992; Freitas et al., 2007). Morcrette et al. (2007) demonstrated that accurately predicting isolated thunderstorms requires an accurate representation of both favorable synoptic-scale dynamics and local (mesoscale) surface convergence boundaries. Depicting these fine-scale features has remained a challenge for many weather models, especially models that do not explicitly resolve convection or have poor horizontal resolution (e.g., Hock et al., 2022). With the exception of high-resolution large-eddy simulation (LES) models or similar mesoscale models (e.g., Nicholls et al., 1991; Abulikemu et al., 2016), the incredibly fine mesoscale structure of the sea-breeze circulation remains beyond many weather models' ability to accurately predict when sea-breezes can trigger deep convective thunderstorms (Crosman and Horel, 2010; Wang et al., 2018).

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The Experiment of Sea Breeze Convection, Aerosols, Precipitation and Environment (ESCAPE) field project took place from 27 May 2022 through 2 July 2022 in the vicinity of Houston, TX, focusing on how meteorological conditions, dynamics, and aerosols control the initiation, early growth stage, and evolution of coastal convective clouds. A companion paper (Kollias et al. 2024,*in press*) fully describes the ESCAPE field campaign, objectives, instruments, and project goals. As part of ESCAPE, a study of sea-breeze formation, the influence of the sea breeze on daytime thunderstorm formation, and aerosol-cloud interactions in the context of sea-breeze generated thunderstorms is critical. ESCAPE took place concurrently with the Tracking Aerosol Convection interactions Experiment (TRACER; Jensen et al., 2022), with TRACER starting to collect observations in the Houston area in Summer 2021. Houston was selected given its ideal location for frequent daytime (diurnal) cloud cover, considerable presence of aerosols, and logistical considerations (e.g., Fan et al., 2007; Yuan et al., 2008; Zhang et al., 2021), all of which are critical to the broader ESCAPE science goals seeking to take measurements of the sea breeze, sea-breeze driven convective clouds, and environmental aerosols during the entire sea breeze and convection life cycles, respectively. To meet ESCAPE's required goals and needs, a dedicated Forecasting and Nowcasting team was assembled to provide short-term forecasts and real-time nowcasts, especially knowing that the quality of the collected datasets would be dependent on sampling the best available conditions during the campaign.

Accounting for the fact that ESCAPE was among the first field campaigns since the peak of the COVID pandemic, the Forecasting and Nowcasting teams leaned heavily on a hybrid work structure of in-person and remote support to meet the objectives of the project, particularly for the deployment of airborne- and ground-based assets (Kollias et al., 2024). The hybrid nature of the forecasts/nowcasts provided unique opportunities and challenges. Given that hybrid work environments have continued to persist since the end of the COVID pandemic, one of the goals of this article is to provide guidance for future campaigns based on the ESCAPE experience. The next section of this article describes the meteorological analysis performed and completed during each forecasting or nowcasting shift, while the following section describes the forecasting operations and hybrid work structure used during ESCAPE.

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2. Meteorological Analysis

Identifying atmospheric conditions favoring sea-breeze convection requires an innate understanding of both the synoptic-scale setup and mesoscale meteorology. To meet ESCAPE science goals, the Forecasting team developed a decision matrix to determine the likelihood of sea-breeze driven convection based on numerous criteria: the more criteria that were met (e.g., favorable humidity, low vertical wind shear) the higher the probability of sea-breeze driven convection. Each criterion in this decision matrix was weighted equally, and uniquely tailored for the ESCAPE field campaign. These criteria are highlighted in Table 1 and were determined from a variety of previous studies (e.g., Miller et al., 2003; Reddy et al., 2020) showing that these conditions favored the onset of sea-breeze driven convection. One of the pros of using a decision matrix is that it allowed the forecasting team to organize all pertinent information related to sea-breeze convection forecasting into a single location, which helped facilitate efficient forecast discussions. Over the course of the campaign, no forecast “busts” occurred, which the Forecasting team attributes to the use of this decision matrix for guiding forecast discussions and gauging overall forecast confidence. The next subsections describe in detail the rationale behind the criteria used in the Forecasting team’s decision making. These criteria were assumed to have equal importance in determining the likelihood of sea-breeze driven convection during the forecast operation.

Table 1: The decision matrix used by the ESCAPE Forecasting team to evaluate atmospheric conditions conducive for sea-breeze driven convection. Each criterion was evaluated in 3-hour increments between 0600 CDT and 1800 CDT for the target domain.

Criteria	**Reasoning for criteria**
Is model 1000 hPa RH > 70% in target domain?	Ensure sufficient surface moisture

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Is model 850 hPa RH > 70% in target domain?	Ensure sufficient moisture for cumulus/convection near the top of the boundary layer
Is model 700 hPa RH > 70% in target domain?	Ensure sufficient moisture available for deepening convection
Is model 500 hPa RH > 50% in target domain?	Ensure sufficient moisture available for deepening convection
Is model low-level cloud cover present (> 30% cloud fraction)?	Assess probability of cumulus formation
Is model mid-level cloud cover present (> 30% cloud fraction)?	Assess probability of deep convection formation
Do HYSPLIT forward trajectories favor onshore flow across target domain?	Ensure that a sea breeze is likely during the afternoon
Does the forecasted land-sea temperature difference along the coast exceed 5°C (9°F)?	Ensure that thermodynamic conditions favor sea-breeze formation
Are shoreline model wind speeds less than 10 kts?	Assess likelihood that convective development is the result of a sea breeze compared to synoptic-scale flow
Is the nearest cold-front or MCS more than 1000 nm away?	Ensure limited influence of synoptic-scale or mesoscale weather
Is there a ridge or surface high pressure system located east of Houston?	Ensure favorable onshore flow conditions

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Is sufficient modeled MLCAPE present (e.g., > 1000 J/kg)?	Ensure enough energy is available to sustain convection once triggered
Is modeled vertical wind shear low (< 20 kts)?	Added criteria to ensure thunderstorm activity isn't severe, and only the result of sea-breeze driven convection
Does HRRR simulated reflectivity suggest isolated convection?	Ensure model agreement with the probability of isolated convection
If convection is possible, do all convection-allowing models agree on mode of convection?	Ensure general agreement between convection-allowing models and their probabilities of convection during the afternoon.

