# MOBILE RADAR AS AN UNDERGRADUATE EDUCATION AND RESEARCH TOOL

## The ERAU C-BREESE Field Experience with the Doppler on Wheels

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ERAU C-BREESE was an 18-day Doppler on Wheels educational deployment that investigated sea-breeze processes and convection across central Florida.

Embry-Riddle Aeronautical University Convective-Boundary Research Engaging Educational Student Experiences (ERAU C-BREESE) was an 18-day Doppler on Wheels (DOW) educational deployment through the Center for Severe Weather Research (CSWR) and funded by the National Science Foundation (NSF). ERAU C-BREESE ran from 4 to 21 May 2015; the deployment was organized and operated at ERAU in Daytona Beach, Florida, and was offered as a three-credit undergraduate summer course. Thirteen ERAU students, three ERAU meteorology faculty and staff, and one CSWR technician (Alycia Gilliland) participated in ERAU C-BREESE. Figure 1 shows the ERAU C-BREESE team standing outside of CSWR DOW-6.

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DOW educational deployments are funded through the NSF Lower-Atmospheric Observing Facilities program (UCAR EOL 2016a). Educational deployments of DOWs and other mobile facilities began in 2008, and in 2015 a record nine educational deployments were funded (Table 1). Table 1 details a complete list of DOW educational deployments since 2008, including project name, host university, and area of scientific focus. Some universities, such as the University of Nebraska–Lincoln (four) and University of Illinois at Urbana–Champaign (three), have hosted the DOW for more than one educational deployment, with a slightly different scientific focus each time.

DOW deployments relevant to ERAU C-BREESE include but are not limited to the Pennsylvania Area Mobile Radar Experiment (PAMREX) at The Pennsylvania State University (Richardson et al. 2008), the DOW Radar Observations at Purdue University Study

(DROPS; Toth et al. 2011), the Hawaiian Educational Radar Opportunity (HERO) at the University of Hawaiʻi at Mānoa (Bell et al. 2015), the Doppler Radar for Education and Mesoscale Studies (DREAMS; UCAR EOL 2016b), a sea-breeze-centric project conducted by Stony Brook University in 2013, and the Florida DOW Experiment and Weather Study (F-DEWS) at the Florida Institute of Technology, which took place in 2015, 4 months after ERAU C-BREESE.

Many of the educational deployments listed in Table 1 took place during typical 12–15-week semesters, whereas a few such as DREAMS (UCAR EOL 2016b) and ERAU C-BREESE were shorter deployments during summer terms. The abbreviated 6-week summer term at ERAU allowed for only 3 weeks of postdeployment data analysis and student research projects during the summer course. In addition, most educational deployments (Table 1; UCAR EOL 2016a) integrated both graduate and undergraduate students. Since ERAU's meteorology program is undergraduate only, this was not an option for ERAU C-BREESE. As a result, faculty had to ensure that the undergraduate students, who came

**Table 1. A list of NSF-funded educational deployments of the DOW from 2008 to 2016. Detailed from left to right are project name, year, host university, and scientific focus. Data for the table were compiled from UCAR EOL (2016a) (available online at www.eol.ucar.edu/educational-deployments).**

| Project acronym | Full project name | Year | Host university | Scientific focuses |
|---|---|---|---|---|
| UNDEO 1 | University of Nebraska DOW Education and Outreach | 2008 | University of Nebraska–Lincoln | Mixed-phase precipitation, mesoscale boundaries, and downbursts |
| DROPS 1 | Doppler on Wheels Radar at Purdue | 2009 | Purdue University | Convection, lake-effect snow, and mesoscale convective systems |
| NAPEP | Northern Autumn Plains Echo Patterns | 2010 | St. Cloud State University | Frontal structures and precipitation |
| SNOwD UNDER | Student Nowcasting and Observations of Winter Weather with the DOW at University of North Dakota Education in Research | 2010 | University of North Dakota | Winter storms and radar technology |
| UIDOW 1 | University of Illinois DOW Education, Research and Outreach | 2010 | University of Illinois at Urbana–Champaign | Winter weather, fronts, and lake-effect snow |
| UNDEO 2 | University of Nebraska DOW Education and Outreach | 2010 | University of Nebraska–Lincoln | Convection and mesoscale boundaries |
| CM$^3$ | Coordinated Mesoscale Measurements in Mississippi | 2011 | Jackson State University | Small-scale frontal structures and environments |
| DOWNEWS 1 | DOW Observations of New England Winter Storms | 2011 | Lyndon State College | Winter storms and associated precipitation |
| SOLPEX-REO | Sounding Observations of Lake-Effect Precipitation Experiment—Radar Education and Outreach | 2011 | University of Utah | Lake-effect precipitation, orographic precipitation, and fronts |
| TOM | Teaching Flow over Mountains | 2011 | University of Colorado Boulder | Winter storms and snowfall |
| DOLE | DOW Observations of Lake-Effects | 2012 | State University of New York (SUNY)–Oswego | Snowstorms, lake breezes, and lake-effect showers and thunderstorms |
| DOWNEWS 2 | DOW Observations of New England Winter Storms | 2012 | Lyndon State College | Dual-polarization radar interpretation, and stratiform precipitation |
| DROPS 2 | Doppler on Wheels Radar at Purdue | 2012 | Purdue University | Synoptically forced precipitation |
| PRESSES | Polarimetric Radar for Examining Streamflow and Soil Erosion Studies | 2012 | University of Missouri | Dual-polarization radar interpretation and agricultural issues |
| UIDOW 2 | University of Nebraska DOW Education and Outreach | 2012 | University of Illinois at Urbana–Champaign | Fronts, synoptic-scale cyclones, and associated precipitation |
| DREAMS | Doppler Radar for Education and Mesoscale Studies | 2013 | Stony Brook University | Sea breezes and convection |

into the course with diverse meteorological backgrounds and levels of experience, were all prepared to handle the requirements of operating the DOW and collecting data.

As examples of the diverse scientific objectives of DOW educational deployments, PAMREX (Richardson et al. 2008) and HERO (Bell et al. 2015) primarily focused on mobile radar observations of atmospheric phenomena in regions of complex terrain in Pennsylvania and Hawaii, respectively. Meanwhile, DROPS (Toth et al. 2011) took DOW observations of wind farms in Indiana. Educational deployments most related to ERAU C-BREESE include F-DEWS; Texas A&M DOW (TAMU DOW), which studied bay-breeze convection in Texas; and DREAMS (UCAR EOL 2016b), which studied sea-breeze processes and convection in Long Island, New York. Long Island is similar to Florida in that it is a heavily populated peninsula, albeit a much narrower one. Many of the educational deployments (Table 1) also had similar outreach objectives to ERAU C-BREESE, integrating high school and community college students into the project in addition to visiting several local schools (see "Education" section).

