Analysis of Sea Breeze Types using WRF and Lagrangian methods: Update using RU-WRF configuration

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1. INTRODUCTION

Our 2018 study of two pure sea breeze cases that occurred in New Jersey (NJ) in 2012 and 2013 enabled deeper understanding of the nearly daily summer sea breeze phenomenon that is so important for offshore wind energy in NJ. We learned that large scale atmospheric flow affected sea breeze onshore extent more than offshore extent, which confirmed our hypothesis for the pure sea breeze (Seroka et al. 2018). We also learned that coastal upwelling did not affect sea breeze extent, but did produce an earlier, sharper, and stronger sea breeze. The study was a “proof of concept” to show that the new Lagrangian method called relative dispersion (RD) worked very well for clarifying the sea breeze circulation both onshore and offshore.

We then wanted to extend the method from just the pure sea breeze to the three other sea breeze types: corkscrew, backdoor, and synoptic. We used the same exact setup as Seroka et al. (2018) for the modeling (Weather Research and Forecasting, WRF) and Lagrangian methods (initial particle seeding, trajectories, and RD calculation), except we updated to the most recent WRF version available, WRF v 4.0 (Seroka et al. 2019).

We found that strong divergence emanated from the New York Harbor/Raritan Bay and Delaware Bay offshore across all sea breeze types that were studied, regardless of atmospheric flow out of or into the bays. We also found that for the pure, backdoor, and corkscrew sea breeze cases, general divergence at 100 m hub height over the NJ Wind Energy Area (WEA) was slowly replaced by a mix of convergence and divergence, which is consistent with sea breeze theory. For the synoptic-enhanced sea breeze case, a convergence zone possibly propagated offshore with time, which indicated a sort of frontal convergence that propagates offshore in that sea breeze type (Seroka et al. 2019). This would be consistent with our hypothesis that a convergent zone could propagate offshore from the coastline in the synoptic-enhanced sea breeze, much like the convergent frontal zone propagates onshore from the coastline in the pure (and corkscrew, backdoor) sea breeze.

The National Renewable Energy Laboratory (NREL) recently completed assessment of the Rutgers University-WRF (RU-WRF) model, which is used for characterizing the NJ offshore wind resource. In their report, the authors provided several recommendations to improve RU-WRF (Optis et al. 2020). These recommendations were used to update RU-WRF, and in turn we updated our modeling here. We now very closely match RU-WRF’s configuration, with only a few exceptions outlined below in the Methods.

We have re-run the simulations of the four sea breeze cases using the new RU-WRF setup, and have completed the 2-dimensional (2D) trajectories and RD calculations. We provide clear comparisons between the old WRF setup and the new. Finally, 3-dimensional (3D) trajectories and RD calculations of the same four cases have commenced, for which we will provide some preliminary results.

2. METHODS

The same four sea breeze cases that were analyzed in our previous study were used here:

- Pure sea breeze: April 5, 2017
- Backdoor: April 14, 2017
- Corkscrew: June 22, 2017 (with coastal upwelling)
- Synoptic: August 4, 2017

The most recent WRF version available, WRF v 4.1.2, was used and configured to match as closely as possible to the new real-time RU-WRF model (https://rucool.marine.rutgers.edu/data/meteorological-modeling/ruwrf-mesoscale-meteorological-model-forecast/). This consisted of the same RU-WRF 9-km resolution parent nest, and 3-km and 1-km resolution inner nests. Other pertinent updates to the WRF setup include:

1) Increased number of vertical levels (from 35 to 48 levels),
2) Increased vertical resolution, especially near the surface around 100-m hub height, and
3) Mellor–Yamada Nakanishi Niino (MYNN) Level 2.5 planetary boundary layer (PBL) physics option, which has been shown to be best for offshore conditions (Munoz-Esparza and Canadillas 2012), instead of the Yonsei University Scheme (YSU). This was also used to take advantage of the WRF 4.0 improvements in the MYNN scheme.