A. Moisture

For deep convection to develop, sufficent moisture must be present especially in the low- and mid-levels of the atmosphere. The ESCAPE forecast/nowcast team checked if model RH was at least 70% or greater at 1000 hPa, 850 hPa and 700 hPa as well as greater than 50% at 500 hPa. Since each criterion in Table 1 was weighted equally for determining the probability of sea-breeze driven convection, having moisture criteria represent 4 out of the 15 total criteria ensured that humidity carried the greatest weight in forecast decision making. Several models were examined (i.e., GFS, NAM, ECMWF, HRRR) to evaluate the predicted presence of not only humidity, but also surface and mid-level cloud cover development during the forecast period. If model disagreements existed, forecast participants would lean on the convection-allowing models (HRRR), since global models like the GFS or ECMWF do not explicitly resolve convection in the short term. Modeled cloud development represented another important marker that clouds were forecast to be present and, in conjunction with the humidity criteria, added confidence that enough moisture was indeed available to develop clouds through at least the

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mid-levels of the atmosphere. High-altitude cloud cover was excluded from the decision-making criteria to ensure advected cirrus clouds did not result in “false positive” readings. Rather, with other metrics such as MLCAPE and convection in the HRRR, high-level cloud cover resulting from the rapid deepening of an isolated thunderstorm was implicitly accounted for.

B. Synoptic-Scale Weather

Another important component of the forecast decision involved evaluating the overall and evolving synoptic-scale meteorological pattern. The presence of an upper-level ridge east of Texas (e.g., over the SE US), the presence of a surface high pressure system over the Gulf of Mexico, or even the expanse of the Bermuda high into the eastern Gulf of Mexico qualified as a positive criterion for sea-breeze driven convection. Having a high-pressure system or ridge in these regions implied large-scale atmospheric flow was conducive to onshore moisture advection as well as “kickstarting” an afternoon sea-breeze over the SE TX shoreline. In addition to favoring afternoon sea-breeze conditions, the presence of a ridge or high-pressure system to the east also favors consistent onshore moisture advection, which is a key component for increasing buoyancy in the atmospheric boundary layer (Shin et al., 2021).

The forecast team also checked for the presence of nearby frontal systems and mesoscale convective complexes (MCSs) that could leave residual frontal-like forcing along outflows. Organized lift along such a frontal system in SE TX would imply convection along the front was the result of synoptic-scale organization rather than sea-breeze driven. Frontal systems over the central and southern United States are not uncommon during early summer and late spring (Barth et al., 2015), and these systems often interact with the southerly flow to initiate convection beyond sea-breeze effects (Huang et al., 2019). The decision-making process involved verifying whether such MCS or frontal systems were forecast to approach within 1000 nm (i.e., as far away as central Nebraska from Houston) to assess whether convection was influenced by MCS outflow or convergent flow. Finally, global models such as the ECMWF and

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GFS were weighted more in the decision-making process here especially beyond 48-hours due to their longer model run-time and reliability (Rodwell and Wernli, 2023).

C. Afternoon Sea Breeze

After evaluating atmospheric moisture and large-scale dynamics, the probability of an afternoon sea breeze (usually between noon and 3pm local time) was examined. One criterion was to determine if the afternoon land (i.e., the experiment region, either east or southwest of Houston) and respective sea-surface temperature difference exceeded 5°C (9°F), consistent with accepted values in previous modeling and observational studies of coastal sea-breezes (e.g., Wermter et al., 2022). Another criterion was to see if the morning and afternoon coastal winds exceeded 10 kts. The purpose of checking both morning and afternoon wind speeds elucidated the role of large-scale atmospheric flow versus sea-breeze driven flow. Optimum conditions required calm/variable wind speeds in the morning followed by a modest 5-10 kt increase in wind speed in the afternoon - a clear sign that the onshore wind was sea-breeze driven and not synoptically driven. This is especially important because wind (along with coastal morphology) represents the most important factor determining the inland extent of the sea breeze (Park et al., 2020; Hock et al., 2022) — a matter of crucial importance for deciding the positioning of mobile observing assets. The forecast team was also mindful of the fact that sea-breezes can manifest earlier than models predict, owing to recent results showing that mid-morning cold temperature biases (underestimated surface heat fluxes) frequently occur in models (Caicedo et al., 2019).

D. Model Evaluation and Sounding Analysis

Several forecast models were used for real-time nowcasting, short-term forecasting and long-term forecasting of moisture, synoptic-scale weather and sea breeze (see Table 2 for a detailed description of each of these models). The HYbrid Single-Particle Lagrangian Integrated

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Trajectory (HYSPLIT) model (Draxler and Rolph, 2010) was used with a variety of model outputs (including, for example, GFS and HRRR) to examine the evolution of the boundary layer wind field through the morning and afternoon hours. HYSPLIT has been used in many previous studies evaluating the evolution of daytime sea breezes (e.g., Han et al., 2022; Trošić Lesar and Filipčić, 2022). HYSPLIT was also used to check the degree of midday mixing and provide a secondary evaluation of the likelihood that surface-based air parcels in a convectively favorable environment could develop into deep convection. In this regard, HYSPLIT proved to be an invaluable tool to the ESCAPE Forecasting team.

Table 2: The list of weather forecasting models used by the ESCAPE Forecasting and Nowcasting Teams, including information on the type of model, horizontal resolution, number of model levels, primary use, and a reference for further detailed information on each model setup.

Model	Type	Horizontal Resolution and Levels	Use	Reference
European Center for Medium Range Weather Forecasting (ECMWF)	Global	9 km / 137 levels	Short- and long-term weather forecasting.	https://confluence.ecmwf.int/display/FUG/Section+2.1.2+Model+Configurations
Global Forecast System (GFS)	Global	13 km / 127 levels	Short- and long-term weather forecasting.	https://www.emc.ncep.noaa.gov/emc/pages/numerical_forecast_systems/gfs/documentation.php
North American Mesoscale (NAM)	Regional and Limited area mesoscale	12 km (regional) or 1.5 km (nested) / 60 levels	Short- and long-term weather forecasting.	https://www.emc.ncep.noaa.gov/emc/pages/numerical_forecast_systems/nam.php
Weather Research and Forecasting (WRF)	Limited area mesoscale/ high-resolution.	1 km / variable levels	Short-term (< 24 hr) forecasting, diagnose convective initiation, locate sea breeze & assess	Skamarock, W. C., Klemp, and coauthors, 2021: A Description of the Advanced Research WRF Model Version 4.3 (No. NCAR/TN-556+STR). doi:10.5065/1dfh-6p97.

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			evolution. Primary Nowcasting Team tool.	
High-Resolution Rapid Refresh (HRRR)	Limited area mesoscale/ high-resolution.	3 km / 51 levels	Short-term (< 24 hr) forecasting, diagnose convective initiation, locate sea breeze & assess evolution. Primary Nowcasting Team tool.	Dowell, D. C., and Coauthors, 2022: The High-Resolution Rapid Refresh (HRRR): An Hourly Updating Convection-Allowing Forecast Model. Part I: Motivation and System Description. *Wea. Forecasting*, **37**, 1371–1395, https://doi.org/10.1175/WAF-D-21-0151.1.
Hybrid Single-Particle Lagrangian Integrated Trajectory model (HYSPLIT)	Limited area mesoscale/ high resolution.	3 km (HRRR) or 27 km (GFS) / 37 levels (HRRR) or 56 levels (GFS)	Used in conjunction with HRRR to verify air mass origination and verify sea breeze strength/location.	Stein, A. R., R. R. Draxler, G. D. Rolph, B. J. B. Stunder, and M. D. Cohen, 2015: NOAA's HYSPLIT atmospheric transport and dispersion modeling system. *Bull. Amer. Meteor. Soc.*, **96**, 2059–2077, https://doi.org/10.1175/BAMS-D-14-00110.1.