**Table 1. Continued.**

| Project acronym | Full project name | Year | Host university | Scientific focuses |
|---|---|---|---|---|
| GEO-WIND-HWS | Geoscience Education and Outreach of Weather in New York using the DOW at Hobart and William Smith Colleges | 2013 | Hobart and William Smith Colleges | Dual-polarization radar interpretation, lake-effect snow, and mixed-phase precipitation |
| HERO | Hawaiian Educational Radar Opportunity | 2013 | University of Hawaiʻi at Mānoa | Orographic processes and rainfall |
| UNDEO 3 | University of Nebraska DOW Education and Outreach | 2013 | University of Nebraska–Lincoln | Supercell convection, wind farms, and radar theory |
| WIUDOW 1 | Western Illinois University DOW Radar Observations | 2013 | Western Illinois University | Wind farms, smoke stack emissions, and thunderstorms |
| FR-DOW | Northern Colorado Front Range Doppler on Wheels | 2014 | University of Northern Colorado | Cold fronts and winter weather |
| PSU-DROPS | Penn State University—Dual-pol Radar for Outreach and Precipitation Studies | 2014 | The Pennsylvania State University | Dual-polarization radar interpretation |
| PSUMet-DOW | Plymouth State Meteorology DOW Project | 2014 | Plymouth State University | Cold-air damming and mixed-phase precipitation |
| DOWNEWS 3 | DOW Observations of New England Winter Storms | 2015 | Lyndon State College | East Coast winter storms and local mesoscale phenomena |
| ERAU C-BREESE | Embry-Riddle Aeronautical University Convective-Boundary Research Engaging Educational Experiences | 2015 | Embry-Riddle Aeronautical University | Central Florida sea breezes and convection |
| F-DEWS | Florida DOW Experiment and Weather Study | 2015 | Florida Institute of Technology | Sea and lagoon breezes, convective initiation, and tropical cyclones |
| GEO-WIND-HWS II | Geoscience Education and Outreach of Weather in New York using the DOW at Hobart and William Smith Colleges | 2015 | Hobart and William Smith Colleges | Mixed-phase precipitation and warm-frontal snow |
| TAMU DOW | Texas A&M University DOW | 2015 | Texas A&M University | Bay-breeze convection |
| UNDEO 4 | University of Nebraska DOW Education and Outreach | 2015 | University of Nebraska–Lincoln | Multicell and supercell convection |
| WIUDOW 2 | Western Illinois University DOW Radar Observations | 2015 | Western Illinois University | Remote sensing and local weather |
| MEDOW | Millersville University Educational DOW | 2016 | Millersville University | Convection in a radar-sparse area and warning improvement |
| UIDOW 3 | University of Illinois DOW Education, Research and Outreach | 2016 | University of Illinois at Urbana–Champaign | Blizzards, convection, and remote sensing |


**Fig. 1. The ERAU C-BREESE team in front of the CSWR DOW-6 during IOP8.**

ERAU C-BREESE was scientifically different from, for example, TAMU DOW and DREAMS in that sea-breeze convergence and convection are an everyday occurrence in a typical warm season across the Florida peninsula (e.g., Byers and Rodebush 1948; Hodanish et al. 1997), such that Florida is the lightning capital of the United States (e.g., Orville and Huffines 2001). Specifically, with respect to DREAMS, Long Island Sound pales in size to the Gulf of Mexico, the latter of which makes a large contribution to the almost daily sea-breeze convergence and convection in the Florida peninsula. On the other hand, Florida is typically far removed from the polar jet stream in summer, while Long Island is not. As a result, the DREAMS project included scanning severe thunderstorms, while ERAU C-BREESE experienced only one marginally severe event (see "IOP9: Forecasts and observations" section).

The overall objectives of ERAU C-BREESE were to 1) use experiential learning (e.g., Eyler and Giles 1999; Eyler 2002) to further undergraduate meteorology education by incorporating the DOW into a field campaign involving real-world forecast and observational techniques, 2) expose ERAU meteorology undergraduates to meteorological data collection and analysis, 3) utilize DOW data to further the understanding of sea-breeze processes and convection in central Florida, and 4) expose local K–12 students and the general public to Doppler radar technology, atmospheric science field research, and ERAU meteorology.

Thunderstorms are a frequent occurrence in Florida in the warm season (May–September), such that the state experiences the highest number of thunderstorm days in a given year (Ahrens and Henson 2016) and the largest mean annual lightning flash density (Orville and Huffines 2001). Curran et al. (2000) compiled a 35-yr climatology of lightning strikes across the United States and found that during that time period, Florida had the largest number of fatalities (345) and injuries (1,178) of any state solely due to lightning. Lericos et al. (2002) assembled a synoptic climatology of warm-season lightning events and found that the position of the subtropical ridge had a large impact on the frequency and location of lightning strikes within the Florida peninsula. Shafer and Fuelberg (2006, 2008) used the results of the aforementioned climatologies to devise statistical procedures to help forecast the location and frequency of warm-season lightning strikes in Florida. However, not all areas in the state are created equal. Byers and Rodebush (1948) first noticed a disparity between the Florida Panhandle and the Florida peninsula (excluding the keys), as thunderstorms occur with a 50% greater frequency in the peninsula. These observed patterns in thunderstorm frequency are consistent with lightning-strike climatologies in Florida, including Hodanish et al. (1997), Williams et al. (1999), and Curran et al. (2000).

Sea breezes are a common daytime phenomenon in coastal locations. As the land surface heats faster than the nearby water, a shallow surface low pressure forms over the land, and a shallow surface high pressure forms over the water. The wind subsequently starts to blow from high to low pressure, resulting in a sea breeze blowing from water to land (e.g., Simpson 1994). At night, the land cools more quickly than the water, resulting in a reversal of the circulation (land breeze). For a full explanation of sea-breeze formation and processes, the reader is referred to Simpson (1994).

Byers and Rodebush (1948) speculated that lower-tropospheric sea-breeze convergence, in which the

Atlantic sea breeze meets the prevailing wind and/or the Gulf sea breeze, is the primary dynamic mechanism for ascent and thunderstorm formation over the Florida peninsula. Observational (e.g., Gentry and Moore 1954; Estoque 1962; Kingsmill 1995) and numerical modeling (e.g., Pielke 1974; Dalu and Pielke 1989; Nicholls et al. 1991; Robinson et al. 2013) studies later confirmed and added dynamical insight to the original Byers and Rodebush (1948) calculations. Sea-breeze convection also has a large impact on the local hydrological cycle (e.g., Baker et al. 2001). Schwartz and Bosart (1979) and Blanchard and Lopez (1985) found that approximately half of the Florida peninsula's annual rainfall occurs from May to September. In addition, Burpee and Lahiff (1984) reported that 35%–40% of warm-season rainfall occurs purely as a result of sea-breeze-related processes.