The only differences between RU-WRF and this study's WRF setup are as follows. Here, we used:

1) A reanalysis product (North American Regional Reanalysis, NARR) for initial and lateral boundary conditions, which NREL suggested to use for hindcasts like here. These have been found to be more accurate than a predictive product like the Global Forecast System (GFS) that RU-WRF uses;
2) Real-Time Global High Resolution (RTG HR) for sea surface temperature (SST), as it was readily available and provided a smooth and consistent SST product for WRF simulation. NREL had suggested to use RTG HR SST as backup to the coldest pixel composite of Advanced Very-High-Resolution Radiometer (AVHRR) scans, instead of the NASA Short-term Prediction Research and Transition Center (SPoRT) SST product as backup. The SST product that RU-WRF uses is still under development, and adding the limited clear-sky AVHRR granules for the cases analyzed here would not have significantly affected the results;
3) An inner-most 1-km resolution nest, which is available in RU-WRF but not always used; and
4) 10-minute output from WRF, rather than RU-WRF's hourly output, to enable the hour-long trajectory simulations (time step of 10 minutes) and Lagrangian analyses.

We used the same 2D Lagrangian methods as Seroka et al. (2018), with a slightly smaller particle seeding 10-km resolution grid within the WRF 3-km nest. Comparisons between the old WRF/2D Lagrangian analysis setup and new setup were performed, as will be shown below. Finally, 3D particle trajectories and Lagrangian analyses were begun, using as close to the same setup as for the 2D trajectories (particle seeding domain, resolution, and vertical levels). Some preliminary results showing several 3D particle trajectories will be presented in a final figure.

3. RESULTS

Figure 1 shows the results from the pure sea breeze case on April 5, 2017. As before, there is good agreement between what the KDIX weather radar imagery depicts as the location of the sea breeze front, and what the relative dispersion (RD) depicts as the location of that front. The front in the weather radar imagery (left) is shown as a linear collection of higher returns nearly parallel to the coast and just inland at 1700 UTC (top left), propagating to past Philadelphia at 2300 UTC (bottom left). In the RD plots (middle and right panels), the blue shading indicates convergence in the Lagrangian wind field, corresponding to the location of the inland NJ sea breeze front. Red shading indicates divergence in the Lagrangian wind field.

Focusing on the middle (old WRF setup) and right (new WRF setup) panels, we see very similar results between old and new WRF setup. This is good, as it shows that there has been consistency between our research-mode WRF and real-time RU-WRF over the past few years. The main difference at 1700 UTC are a switch from divergence (top middle) to convergence (top right) in the northern section of the NJ WEA. Also, stronger divergence (red) occurs offshore of the NJ WEA in the new WRF setup (top right). At 2000 UTC, weaker onshore blue convergence occurs in the new WRF setup (middle right), but with stronger winds from the southwest (middle right) than the southeast (middle center). At 2300 UTC, the main difference is blue convergence across the entire NJ WEA in the new WRF setup (bottom right) versus convergence in the southern WEA and divergence in the northern WEA in the old WRF setup (bottom middle).