Global forecast models (GFS, ECMWF) and their ensemble systems provided valuable context about the large-scale synoptic pattern. One important synoptic pattern is the presence of an upper-level 500 hPa ridge. Figures 4-6 of Wang et al. 2022 show that a 500 hPa ridge is a common feature of the Houston summer months, including June, and that subtle shifts in the position of the ridge influence sea breeze circulations and the frequency of convection. Hence, it is not only that a ridge was present, but specifically the variability in the position of the ridge that influenced the favorability in convection from day to day. Variability across the forecast models allowed for assessment of the uncertainty in synoptic-scale vertical velocity and moisture advection, giving confidence in the synoptic setting in which the mesoscale dynamics of interest to the project were taking place.

Convection-allowing models were also examined to determine the probability of convection. HRRR model forecasts were mainly used to check for the timing of sea-breeze

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initiation as well as to identify weak surface high pressure systems over the SE TX coastline. Surface high pressure systems off the SE TX coast were ideal for driving overnight offshore flow (land breezes) and provided favorable small-scale dynamics for mid-afternoon convergence zones across the SE TX coastline. As one example, inland surface high pressure systems often produce offshore flow, but a sea-breeze can still advance inland even if offshore flow exceeds 10 m/s (Arritt 1993). In addition to identifying regions of convergence along the coastline during the afternoon, the HRRR provided critical timing information regarding isolated shower or thunderstorm development. Knowing that convergence along a sea-breeze front or convective outflow/sea-breeze front interactions are not enough to trigger deep convection (Kingsmill 1995), using the HRRR in conjunction with other data sources helped the Forecasting and Nowcasting teams assess the likelihood these boundaries would trigger deep convection.

In addition to the HRRR, customized 1-km real-time model runs from the Weather Research and Forecasting (WRF) model, Version 4.4 (Skamarock et al., 2022), provided additional guidance for assisting the forecast (and nowcast) teams in identifying times and locations for deploying airborne and ground-based assets. The forecasting domain is shown in Figure 1. During ESCAPE, the WRF simulations were automatically initialized twice daily at 06Z and 12Z and run for a 24-hour forecasting period. The simulations were automatically postprocessed to generate GeoJSON files that were made publicly available on the Internet using Mapbox. In total, more than 1600 real-time WRF simulations were conducted for the ESCAPE field campaign. Featuring a various combination of initial forcings, aerosol loadings, microphysical schemes and planetary boundary layer schemes, the large ensemble of high-resolution WRF simulations not only aided forecasts and nowcasts but also allow for statistically robust post-campaign analysis. Details regarding the WRF model configurations and performance evaluations can be found in Hu et. al. (2023).

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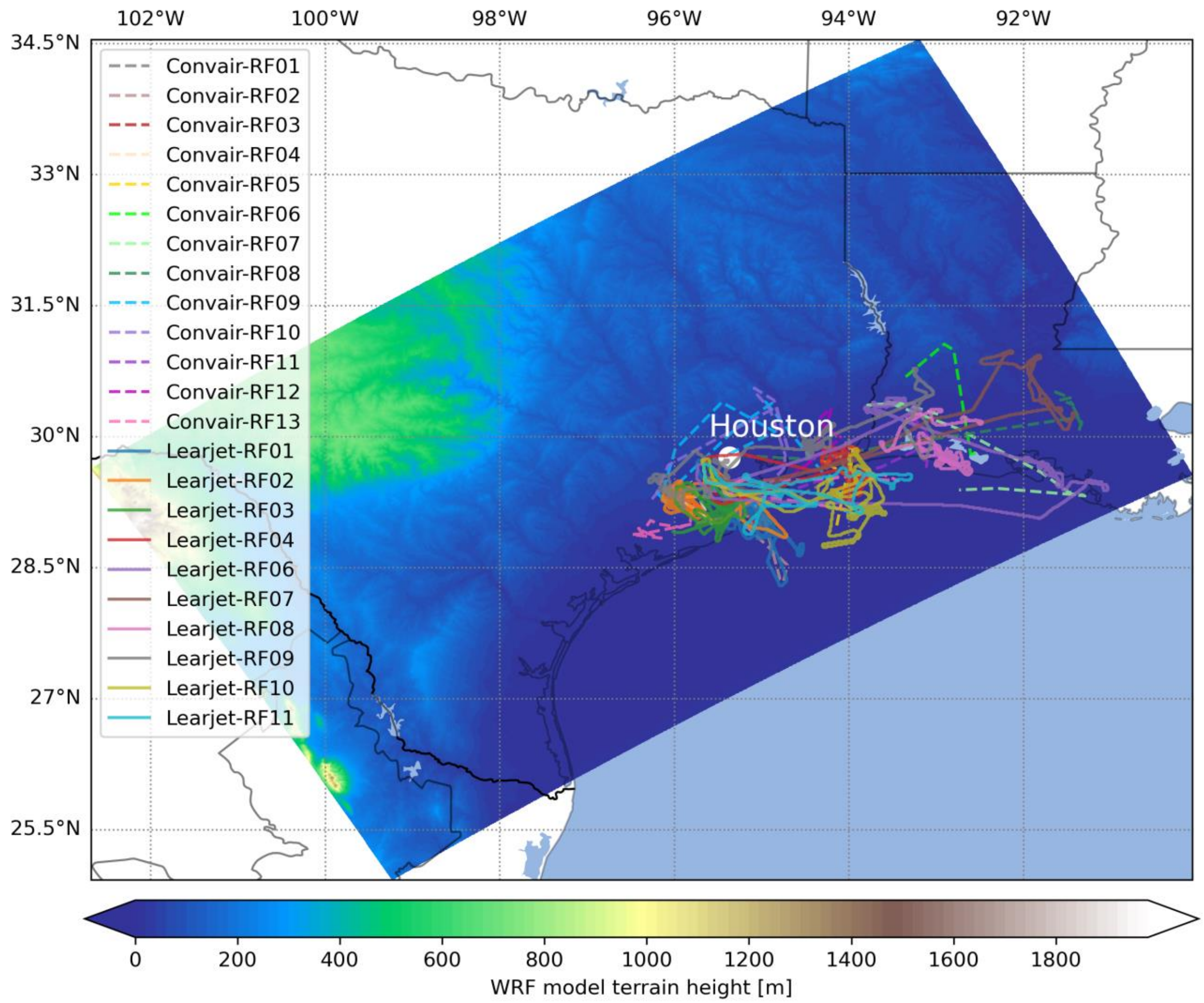

Figure 1: WRF model domain overlayed with Convair and Learjet research flight tracks. The forecast operation center is indicated by the white dot and text. Note that the domain is not centered over Houston to better capture convection by sea-breeze and frontal systems for computational efficiency. Note that the western and eastern domains are (respectively) the land areas to the WSW and E of Houston.