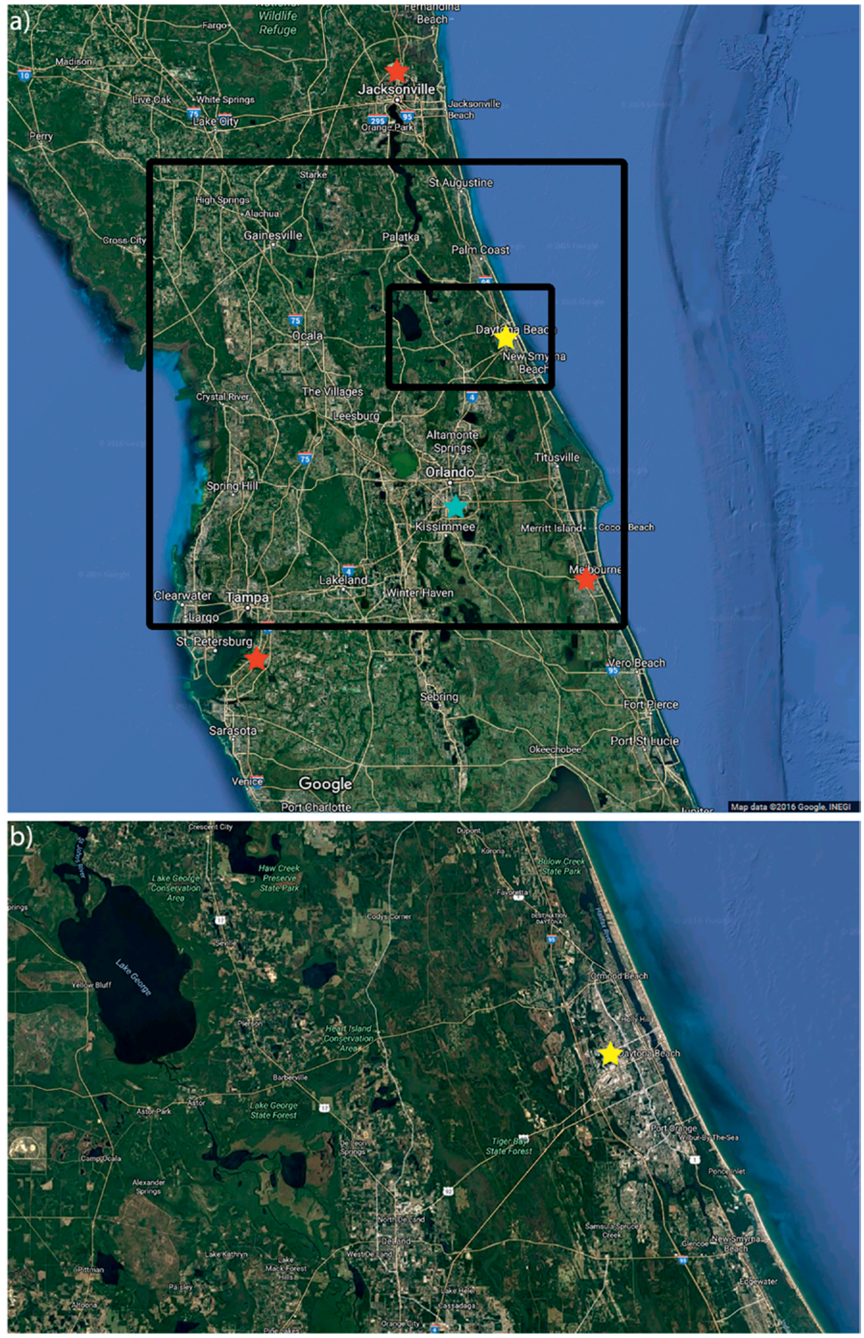


**Fig. 2. Google terrain maps of central Florida (Google Maps 2016) for (a) the ERAU C-BREESE domain, outlined by the large black box, and (b) the inset near Daytona Beach outlined by the small black box in (a). The location of the ERAU campus is marked on both panels with a yellow star. In (a), the MLB, JAX, and TBW WSR-88Ds are marked with red stars and the Orlando (MCO) TDWR is identified with a turquoise star.**

Central Florida, with its dual sea breezes and multiple river and lake breezes (e.g., Tampa Bay, Indian River, St. Johns River, Halifax River, and Mosquito Lagoon) on both coasts, is an ideal location to study warm-season sea-breeze convection. The Cape Canaveral area, home to Kennedy Space Center, has been well documented as a local lightning frequency maximum, at least in part due to its multiple sea and river breezes (e.g., Laird et al. 1995; Rao et al. 1999; Rao and Fuelberg 2000). Gremillion and Orville (1999) and Hansen et al. (2010) also studied lightning impacts in the Cape Canaveral area, which was deliberately included in the ERAU C-BREESE domain.

The ERAU C-BREESE domain (Fig. 2a) was chosen with climatologically favored regions of sea-breeze convergence in mind. Figure 2a also displays the locations of the three closest National Weather Service (NWS) Weather Surveillance Radar-1988 Dopplers (WSR-88Ds): to the north in Jacksonville (JAX), to the south in Melbourne (MLB), and to the southwest near Tampa Bay (TBW). In addition, the Federal Aviation Administration (FAA) operates a Terminal Doppler Weather Radar (TDWR) at Orlando International Airport (Fig. 2a). In the "IOP9: Forecasts and observations" section, WSR-88D data are discussed along with DOW data in the context of the most successful ERAU C-BREESE intensive observation period (IOP), IOP9.

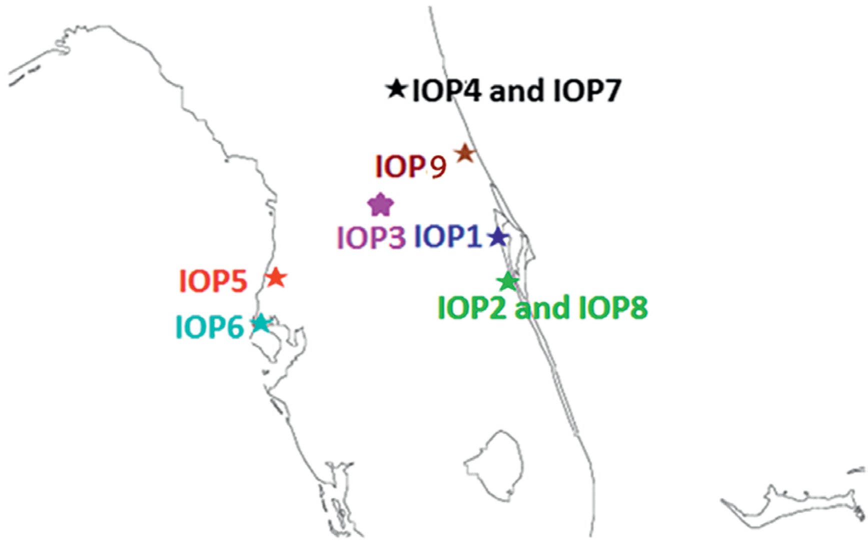


**Fig. 3. Map of the nine IOP locations during ERAU C-BREESE, as detailed in Table 2.**

In total, ERAU C-BREESE had nine IOPs, with six near the Atlantic coast, two near the Gulf Coast, and one in the center of the peninsula (Fig. 3; Table 2). One of the primary issues for ERAU C-BREESE was that most of central Florida is lined with tall trees. Scanning toward the coast (e.g., Atlantic Ocean) was typically not a problem, but choosing acceptable locations for scans pointed inland was challenging. Figure 2b shows the terrain located near and just to the west of Daytona Beach. While views toward the ocean were largely unobstructed, areas even a few kilometers inland feature thick forests and brush that resulted in radar beam blockage. Advance in-person and Google Maps terrain and street views (Google Maps 2016) scouting of potential scanning locations was mostly completed in the weeks and months prior to ERAU C-BREESE, such that beam blockage issues could be minimized during the deployment.

**Table 2. Overview of the (left) nine IOPs during ERAU C-BREESE, including (middle) dates and deployment locations and (right) observed phenomena.**

| IOP | Date and location | Observed phenomena |
|---|---|---|
| 1 | 9 May 2015<br>Titusville, Florida | Sea-breeze front |
| 2 | 10 May 2015<br>Rockledge, Florida | Sea-breeze front; distant ordinary thunderstorms |
| 3 | 11 May 2015<br>Grand Island, Florida | Sea-breeze front and convergence; ordinary thunderstorms |
| 4 | 12 May 2015<br>Hastings, Florida | Sea-breeze front and convergence; strong thunderstorms; weak rotation |
| 5 | 15 May 2015<br>Pasco County, Florida | Strong ordinary thunderstorms; Gulf Coast sea-breeze front |
| 6 | 16 May 2015<br>Clearwater, Florida | Gulf Coast sea-breeze front; distant thunderstorms |
| 7 | 19 May 2015<br>Hastings, Florida | Sea-breeze front; numerous ordinary thunderstorms |
| 8 | 20 May 2015<br>Rockledge, Florida | Sea-breeze front |
| 9 | 20 May 2015<br>Daytona Beach, Florida | Severe thunderstorms; shelf clouds, mammatus, and gust fronts |

The remainder of this paper is organized as follows: the "Education and outreach" section recaps educational concepts and local outreach efforts, the "Field experiment setup" section discusses IOP preparation and data collection strategies, while the "IOP9: Forecasts and observations" section details IOP9, the most successful IOP, from both forecast and observational perspectives. Finally, a summary and lessons learned are presented.

## EDUCATION AND OUTREACH.

*Education.* CSWR DOW-6 arrived at ERAU on 4 May 2015 for student and faculty training. Training concepts included the differences between high- and low-frequency radar pulses, plan position indicator (PPI) elevation angles, and range–height indicator (RHI) scans. ERAU C-BREESE students and staff also learned how to operate the DOW-6 computer and properly take deployment notes. Finally, students were introduced to CSWR preprepared sample animations, including from Hurricane Isaac (2012) in Louisiana and the Goshen, Wyoming, tornado (2009) during the second Verification of the Origins of Rotation in Tornadoes Experiment (VORTEX2; e.g., Wurman et al. 2012). These sample animations were subsequently used for all outreach events during ERAU C-BREESE.