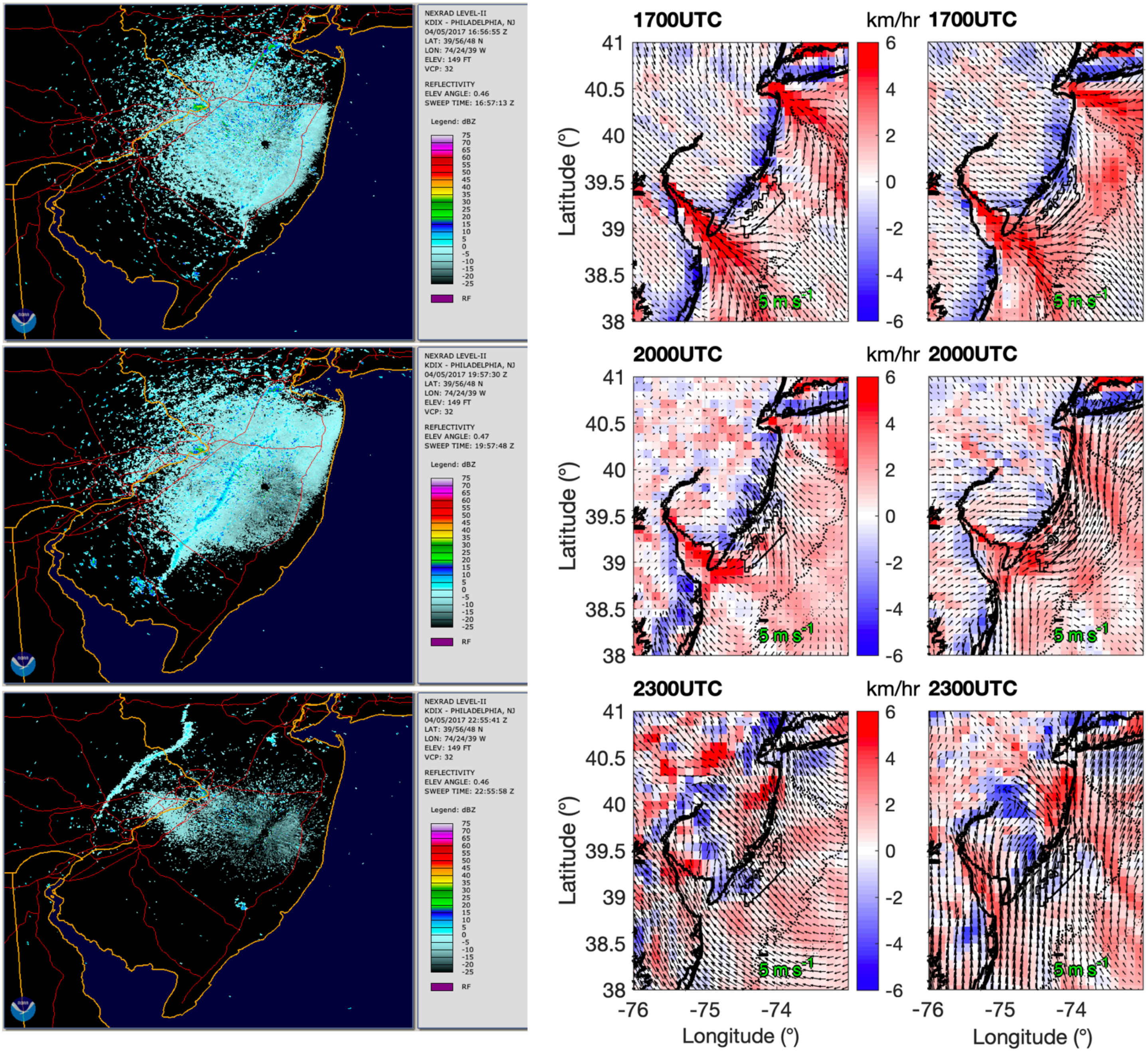

Figure 1: Pure sea breeze case on April 5, 2017. Left panel is KDIX weather radar imagery base elevation clear air mode at 1700, 2000, and 2300 UTC, and middle (old WRF setup) and right (new WRF setup) panels are shaded RD-10 km (km/hr) at 100 m from WRF/2-D trajectory/RD calculations at the same three times. Red shading indicates divergence and blue shading indicates convergence in the Lagrangian wind field. In middle and right panels, NJ WEA marked in black boxed contour, 50-m isobath in thick dotted black contour, 200-m isobath in thin dotted black contour, and green 5 m/s legend scale vector for black WRF 100-m wind vectors averaged across the hour beginning at time indicated on panel.

Figure 2 shows the results for the backdoor sea breeze on April 14, 2017. Overall, there is very good agreement with the observed KDIX weather radar location of the sea breeze front (left) and the old and new WRF simulated sea breeze front (inland blue in middle and right panels).

The main difference between the old and new WRF setup at 1700 UTC is again weaker blue convergence just inland of the NJ coastline, and weaker red divergence across the NJ WEA. At 2000 UTC, weaker blue convergence once again occurs in the new WRF setup (middle right), and uniform red divergence over the NJ WEA (middle right) versus a mix of convergence and divergence in the old WRF setup (middle center). Finally, at 2300 UTC, the main differences are the blue convergent areas offshore of the NY Harbor and Atlantic City in the old WRF setup (bottom middle), which are purely divergent areas in the new WRF setup (bottom right).