Finally, an extensive multi-model sounding analysis was performed to finalize each forecast. Model-derived soundings were analyzed using the Sounding and Hodograph Analysis and Research Program in Python (SHARPpy) software package (Blumberg et al., 2017). SHARPpy provided multiple forecasting inputs such as Convective Available Potential Energy (CAPE), Convective Inhibition (CIN), Lifting Condensation Level (LCL), Level of Free Convection (LFC),

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wind shear (between 850 and 500 mb), inversion identification, and moisture aloft, all of which provided a detailed picture of cumulus and thunderstorm formation likelihood. Wind shear was examined for each sounding: for isolated sea-breeze driven convection, low wind shear (< 20 kts) was considered ideal as it implied a vertically stacked atmosphere and limited influence by upper-level dynamical features such as nearby frontal systems or mid-level shortwave eddies. Atmospheric soundings also revealed the presence of subsidence inversions aloft, which were important for assessing the likelihood of deepening convection versus the probability of shallow cumulus or congestus cloud formation (Morcrette et al., 2007; Park et al., 2020). Inversion strength was not included in the decision-making criteria for a few reasons: inversions were almost always associated with warm and dry layers (covered by the RH criteria) and slight inversions (< 0.5ºC) are ideal for temporarily suppressing convection and allowing enough CAPE to build up in the late morning/early afternoon thereby increasing the probability of deep convection later in the afternoon. Cloud top and cloud base were also estimated from the large ensemble of model soundings, providing a crucial input for flight planning. Finally, forecast soundings were selected and analyzed at and around (e.g., within 25-50 km) of areas expected to produce sea-breeze driven convection.

3. Forecasting Operations

The ESCAPE Forecasting team included both an in-person team and a virtual team. The in-person Forecasting team focused primarily on short-term forecasting for determining on which days the National Research Council of Canada Convair-580 and Stratton Park Engineering Company (SPEC Inc.) Learjet would fly, as well as identifying priority targets for sampling convection. The ESCAPE forecast was closely communicated with the other TRACER-related project teams during the TRACER Intensive Observation Period (IOP). The virtual Forecasting team supported the TRACER Forecasting team and focused more broadly on meteorological evolution around the Houston area. A typical day-to-day schedule for both the in-person and virtual forecasting operations is given in Table 3.

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Table 3: A typical schedule for research flight days and non-flight days. The key difference in routine for flight and non-flight days was the need for nowcasting support and an early-morning pre-flight forecast briefing. The main forecasting preparation and meeting times were otherwise the same every day of the campaign.

Time of Day (Local)	Flight Day Routine	Non-Flight Day Routine
4:00am to 5:30am	Pre-flight forecast briefing preparation	
5:30am to 6:00am	Pre-flight forecast briefing to pilots and project scientists	
6:00am to 7:00am	Breakfast Break (contingent on scheduled flight time)	
7:00am to 9:00am	Pre-flight now-casting support	
9:00am to End-of-Flight	Nowcasting support	
9:00am to 1:00pm	Hybrid Forecasting Shift Meeting for Forecast Preparation	Hybrid Forecasting Shift Meeting for Forecast Preparation
1:00pm to 2:00pm	Lunch Break (contingent on scheduled flight time)	Lunch Break
2:00pm to 3:00pm	TRACER Forecast Briefing	TRACER Forecast Briefing
3:00pm to 4:30pm	Hybrid Forecast Briefing & Flight Planning	Hybrid Forecast Briefing & Flight Planning
End-of-Flight	Forecasting team leaders attend post-research flight de-brief	

a. Pre-Campaign Workshop and Training

Prior to the start of the campaign, the Forecasting and Nowcasting Team leaders hosted a virtual forecasting workshop. This workshop established a basic operational workflow that all participants could follow throughout the campaign. For both the seasoned and first-time forecasters on the team, the workshop was helpful at identifying the most important criteria for sea-breeze convection forecasting and development of the forecasting guide/checklist given in Table 1. Focusing on specific atmospheric conditions was also helpful in consolidating time and the number of resources needed to produce accurate forecasts. The workshop also allowed the Forecasting and Nowcasting teams to familiarize themselves with the NCAR EOL field catalog (see Fig. 2 as an example). Finally, the forecasting workshop aided the forecasting co-leaders in future decision making and identifying areas of improvement, which were achieved quickly after the ESCAPE campaign formally started.

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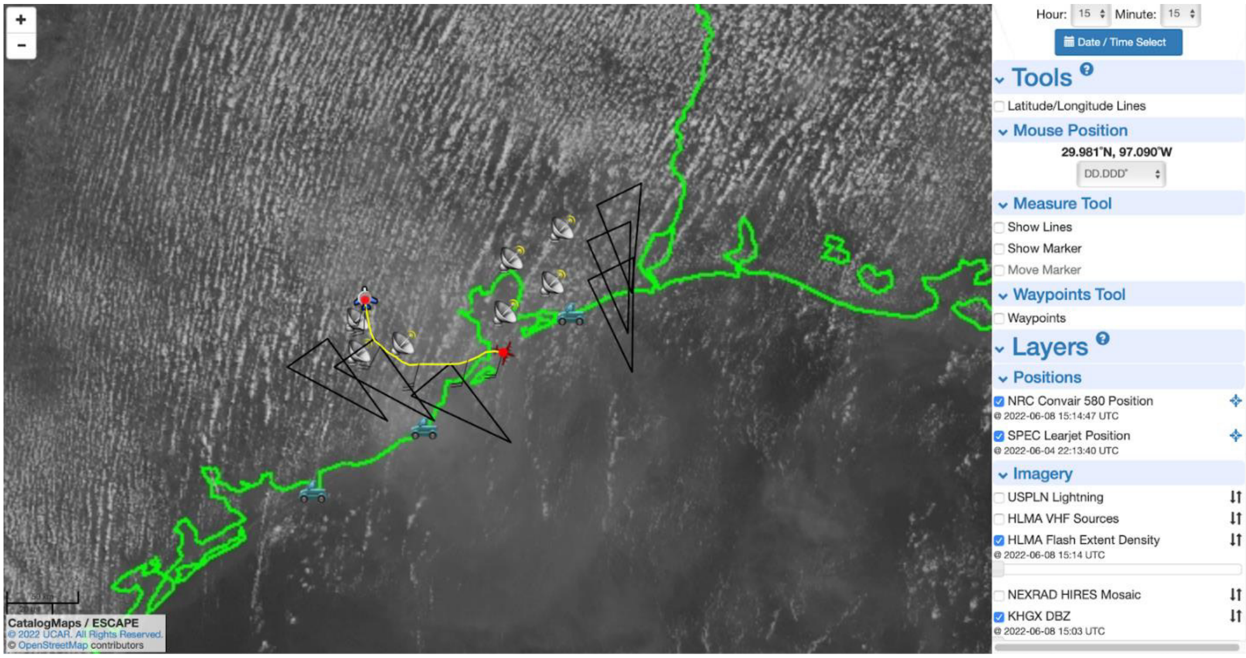