**Fig. 4. (a),(b) ERAU C-BREESE students giving tours and DOW demonstrations during outreach visits to central Florida schools, (c),(d) photographs taken during the ERAU C-BREESE outreach day at the hurricane awareness tour in St. Augustine and (e) ERAU C-BREESE student Katie Lenninger being interviewed by CBS Jacksonville during IOP4.**

The students who participated in ERAU C-BREESE entered with a relatively wide range of meteorological educational backgrounds. ERAU meteorology majors ranged from rising sophomores to rising seniors, while two students were meteorology minors, aeronautical science majors who are required to take five meteorology courses during their undergraduate career. All students had to have at a minimum completed three undergraduate meteorology courses, including two introductory courses and one of the following midlevel undergraduate courses: introduction to weather forecasting, thunderstorms, or satellite and radar interpretation.

The first few days of ERAU C-BREESE educated students how to properly operate the DOW and interpret the scans and served as a reminder of how to forecast and observe sea-breeze processes and convection. To that end, a Florida-centric forecasting links web page was established in-house for students to use for the duration of the deployment, and weather forecast discussions were held each morning. Further details on specific IOP preparation tasks are discussed in the next two sections.

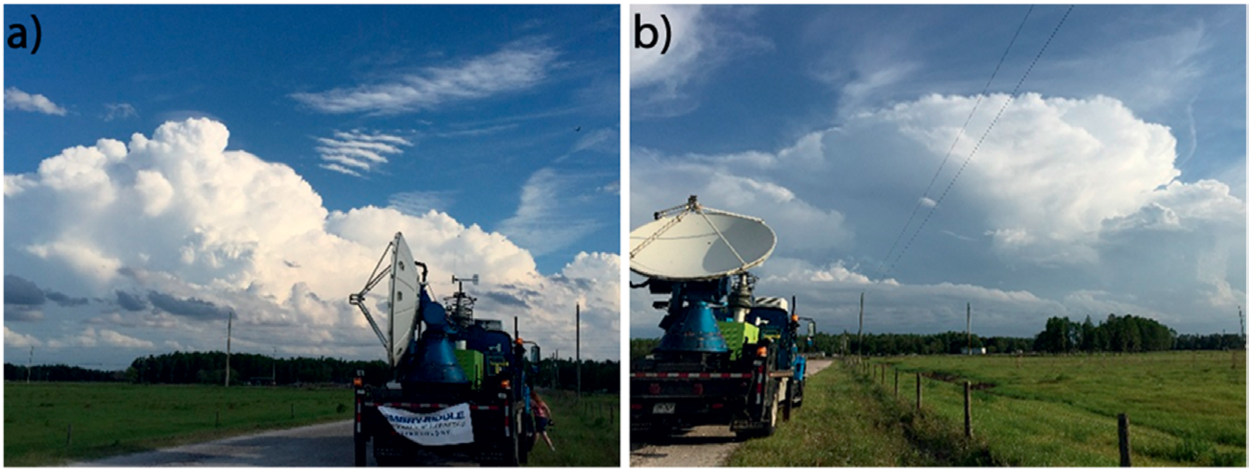


**Fig. 5. DOW-6 looking south toward thunderstorms over Tampa Bay during IOP5 on 15 May 2015. (a) A towering cumulus, pileus (cap) cloud, and possible gravity wave signature; (b) a fully developed thunderstorm over Tampa Bay approximately 1 h later.**

*Outreach.* One of the primary missions of ERAU C-BREESE was to perform outreach to the local community, particularly kindergarten through twelfth grade (K–12) students. This serves several purposes: it increases awareness of Doppler radar technology, exposes local K–12 students to atmospheric instrumentation and data collection, and increases the visibility of the ERAU meteorology program in central Florida.

Most of the outreach events were held in the first week of the deployment, including five local school visits. Across all outreach events, more than 1,200 people toured DOW-6 and learned about ERAU C-BREESE. At each outreach stop, one ERAU C-BREESE student remained inside DOW-6 at all times, explaining the sample animations on the screens. One or two additional ERAU C-BREESE students would staff the tornado pod, which was typically placed on the sidewalk outside DOW-6. Faculty and staff were on hand to supervise, but the meteorological concepts were always explained by ERAU C-BREESE students. In Fig. 4a, an ERAU C-BREESE student is explaining the mesonet tower and instrumentation of DOW-6 to high school science students at a K–12 outreach stop. At another school, an ERAU C-BREESE student is shown explaining the tornado pod to a group of third graders (Fig. 4b).

**Table 3. Scanning strategies for each of the nine IOPs, including radar beam elevations. Both low- and high-frequency scans were performed for every IOP.**

| IOP | Elevations |
|---|---|
| 1 | 0.5°, 1°, 3°, 5°, 10° |
| 2 | 0.5°, 1°, 3°, 5°, 10° |
| 3 | 0.5°, 1°, 3°, 5°, 10° |
| 4 | 0.5°, 1°, 3°, 5°, 10°, RHI |
| 5 | 0.5°, 1°, 3°, 5°, 10°, RHI |
| 6 | 0.5°, 1°, 3°, 5°, 10° |
| 7 | 0.5°, 1°, 3°, 5°, 10° |
| 8 | 0.5°, 1°, 3°, 5°, 10° |
| 9 | 0.5°, 1°, 3°, 5°, 10°, RHI |

In collaboration with the NWS in Jacksonville, ERAU C-BREESE was invited to participate in the NOAA hurricane awareness tour stop at Saint Augustine, Florida, an all-day public event on 7 May 2015 (Figs. 4c,d). Two NOAA hurricane hunter aircraft (G-IV and P-3; Fig. 4c) were available for school and media tours in the morning and general public tours in the afternoon. In addition, ERAU C-BREESE students were able to tour the NOAA aircraft and meet with the hurricane hunters.

ERAU C-BREESE also had two comprehensive television news interviews during the deployment: Action News (CBS) Jacksonville, during the hurricane awareness tour and IOP7, and News13 (Orlando), during IOP8. Figure 4e shows ERAU C-BREESE student Katie Lenninger being interviewed by Action News during IOP7 near Hastings, Florida (Fig. 3; Table 2); the interview included a live shot on the local evening newscast of the thunderstorms that DOW-6 was scanning at the time.

Overall, outreach events and media coverage were very rewarding. They allowed ERAU students to accumulate experience with public speaking and explaining scientific concepts to younger students. The events also increased the visibility of the ERAU

**Table 4. An example of the mandatory student worksheets used during ERAU C-BREESE. (Left) Questions designed by faculty and staff that students needed to answer and (right) student responses during IOP9.**

| Questions | IOP9 student responses |
|---|---|
| How frequently is the DOW taking a horizontal scan? | Every 1 min 45 s. |
| Describe the phenomena that the DOW is scanning. Include approximate location (direction and distance) and time information. | Thunderstorms, one located overhead, and one 15 km to the southeast. Both are moving toward the southeast. |
| What are the spatial dimensions (i.e., width) of the phenomena the DOW is scanning? | Approximately 5 km by 5 km. |
| What are the maximum reflectivity values of the phenomena being scanned, and at which elevation angle are reflectivity values the strongest? | 2206 UTC: For the thunderstorm to the southeast, 55 dBZ at the 5° elevation angle. RHI (vertical) scans also show a strong updraft.<br>2248 UTC: For the thunderstorm that is now located 20 km to the south-southeast, 60 dBZ at the 5° elevation angle. |
| What is the magnitude of the radial velocity? Do you see any radial velocity couplets? If so, describe their intensity and location. | 2224 UTC: A weak couplet is evident on the 5° elevation scan for the thunderstorm located 15 km to the south. A +18 kt pixel is located next to a –9 kt pixel. |
| Do you see a microburst or downburst signature? If so, describe their intensity and location. | There are no downburst signatures. |
| How have the phenomena being scanned changed over time? Be as descriptive as possible. | 2206 UTC: 55 dBZ at the 5° elevation angle for the thunderstorm to the southeast.<br>2224 UTC: Radial velocity couplet observed.<br>2229 UTC: Truck repositioned because it was slightly unlevel.<br>2246 UTC: Strong vertical updraft on RHI scan.<br>2248 UTC: 60 dBZ 5° elevation angle for the thunderstorm to the southeast.<br>2308 UTC: Gust front/outflow boundary evident on radial velocity at the 3° elevation angle. |
| How do the DOW scans compare to what you are observing visually? | 2215 UTC: Two shelf clouds are visible outside DOW-6. |

meteorology program and the CSWR and NSF educational deployment programs.