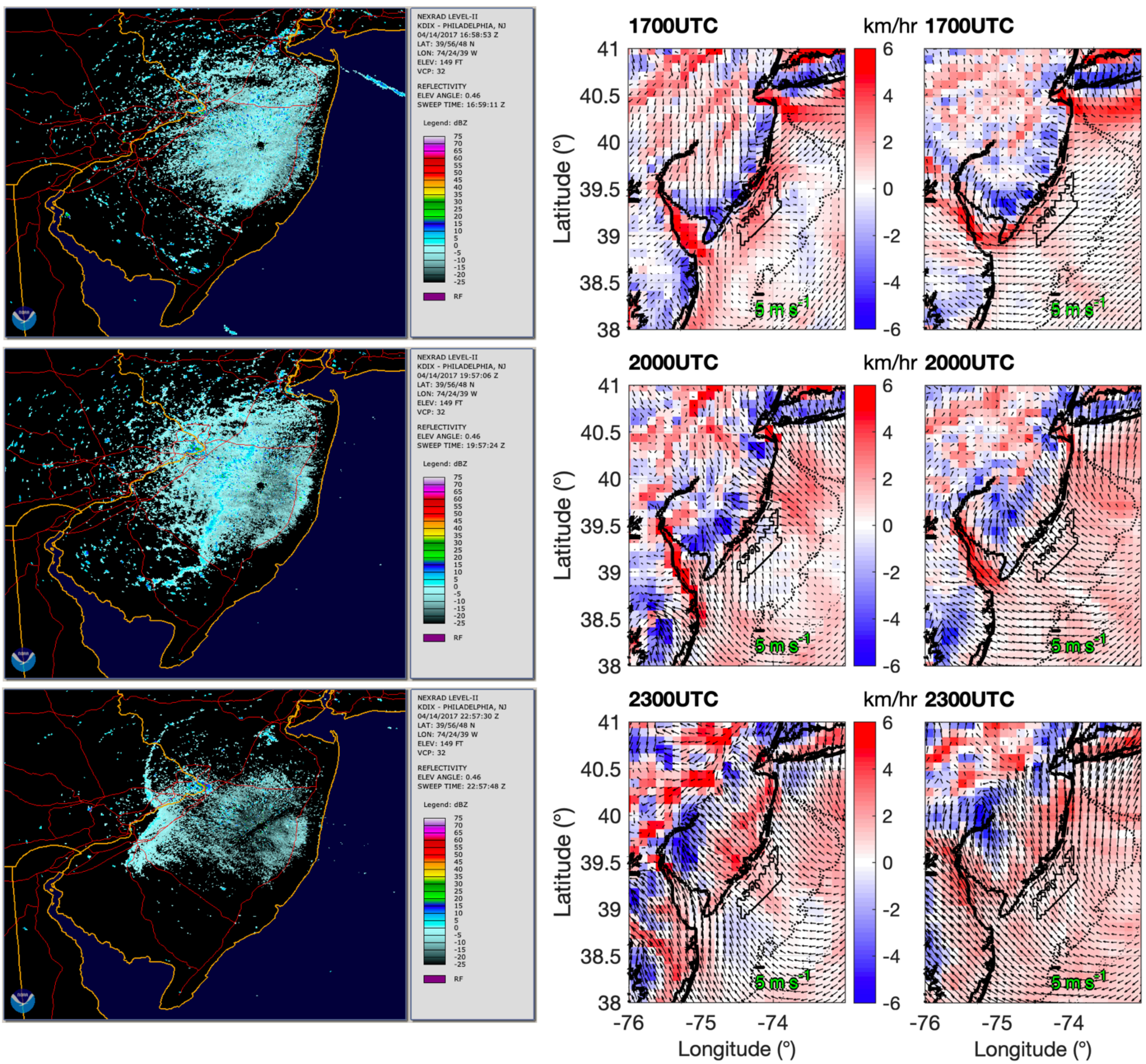

Figure 2: Same as Figure 1, but for backdoor sea breeze case on April 14, 2017.

In Figure 3, the corkscrew sea breeze case from June 22, 2017 is displayed. At 1700 UTC, the old WRF setup shows a clear sea breeze front in the blue shading well inland of NJ (top middle), whereas the new WRF setup shows the front along the NJ coastline (top right). A similar pattern occurs for the sea breeze front along the Delaware and Maryland coastlines. At 2000 UTC, much stronger winds from the southwest are occurring in the new WRF setup, with weaker blue convergence inland of NJ near Philadelphia and some blue convergence in the northern NJ WEA (middle right). At 2300 UTC, stronger red divergence appears across the entire NJ WEA in the new WRF setup (bottom right), with winds more from the southwest (new WRF setup, bottom right) rather than the south-southwest (old WRF setup, bottom middle).