Figure 2: Example of the EOL catalog (http://catalog.eol.ucar.edu/escape) during RF05 on Wednesday, June 8, 2022 at ~10:15am CDT. The Convair had taken off and was headed for the southernmost triangle in the eastern domain to sample convective roll clouds (cloud streets) heading onshore.

An important function of field campaigns is to train students and future scientists. Students that were in the field supporting instrumentation joined forecasting operations to supplement their instrument responsibilities. This is mutually beneficial in providing students with a deeper understanding of the meteorological conditions sampled by the instrumentation. As one example, three students from Texas Tech University played a significant role in ESCAPE forecasting operations while also supporting the Texas Tech University Lightning Mapping Array (LMA) stations (TTU LMA) in collaboration with Texas A&M's Houston LMA (Logan, 2020; Chmielewski and Bruning 2016). As another example, two students supporting the Holographic Detector for Clouds (HOLODEC) airborne cloud probe (Spuler et al. 2011; Fugal et al. 2009) and one student supporting the NRC cloud probe analysis were trained to provide crucial support to the Forecasting and Nowcasting teams. Students who traveled to the field to gain experience with mobile radar deployments also contributed to daily forecast reports. Students not directly

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involved with an instrument team but will use project data also participated as members of the Forecasting and Nowcasting teams.

b. In-Person Field Operation

The in-person ESCAPE Forecasting team focused their efforts on selecting targeted flight locations and sampling times given the goal to sample sea-breeze generated convection.

The in-person team had three main foci:

1. Identify possible sea-breeze events and possible target domains. The in-person team met every morning at 9 am local time for a 3-hour shift, examining a variety of weather model output, balloon-borne soundings, satellite data, radar data, and trajectory model analyses to gain an overarching understanding of the synoptic-scale environment. CAPE/CIN, presence of temperature inversions, and orientation of surface-level flow relative to the shoreline were all critical for establishing if - at minimum - a low-level cumulus field would form, and if any probability of isolated thunderstorms forming from that cumulus field was possible. Using these criteria, the forecast team identified which of the two predetermined sampling areas (i.e., the western or eastern domain) was the optimum target for a prospective flight. At the ESCAPE forecast meeting, held at 2 PM on non-flight days immediately after the general TRACER forecast meeting, the forecast team gave a recommendation of the possibility of flights for the next three days. The flight time and target domain were also recommended if a flight was favored for the next day. This meeting included the participation of the ESCAPE PIs and pilots so that flight plans could be finalized and filed.

2. Short term Forecast validation for possible flights the next day. If a highly probable sea breeze event and flight was identified for the next day, a small group of forecasters (3 to 5 people) continued to monitor synoptic and mesoscale weather conditions throughout the day and provided a short-term forecast update the morning of a potential flight.

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During this stage, forecasting efforts focused on sounding and trajectory analysis, such as identifying layers with sufficient CAPE as well as cloud height and base. Satellite data loops were also used for short term forecast validation. A meeting was held with the PIs and pilots at least 3 hours before the planned flight time, to assess whether conditions were still favoring flights and an updated flight time and domain were provided. These forecasting efforts allowed adjustment in flight plans if needed, providing better information on preferred flight altitudes.

3. Nowcasting support for research flights. During each flight, a small group of nowcasters provided live updates for the crew on board the NRC Convair-580 through its bandwidth-limited satellite communication platform. Although there was no direct communication with the crew on the SPEC Learjet, the pilots on the NRC Convair-580 were able to relay important updates to the SPEC Learjet pilots when the aircraft were flying at the same time. With the help of real-time radar, satellite, and flight location information, the nowcasting team gave important guidance to the flight direction with possible target clouds along the flight path.

c. Virtual Operation

A portion of the ESCAPE forecast team operated virtually and took an active role in coordinating and contributing to the TRACER forecasts throughout the aircraft operations period. The virtual methodology offered a route for field campaign participation to those who could not attend in person, and ensured that ESCAPE senior personnel could represent campaign needs in the fully virtual TRACER forecast briefings.

The ESCAPE forecast was well coordinated with the TRACER daily forecast, which was performed virtually. The goal here was to provide 1) a forecast for the morning and afternoon of the next day, and 2) a longer-term forecast for the next 2-7 days. The daily-assigned forecast team had discussions using multiple aforementioned weather model outputs as well as a review of the latest National Weather Service forecast for SE Texas at around 1500 UTC. The

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team also reviewed the TRACER-operated daily high-resolution model simulations focused on the Houston area (Jensen et al., 2022). This discussion was virtual through an online conversation service (i.e., a Slack channel), which also involved the ESCAPE in-person forecast/nowcast team. This allowed for interactions between the two different forecasting teams which had common purposes. Although the discussion generally involved the daily forecast members, all ESCAPE and TRACER participants could join the discussion through the online conversation service.

The discussion was followed by the TRACER forecast briefing at 1 pm local time using an online meeting platform (e.g., Zoom). The ESCAPE in-person forecast/nowcast team also participated in the briefing discussion to ensure that the ESCAPE forecast was consistent with the TRACER forecast . This ensured that both the ESCAPE and TRACER Forecasting teams could resolve discrepancies in the short-term forecasts. This collaboration was paramount for ensuring forecast consistency and to provide the highest amount of detail possible. Right after the TRACER virtual forecast briefing, the ESCAPE hybrid forecast/nowcast briefing was held in-person at the designated ESCAPE operations center with an online meeting platform (e.g., Zoom) used so that remote participation was also possible.

Overall, the hybrid forecast operation of in-person and virtual provided many advantages. First, this operation allowed all PIs, collaborators, and students to participate in the forecast. Another advantage of this operation was that it permitted wide insights and suggestions from both the in-person and virtual participants, allowing for easy facilitation between collaborations with other projects (specifically TRACER). The hybrid, collaborative forecast also supported sharing of real-time observations from research instrumentation across the complex, multi-agency, field campaigns with the objective of cross-checking forecasts produced by the respective ESCAPE and TRACER teams as well as eventually enabling multi-platform studies on sea-breeze convection and related processes.