**FIELD EXPERIMENT SETUP.** Each morning of an IOP, the ERAU C-BREESE team would meet to examine surface and upper-air observations, satellite imagery, and numerical weather prediction (NWP) model output before agreeing on a deployment plan for that day. The weather discussions were led by faculty but were generally informal and collaborative, with active student participation. Forecast discussions would start with current observations, followed by an examination of short-range high-resolution convection-allowing NWP models such as the National Centers for Environmental Prediction (NCEP) High-Resolution Rapid Refresh (HRRR; e.g., Weygandt et al. 2009), which is updated hourly out to 18 h and has a 3-km grid spacing. When viewing NWP model output, the ERAU C-BREESE team primarily focused on analyzing mass fields (e.g., mean sea level pressure and 10-m wind) and convective ingredients (i.e., surface convergence, moisture, instability, and vertical wind shear), but not forecast radar reflectivity. Each forecast discussion concluded by examining atmospheric flow patterns for potential future IOPs. An example of the forecast and observation process during IOP9 is detailed in the next section.

The next step of each morning meeting was to choose a scanning location. Although advanced scouting was performed (see first section), the weather for a particular IOP occasionally dictated the need to find locations that had not been scouted. In such cases, the ERAU C-BREESE team scoured Google Maps Terrain and Street Views (Google Maps 2016) to select a viable scanning location. Figure 5 shows the DOW in Pasco County during IOP5, approximately 40 km north of Tampa Bay, where convection was ongoing. Figures 5a and 5b are representative of many of the ERAU C-BREESE scanning locations away from the immediate coast (i.e., relatively open fields with rows of trees in the distance).


**Fig. 6. Shelf clouds during IOP9 on 20 May 2015: (a) Port Orange at 2210 UTC and (b) Edgewater at 2230 UTC.**

As such, radar beam blockage was often an issue at the lowest (0.5°) elevation angle but not above that.

The final step of each forecast discussion was to establish scanning strategies for that day's IOP. Table 3 details the scanning strategy for each IOP; in general, ERAU C-BREESE maintained the five standard scanning elevations recommended by the CSWR technician (Table 3). During IOPs where strong thunderstorms were observed (e.g., IOP9; Table 3), RHI scans were also performed, so as to better capture a three-dimensional view of the observed phenomena.

There were typically two to four ERAU C-BREESE students inside of DOW-6 during each IOP. When there were more students participating in a particular IOP than could fit in DOW-6, students not in DOW-6 traveled in personal vehicles and kept an eye on surface, WSR-88D, and satellite observations, primarily using smartphones. During each IOP, students were required to take comprehensive notes on the meteorological phenomenon that DOW-6 was scanning and how it was being scanned. For these purposes, mandatory student activity worksheets were created, an example of which is shown in Table 4. Worksheets were collected at the end of each IOP and used to assess student performance and added to the IOP logs.

Table 4 also shows student responses for IOP9 (see next section). There were three students inside

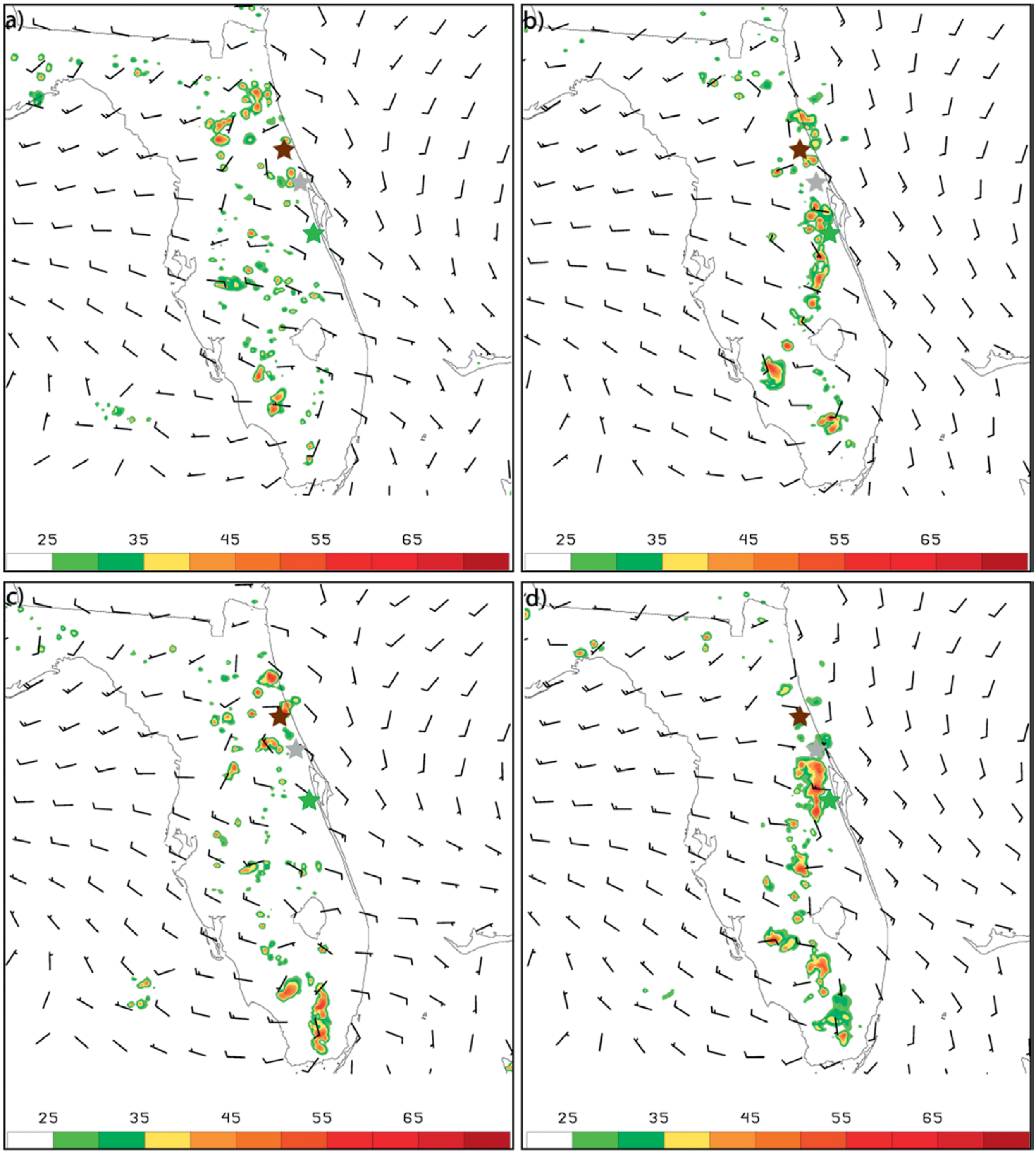


**Fig. 7. NCEP HRRR forecasts initialized at (a),(b) 1200 and (c),(d) 1500 UTC 20 May 2015, verifying at (a),(c) 2100 and (b),(d) 2300 UTC, respectively. Plotted are forecast composite radar reflectivity (dBZ; shaded) and 10-m wind (kt; black barbs). The scanning locations of IOP8, IOP9, and Edgewater are marked with green, brown, and gray stars, respectively.**

DOW-6 and they had to complete one worksheet, ensuring a collaborative approach. Students needed to ensure they comprehensively detailed the time and location of each feature that they were observing on radar, the elevation angle the DOW was scanning at, and the radar reflectivity values (Table 4). During IOP9, there was also a radial velocity couplet, indicative of midlevel rotation (mesocyclone), which the students also described in the worksheet (Table 4). Using the student observations shown in Table 4 as a baseline, the next section details the forecast and observation process during IOP9.

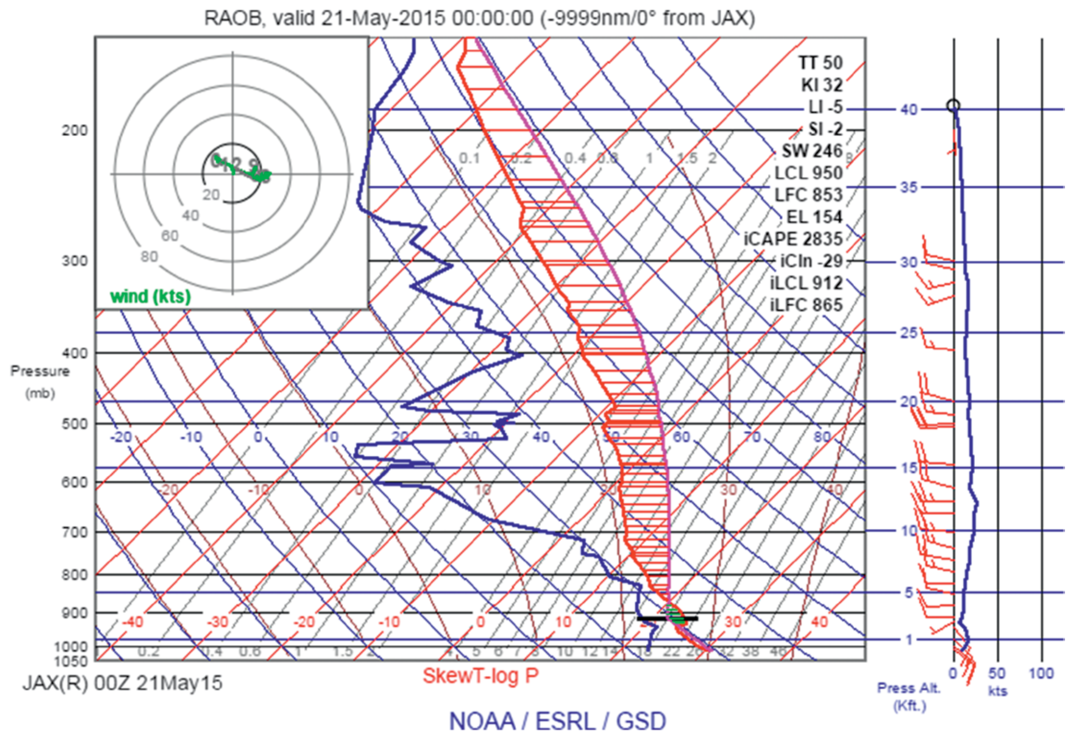


**Fig. 8. The 0000 UTC 21 May 2015 radiosonde sounding (National Oceanic and Atmospheric Administration Earth System Research Laboratory 2016) at KJAX. (left) Temperature (red) and dewpoint (blue) are plotted (°C), along with (right) wind (kt; red barbs). The red hatched area depicts CAPE (J kg$^{-1}$).**

## IOP9: FORECASTS AND OBSERVATIONS.

*Forecasts.*[1] IOP8 and IOP9 both occurred on 20 May 2015. IOP9 was the most successful IOP because it featured the strongest thunderstorms of any IOP, with impressive visual structures. Figures 6a and 6b show photographs of shelf clouds associated with the strong thunderstorms during IOP9 (Table 4), which at times had severe thunderstorm warnings from the NWS.

Figure 7 shows 1200 (top) and 1500 UTC (bottom) HRRR forecasts of composite radar reflectivity and 10-m wind, valid at 2100 (left) and 2300 UTC (right) on 20 May 2015. Both the 1200 and 1500 UTC HRRR runs forecast larger mean sea level pressure values over the Gulf of Mexico than over the Atlantic Ocean (not shown). Larger mean sea level pressure in the Gulf typically indicates westerly background (synoptic scale) surface winds across central Florida (Figs. 7a,c). With westerly background surface winds, Atlantic sea-breeze onset during midafternoon results in sea-breeze convergence and convection closer to the Atlantic coast. The HRRR correctly forecast this surface convergence in east-central Florida by 2100 UTC (Figs. 7a,c), although the meridional location varied with model run. The 1200 UTC HRRR suggested that the strongest convergence would be from Cape Canaveral southward toward Melbourne, Florida, near and south of the green star in Fig. 7a. Forecast radar reflectivity supported this assertion, showing robust thunderstorm development in the Melbourne area by 2300 UTC (Fig. 7b). As such, DOW-6 deployed to Rockledge, Florida (Figs. 3 and 7), 15 km north of Melbourne, for IOP8 around 1500 UTC. Rockledge was chosen largely because of its lack of trees and beam blockage issues.

Starting with the 1500 UTC HRRR run, the forecast location of the convection started to change (Figs. 7c,d). The HRRR then suggested that the strongest convergence and convective initiation would occur farther north, in the Daytona Beach–Edgewater area. HRRR forecast reflectivity supported this assertion, showing thunderstorm formation near Daytona Beach by 2100 UTC (Fig. 7c). One of the tenets of the ERAU C-BREESE forecasting approach was to not overreact to a single model run and in particular to forecast radar reflectivity. However, after four consecutive (1500–1800 UTC) HRRR runs (not shown)

[1] The data visualizations in this section with the exception of the sounding diagram were produced using the Unidata GEMPAK, version 7.2.0, updated from the original version devised by Koch et al. (1983), and the IDV, version 5.2 (Unidata 2016).

that trended northward with the strongest convergence and convective initiation, the ERAU C-BREESE team reconsidered their deployment location. Furthermore, around 1900 UTC, it was visually apparent to the ERAU C-BREESE team that there were no penetrating updrafts (sustained ascent) in the immediate Rockledge area. By 2000 UTC, satellite and WSR-88D data showed that thunderstorms were developing north of Daytona Beach (not shown). As a result, the ERAU C-BREESE team agreed to move from Rockledge back to Daytona Beach near the ERAU campus (IOP9; Fig. 3).

IOP8 was an excellent learning experience for the ERAU C-BREESE students. Although no convection was observed, students experienced in real time the risks and rewards of using NWP models to forecast convection. The 1200 UTC HRRR correctly forecast the general synoptic-scale (i.e., MSLP) pattern and did a reasonable job with the timing of convective initiation but inaccurately predicted the location of the strongest surface convergence and thunderstorm development. Later HRRR runs (i.e., 1500 UTC) were more accurate in terms of the location of the strongest convergence and convective initiation. In an era where reliance on NWP models is commonplace, students learned to question NWP model forecasts as they were produced and rely more on observations (e.g., satellite and surface) and visual cues (e.g., the lack of penetrating updrafts in Rockledge).