On the other hand, the hybrid structure brought out a few of the following challenges. While the TRACER forecast was scheduled at a fixed time every day (usually 1 pm local time for the briefing), ESCAPE needed more flexible timing with the forecast/nowcast operation depending on the flight schedules and mobile truck deployments. The virtual TRACER forecast

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worked to supplement the ESCAPE forecast during the entire ESCAPE IOP, but sometimes it could not be well integrated to the ESCAPE in-person forecast due to the observation schedule. Another challenge involved the use of several online conversation platforms by various participants during the IOP (e.g., Slack, WhatsApp, emails, cell phone text/call, zoom). Not all participants registered on all platforms, causing some participants (especially virtual participants) to miss important information. The virtual participants missed nowcast information because the communication tools were not integrated. For future projects, it is recommended that communication tools should be integrated such that all onsite and virtual participants communicate immediately and smoothly.

d. Nowcasting Operation

Nowcasting operations were essential for capturing the best possible dataset from the campaign. In using the flight time most effectively, on-the-ground nowcasting gives aircraft operators real-time advice on where to target new convection, considering operational factors (distance, scientific goals, etc.) and using information that is not readily available on the plane (e.g., development of convection away from aircraft location). Nowcasting also contributes to safe operation by warning the aircraft operators of nearby lightning activity and watching for potential obstacles to landing. The lead nowcaster was responsible for sending concise recommendations to the Mission Scientist onboard the NRC Convair-580 and closely monitoring the communication channel for requests/feedback from the Mission Scientist. These communications were carried out through a chat interface software that was accessible both from on board the NRC Convair-580 and on the ground. To streamline communication during operations and to avoid creating confusion, the communication between the nowcast team and the Mission Scientist was limited to only the lead nowcaster.

Nowcasting operations benefitted from having multiple team members focusing their analysis on different meteorological tools. Given that a significant focus of the lead nowcaster was directed towards communicating with the mission scientist, the additional nowcasters were essential for frequently checking satellite loops for outflow boundaries, convergence, cumulus organization, and other indications of high probability for convective cell

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development: such loops could not be accessed on the aircraft due to limited bandwidth. Satellite data show the development of cumulus clouds into deepening congestus clouds, and in conjunction with radar reflectivity data, quickly reveal developing precipitation via rapidly increasing radar reflectivity and satellite-based evidence of convective organization. Radar velocity data are also useful for revealing the precise location of the sea-breeze and outflow boundaries from nearby thunderstorms (Morcrette et al., 2007). These boundary features represented ideal target locations for the aircraft to sample. Advantages of convection-allowing models such as HRRR include increased accuracy of convection mode (e.g., discrete vs. organized) and better accuracy at resolving sea-breeze circulations (Cafaro et al., 2019). Cross-referencing these conditions on satellite against the most recent HRRR runs gave nowcasters increased confidence in recommending specific target region(s) during flight. Target areas of interest were discussed amongst the nowcast team before any recommendation was made to the Mission Scientist on the NRC Convair-580.

e. Pandemic and Campaign Management

Undeniably, the pandemic created many challenges for the management of ESCAPE and for the people participating in the campaign. In response, many steps were taken to ensure ESCAPE went smoothly and safely. For example, masks were mandatory in the forecast room, social distancing was practiced, and the number of people in the forecast/nowcast room was restricted (Figure 3). Different platforms and applications (e.g., Zoom, Google Drive/Slides, WhatsApp) were used to maintain communication between those inside and outside the forecast/nowcast room and to optimize engagement in the campaign and discussions. The use of on-line tools also helped document the decision-making process because every forecast report was saved to cloud storage and every meeting was recorded through Zoom. As in many areas of society, a result of the pandemic was a sudden reliance on ubiquitous internet-enabled computing that fostered collaborative, multi-site editing that naturally transitioned into a working reference for teams. With the collective efforts from every team member, the ESCAPE

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team was highly efficient during the campaign and collected a set of valuable data even with the challenges posed by the pandemic.

Figure 3: Photograph of the ESCAPE Forecasting and Nowcasting teams working together during a research flight while following COVID protocols. Pictured: Eric Bruning (top left), Matt Miller (top right), Raymond Shaw (HOLODEC principal investigator; bottom left) and David Singewald (bottom right).

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4. **Campaign Forecasting Operations and Select Research Flights**

As is common during meteorological field experiments, the initial ESCAPE experiment design required constant adaptation to the present atmospheric conditions. Both Forecasting and Nowcasting team participants expected this, knowing that the mix of synoptic-scale weather (e.g., mid-tropospheric ridges, cold fronts) and mesoscale forcing (e.g., the sea breeze, occasional nearby MCS) would add complexity to the interpretation of weather model output and other tools used by the team. Two research flights highlighting a variety of the Forecasting and Nowcasting team's experiences are selected, the 16 June 2022 and 04 June 2022 research flights, and described in the next two subsections.

A. **Convair Research Flight 11 / Learjet Research Flight 08 (LA Coastline)**

A textbook case study of sea-breeze driven convection took place on June 16, 2022 along the SW LA coastline. A weak high-pressure system was present off the SE TX coast, helping aid an overnight land breeze evident in satellite imagery (not shown). The Forecasting team identified these conditions during the previous day's forecast development and discussion. During the morning, clear and calm conditions gave way to rapid daytime heating, creating a sea breeze that began advancing inland between 11am and noon. Both the sea breeze and deepening congestus clouds were evident between these times in the satellite imagery and real-time HRRR weather model output used by the Nowcasting team. As a result of this real-time development, both the Forecasting and Nowcasting teams identifying this time as a high-probability event where further sea-breeze driven convective initiation would occur hereafter. By 1:00 pm CDT, with the NRC Convair-580 airborne, deepening congestus clouds were present along the LA coastline between Calcasieu Lake and Second Lake in SW Louisiana (Figure 4). The NRC Convair-580 successfully sampled clear-air skies before cumulus began developing along the sea-breeze front while also capturing the initial deepening of the

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cumulonimbus into the upper free troposphere by 1 pm CDT (represented in Figure 4). The Learjet also penetrated this deepening convection several times.