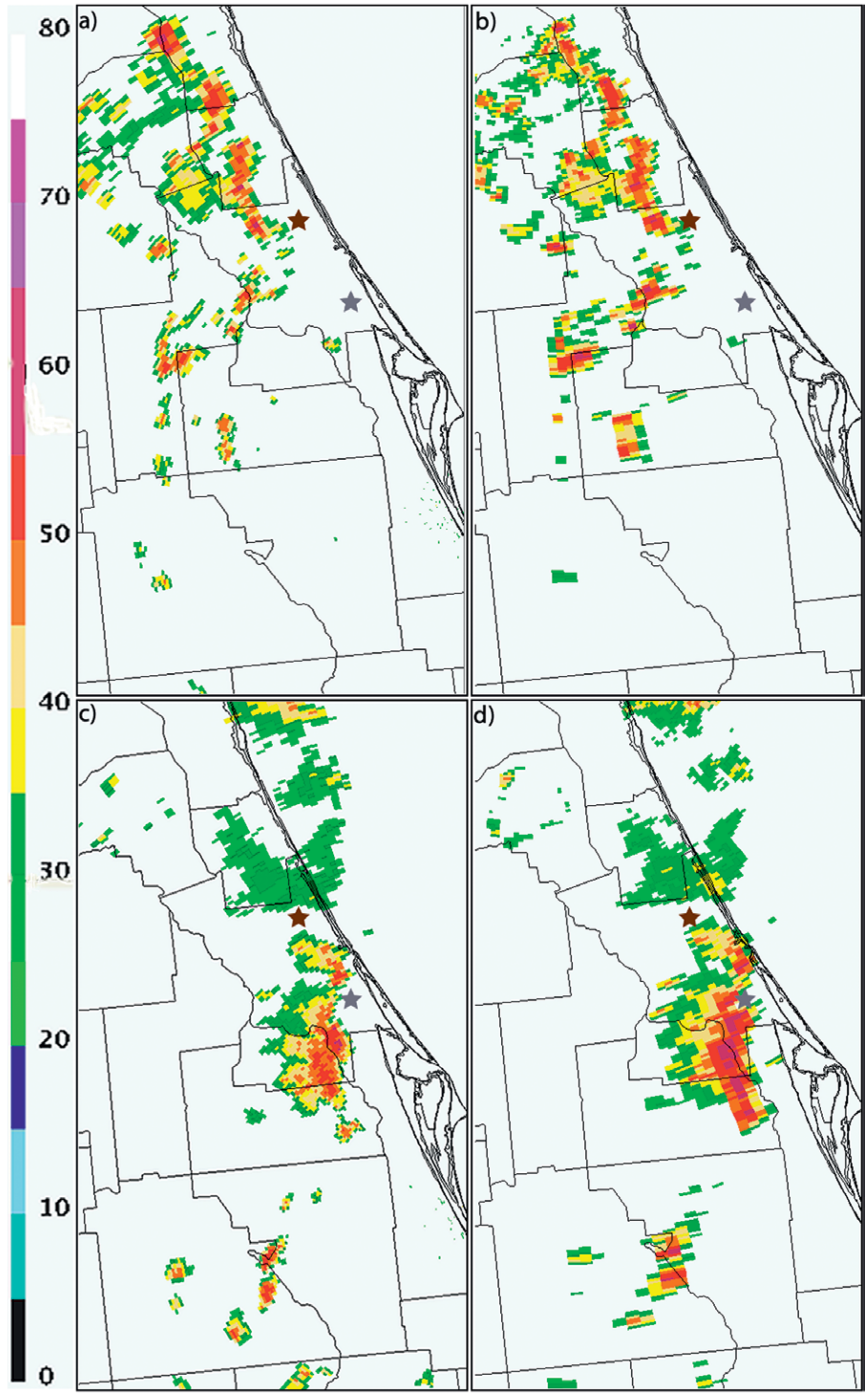

**Fig. 9. (left) NWS MLB and (right) JAX WSR-88D 0.5° base reflectivity (dBZ; shaded) at (a),(b) 2100 and (c),(d) 2230 UTC 20 May 2015, during IOP9. The IOP9 scanning location (Fig. 3; Table 2) and Edgewater are marked with brown and gray stars, respectively.**

*Observations.* Despite the location errors in earlier HRRR forecasts, the environmental conditions during IOP9 were favorable for strong thunderstorms. In addition to the aforementioned surface convergence (ascent mechanism), moisture, instability, and vertical wind shear were also quite favorable. Figure 8

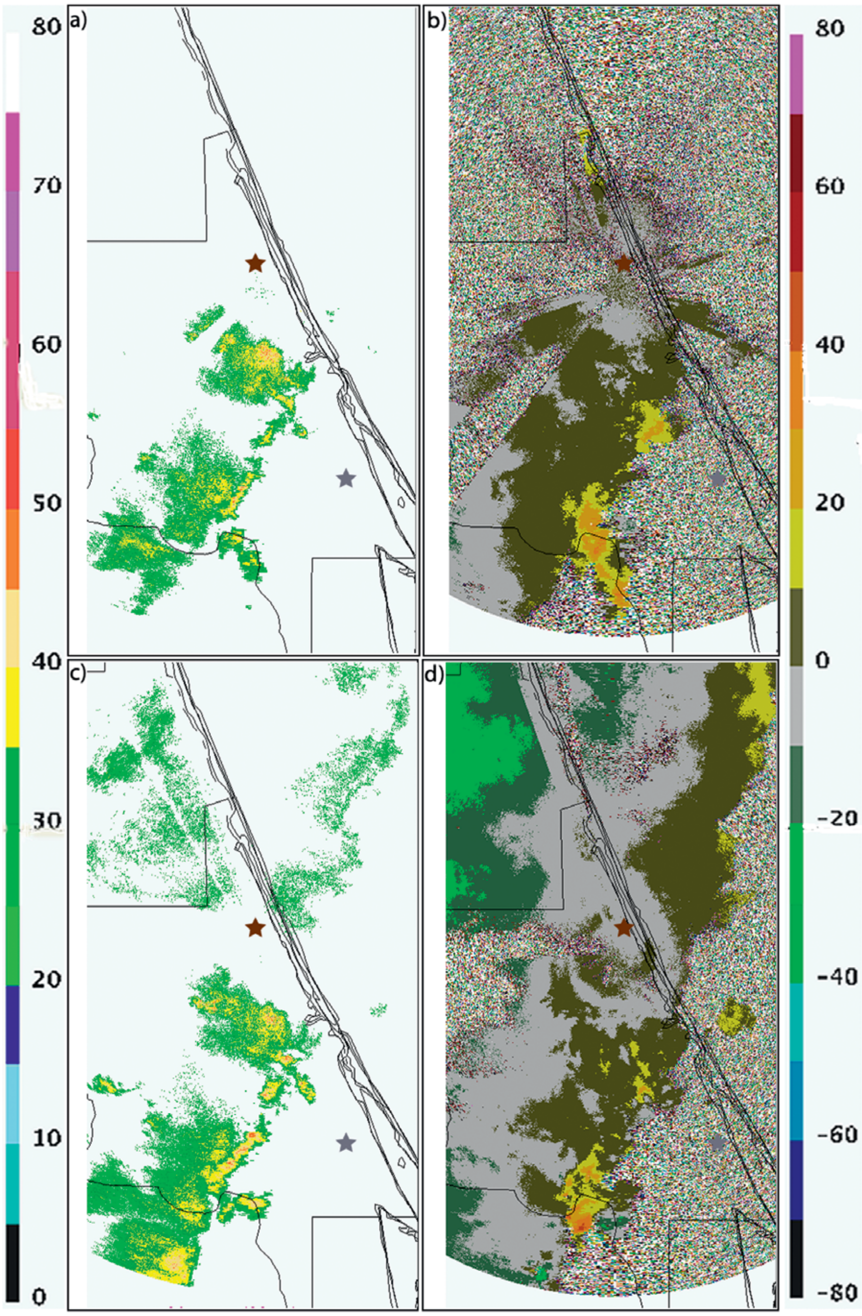


**Fig. 10. (left) DOW-6 base reflectivity (dBZ; shaded) and (right) base radial velocity (kt) at 2230 UTC 20 May 2015, during IOP9, for the (a),(b) 1° and (c),(d) 5° elevation scans. The stippled areas in (b) and (d) are artifacts of the DOW-6 radial velocity scans and should be ignored. As in Fig. 9, the IOP9 scanning location (Fig. 3; Table 2) and Edgewater are marked with brown and gray stars, respectively.**

shows the 0000 UTC 21 May 2015 sounding from Jacksonville (KJAX), representative of the environment in which the IOP9 thunderstorms occurred. Favorable ingredients included 2,835 J kg$^{-1}$ of convective available potential energy (CAPE), a lifted index (LI) of –5, a K index (KI) of 32, and surface dewpoints greater than 20°C. These values of moisture (e.g., surface dewpoints and KI) and instability (CAPE and LI) are more than sufficient for strong ordinary thunderstorms, provided a lifting mechanism (i.e., sea-breeze convergence) is present. However, what made IOP9 unique during the ERAU C-BREESE deployment was the relatively large amount of vertical wind shear present at 0000 UTC 21 May 2015. Figure 8 shows that the 0–6-km bulk wind differential was approximately 25 knots (1 kt = 0.51 m s$^{-1}$), evidenced by 10-kt surface southeasterlies and 20-kt westerlies at 6 km (500 hPa; Fig. 8). Although 25 kt of 0–6-km bulk wind differential, evident of bulk vertical wind shear, is commonplace during the spring severe season in the Great Plains, it is relatively unusual during summer in Florida when the polar jet stream is typically located over the northern United States. These relatively large values likely helped increase the intensity and longevity of the thunderstorms during IOP9.