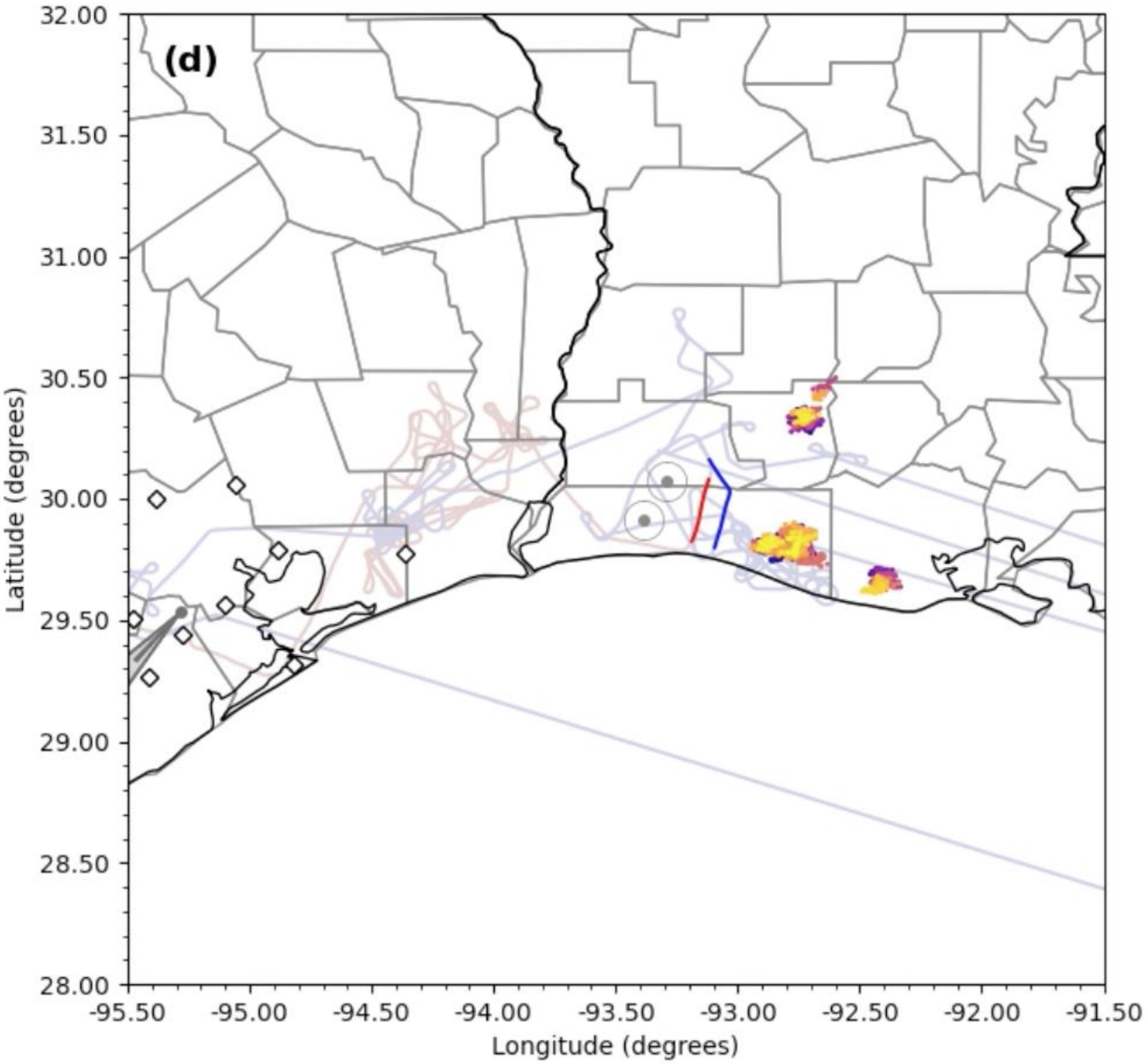

Figure 4: Zoomed view of the primary ESCAPE operations domain (including county boundaries and coastlines), showing LMA detections (colored by time from blue-purple-orange-yellow; stations are white diamonds), aircraft positions (red: Convair; blue: Lear; 5 min highlighted),

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and research radar scan positions (gray dots) from 1822-1827 UTC, 26 June 2022.

This research flight was successful for several reasons. Given that this flight took place near the end of the campaign, the Forecasting team had gained significant experience learning the intricacies of sea-breeze timing and conditions necessary to produce sea-breeze driven convection. Timing was especially important, given ESCAPE's overarching goal to capture the initial development of convection prior to becoming too deep to sample in-situ with aircraft due to a possible threat of hail and lightning. The Nowcasting Team learned from previous research flights the relative time the sea breeze was likely to begin advancing inland, allowing the Nowcasting Team to convey this information to the Forecasting team and gauge this timing against the timing suggested by various forecast models. Furthermore, this timing also allowed the Forecasting team to give better guidance for prospective thunderstorm development. One limitation of the aircraft was the limited flight duration (4 hours for the Convair, 3 hours for the Learjet). Therefore, optimizing the total amount of research hours required as precise information about timing as possible given that the ferry time from Sugar Land Airport to this domain had to be accounted for as well.

B. Convair Research Flight 04 / Learjet Research Flight 03 (June 4)

The 04 June 2022 research flights took place under more complicated conditions compared to the June 16 research flights. Deep convection formed as the result of an interaction between an MCS and the sea-breeze. The 03 June Forecasting team identified a MCS moving through central TX the day before, which arrived in the SE TX domain (western experiment domain to the SW of Houston) during the afternoon of June 4. Deep anvil cirrus was moving over the experiment domain near the start of the flight, with deep cumulonimbus developing dozens of miles to the west of Sugar Land, TX (Figure 5, near 29°N/-96.2°W). Despite this, some deep congestus was measured about 10 nm inland from the SE TX coastline and the Forecasting/Nowcasting teams determined that these clouds were isolated from the MCS to be considered a viable target for a research flight. The Nowcasting team on June 4 verified this

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decision by watching the latest radar and satellite imagery throughout the morning as the sea breeze evolved and forced coastal convection away from the MCS but still well within the western experiment domain. This allowed for the June 4 flight to take on the “pizza slice” flight template where the aircraft flew from the Gulf of Mexico onshore, followed by an along-shore track to measure the sea-breeze/convergence boundary, and repeated these tracks until deep convection triggered

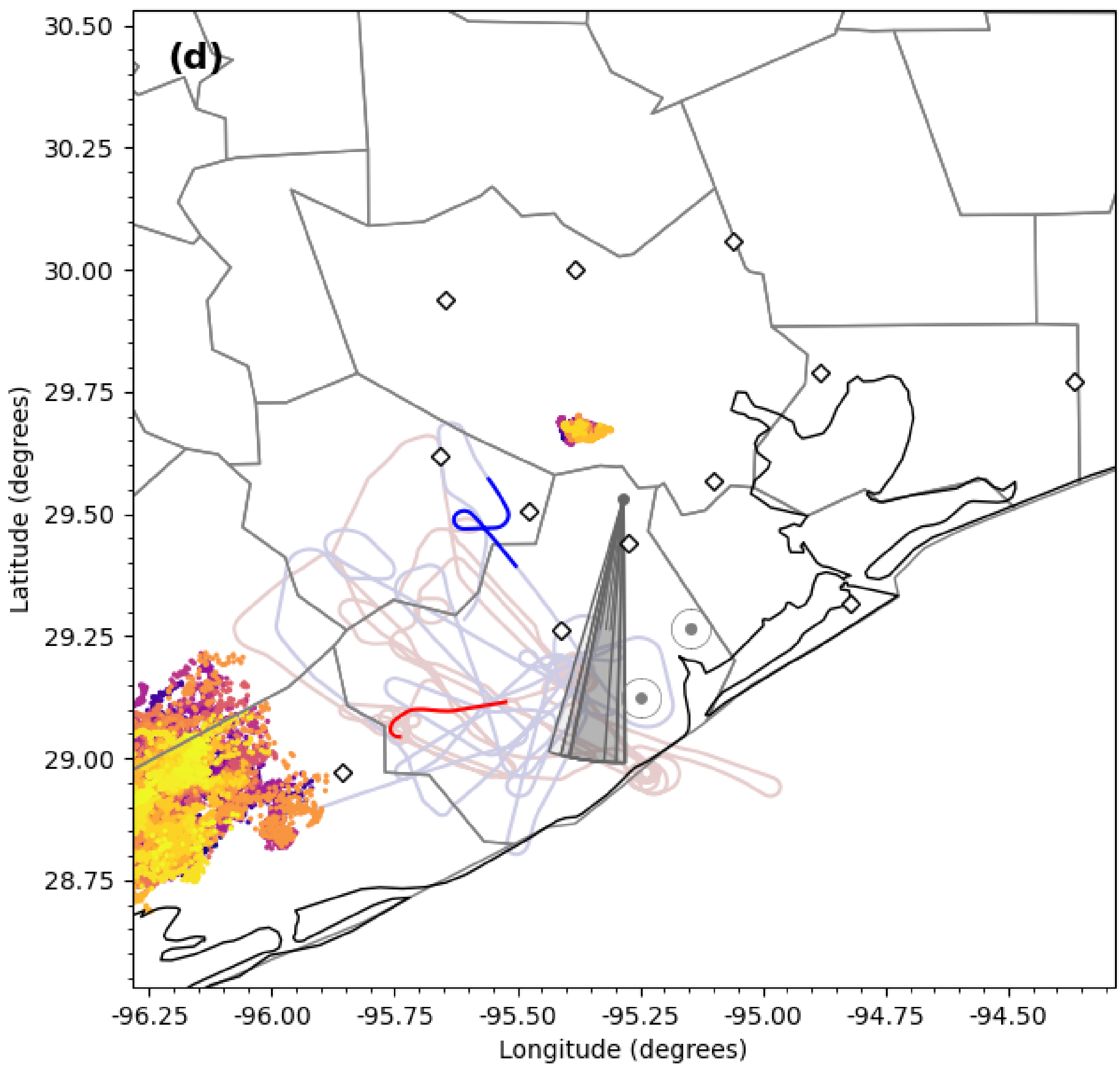

Figure 5: As in Figure 4, but from 2201-2206 UTC, 4 June 2022.

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This particular research flight highlights the complexities of forecasting localized convection when several synoptic-scale and mesoscale influences can affect the mode of convection. The flight was successful in measuring developing thunderstorms, but disentangling this development from the influence of the upper-level shortwave that triggered these deep MCS-style thunderstorms will require further research. The deep congestus along the sea-breeze that ultimately developed into thunderstorms could make for an ideal case study. If this upper-level shortwave had not traversed SE TX, would these thunderstorms have triggered under their own accord given the already ample surface-level moisture and conducive upper-level environment for deep convection? Would these storms have formed later in the afternoon or early evening? From a forecasting point-of-view, these scientific questions merit future research for the sake of guiding operational forecasters being able to discriminate MCS-style convection from sea-breeze convection. The sea-breeze was apparent and clearly contributed to sustained convective development. Finally, student participants on the Forecasting and Nowcasting team benefitted from this forecasting, especially being only the 2nd flight of the campaign, by observing how distinct mesoscale features (i.e., the MCS and sea-breeze) could be disentangled despite the complexity.

5. Conclusions

Overall, the ESCAPE Forecasting and Nowcasting teams succeeded in delivering high quality forecasts throughout the field campaign, which helped the entire team meet their individual science objectives for the project (Kollias et al., 2024, *in press*). Before the campaign began, a forecasting workshop focused on the fundamentals of sea-breeze-driven convection gave every team member a standardized review and set of knowledge. Every member of the team, from experienced scientists to new graduate students, benefitted from this workshop resulting in consistently accurate forecasts. Two such forecasts were highlighted, each

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illustrating the forecasting process, highlights and challenges typical throughout the field campaign.

One aspect of forecasting operations that did not work well was integrating virtual participation during the actual forecasting analysis period. During the morning forecasting preparations, it was logistically difficult to manage virtual participants via Zoom/MS Teams, where participants found this aspect too burdensome on their computers while also analyzing forecast model data/preparing forecast briefings. After a couple of forecasting shifts, this aspect of the hybrid approach was tabled, and hybrid discussions were saved until after everyone on both the in-person and virtual Forecasting teams had a chance to complete their individual analyses. By the end of the campaign, this approach to the hybrid operation worked optimally well for all participants. Given this experience, it is recommended that whether working virtually or in-person, time should be allowed for all participants to perform analysis and develop a forecast before engaging in hybrid discussions and finalizing the forecast. Another recommendation is that forecasting teams should have a pre-campaign forecasting workshop to integrate new or potentially inexperienced personnel into the team as well as ensure a basic forecasting framework tailored to the project's main objectives. The synergy of many forecasting activities demonstrably contributed to the overall quality of every forecast for the ESCAPE campaign. Multiple forecasters worked on specific aspects of the overarching forecast including HYSPLIT forward trajectories of air masses, model soundings for convective instability and likelihood of convection, sufficient isolation from any nearby MCS, short-range forecasting with highly detailed tentative flight suggestions, and long-range forecasting to assess pros-and-cons of assessing meteorological favorability and uncertainty for flights on upcoming days. This allowed the Forecasting team to assess probabilities of sea-breeze convection forecasting in a precise manner, allowing the project PIs to make highly informed decisions regarding the use of aircraft flight hours. We believe this template for sea-breeze convection led to a richly successful forecasting operation and believe it will be a highly serviceable template for future field campaigns focusing on coastal convection.

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7. Data Availability Statement

All ESCAPE data are cataloged at the NCAR EOL ESCAPE data archive: https://data.eol.ucar.edu/project/ESCAPE.

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