The relocation to Daytona Beach was complete by 2100 UTC, as an intense line of thunderstorms approached from the northwest (Figs. 9a,b). While DOW-6 was scanning at the IOP9 site (Fig. 9), an ERAU C-BREESE scout team drove 15 and 25 km south to Port Orange and Edgewater, Florida, respectively (Fig. 9), to visually observe the thunderstorms. At 2210 UTC, the shelf cloud in Fig. 6a was observed by the scout team in Port Orange, and by 2230 UTC, the shelf cloud in Fig. 6b was seen in Edgewater.

**Table 5. Sample calculations of slant range (km) and radar beam height (km) using Eq. (1), for the Edgewater thunderstorm (Figs. 6b, 9, and 10) observed during IOP9 at 2230 UTC 20 May 2015. (from left to right) JAX WSR-88D 0.5° elevation angle, MLB WSR-88D 0.5° elevation angle, DOW-6 1° elevation angle, and DOW-6 5° elevation angle.**

| Radar | JAX 0.5° | MLB 0.5° | DOW-6 1° | DOW-6 5° |
|---|---|---|---|---|
| Slant range (km) | 204 | 110 | 30 | 30 |
| Beam height (km) | 4.34 | 1.74 | 0.58 | 2.67 |

Figure 9 compares MLB and JAX WSR-88D 0.5° base reflectivity at 2100 (Figs. 9a,b) and 2230 UTC (Figs. 9c,d). At the start of ERAU C-BREESE, students calculated that Daytona Beach is closer to MLB (87 km) than JAX (185 km), but both radars would likely be of use during the deployment. For IOP9, the base reflectivity values from both WSR-88Ds were similar at 2100 UTC (Figs. 9a,b). At 2230 UTC, however, 0.5° base reflectivity values for the storms near Edgewater were more intense in the JAX WSR-88D (Fig. 9c) than MLB (Fig. 9d). Since the MLB WSR-88D was closer to the thunderstorms, the JAX beam was higher in the cumulonimbus clouds and more intense reflectivity values were possibly due to hail in the upper troposphere.

Figure 10 shows DOW 1° (top) and 5° (bottom) base reflectivity and radial velocity at 2230 UTC, at the time of the Edgewater shelf cloud (Fig. 6b). The reflectivity shows a line of thunderstorms oriented from southwest to northeast. Reflectivity values were more intense in the 5° scan (Fig. 10c), possibly because of minor beam blockage at 1° looking toward the southwest. Figures 10b and 10d depict winds of 30–40 kt just to the west of Edgewater, which correspond to the shelf clouds (i.e., gust fronts) in Fig. 6. The radial velocity images shown in Figs. 10b and 10d served as a useful educational tool in that they allowed ERAU C-BREESE students to make a connection between radar signatures and the thunderstorm structures they observed visually.

In postdeployment data analysis of IOP9, ERAU C-BREESE students calculated the heights of each WSR-88D and various DOW-6 elevation angle beams. To do so, the standard WSR-88D range–height equation (National Weather Service Warning Decision Training Division 2016) was used:

$$h = R\sin(\varphi) + \frac{R^2}{2(\mathrm{IR})(R_e)} \quad , \qquad (1)$$

where $h$ is the height of the beam centerline above radar level (km), $R$ is the slant range observed on radar (km), $\varphi$ is the radar elevation (°), IR is the refractive index (1.21), and $R_e$ is the radius of Earth (6,371 km). As an example, the calculations for the Edgewater thunderstorm (Figs. 6b, 9, and 10) are presented in Table 5. (Calculations are consistent with the range-versus-height nomogram found online at www.meted.ucar.edu/radar/basic_wxradar/media/graphics/rangevsheight.jpg.)

Students confirmed that the JAX 0.5° beam was higher in the cloud than the MLB 0.5° beam (Table 5), which likely explained the larger reflectivity values (Fig. 9). Similarly, the DOW-6 5° beam was obviously higher in the cloud than the 1° beam (Table 5), resulting in comparatively larger reflectivity values (Fig. 10). This exercise, although basic, was an insightful radar lesson for ERAU C-BREESE students and increased their understanding of how high each radar beam is in a typical thunderstorm in the Daytona Beach area.

## SUMMARY AND LESSONS LEARNED.

Following the departure of DOW-6, ERAU C-BREESE transitioned into a data analysis and research phase for the final 3 weeks of the summer course. Students worked in pairs on the research project of their choice and presented the results to the class on the last day. The only requirements were that the project had to involve DOW data and at least one IOP. Overall, the postdeployment research projects allowed the students to gain insight into the meteorological processes and conditions necessary for sea-breeze convection in central Florida. They also learned data analysis skills and various visualization software packages [e.g., the Unidata general meteorological package (GEMPAK) and the integrated data viewer (IDV)], which will serve them well in future endeavors.

The consensus of all participants was that ERAU C-BREESE was a tremendous success that benefited ERAU and the broader central Florida community. Scientifically, a DOW was for the first time used to closely examine sea-breeze processes and convection in central Florida. In addition, more than 1,000 K–12 students and community members toured DOW-6 and learned about Doppler radar technology and meteorological field research. Most importantly, the students involved in ERAU C-BREESE enjoyed a once-in-an-undergraduate-career opportunity to actively participate in a real-time field campaign. The forecast, observation, data analysis, and scientific outreach skills that they gained through these experiences was invaluable for their futures as scientists.

During ERAU C-BREESE, lessons learned included the following:

- Students work most productively and collaboratively when everyone has a task. Although "storm chasing" involves more waiting than most people realize, as long as students are given observational tasks and feel involved in the decision-making process, they remain engaged throughout.
- The student activity worksheets (Table 4) were an enormous help to both students and faculty. They provided students with general guidelines and features to look for while the DOW was scanning. In addition, they allowed ERAU C-BREESE and CSWR to keep detailed deployment logs, which were very useful for data analysis later in the course.
- Experiential (service) learning results in considerably more engaged and motivated students (e.g., Eyler and Giles 1999; Eyler 2002). Although field campaigns are relatively sparse and expensive, such experiences can result in a large positive change in how an individual student feels about studying and a career in atmospheric science.
- Forecasting sea-breeze-related ordinary thunderstorms in central Florida is challenging. Although convection-allowing NWP models have improved, they still struggle with small-scale features, particularly the exact timing and location of convective initiation. Understanding environmental factors and convective ingredients is crucial to making accurate forecasts.
- Observing thunderstorms with a DOW is quite different from traditional "storm chasing." Not only does one need to find the closest location to the observed phenomena, but that location needs to have unobstructed views. This can be a challenge in a place like central Florida, which is dominated by large trees. As a result, additional planning time and flexibility were required.

On the whole, feedback from ERAU C-BREESE course students was extremely positive. Some anonymous samples of postdeployment student comments include the following:

> "Thanks for making the effort to make this course happen. Regardless of the grade, I really did learn a lot and it was cool to get hands on experience out in the field."

> "The best part was the fact that we went out in the field to learn instead of sitting in a classroom."

> "Being able to use the DOW really helped me to understand the meteorological material."

Finally, ERAU meteorology has established a regularly offered independent study course in which upper-level undergraduate meteorology majors can freely design a research project involving DOW data and work closely with a faculty member to see the project to fruition. The success of ERAU C-BREESE also helped lead to the development of an annual experiential learning storm chasing course in the Great Plains that was launched in 2016 and continued in 2017. The popularity and success of both courses have reinforced the notion that experiential learning courses should be a mainstay of any undergraduate meteorology curriculum.

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