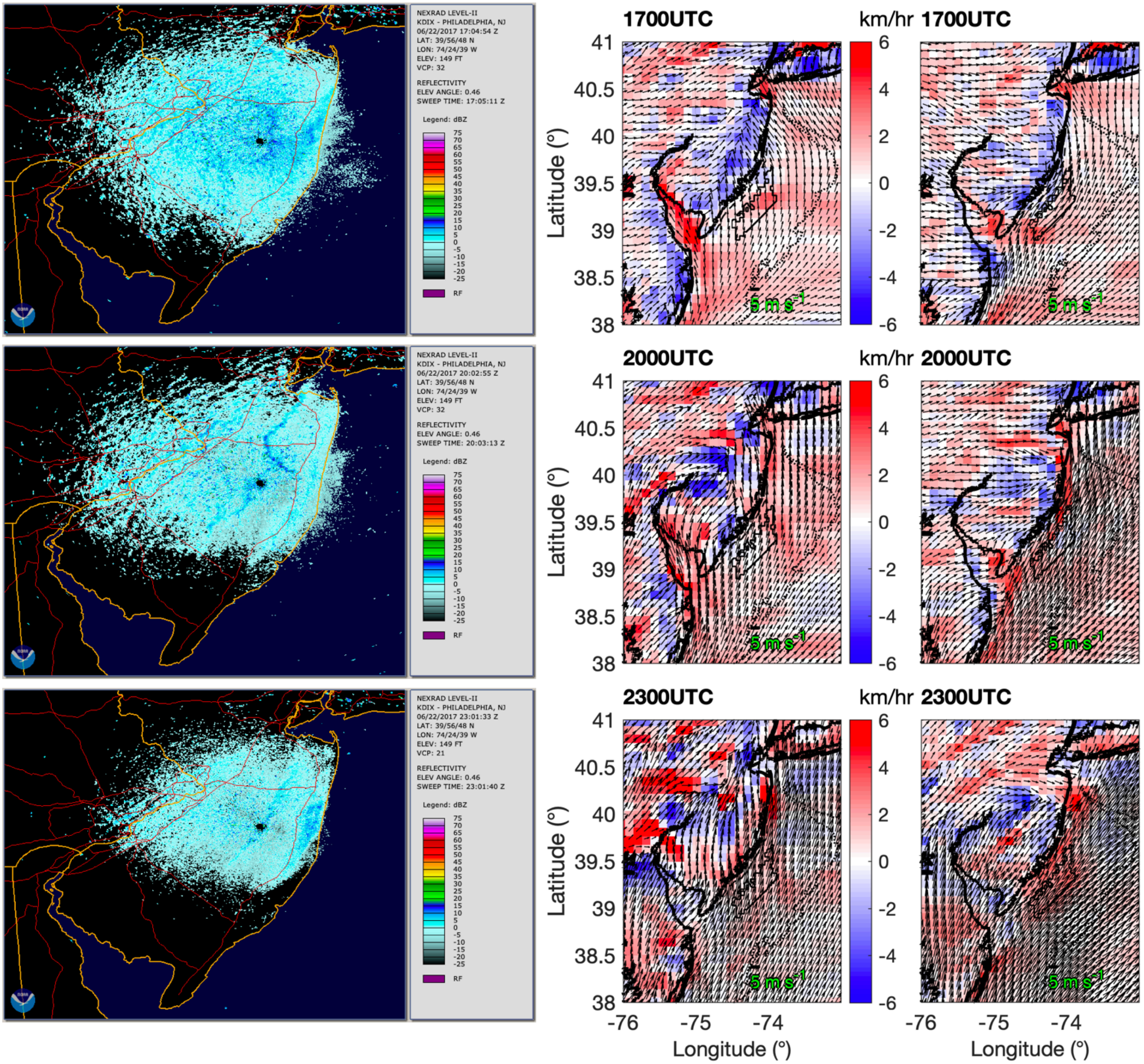

Figure 3: Same as Figure 1, but for corkscrew sea breeze case on June 22, 2017.

Finally, Figure 4 shows the case for the synoptic sea breeze on August 4, 2017. Interestingly, the new WRF setup shows a line of blue convergence just inland of the NJ coastline (top right), which is not apparent in the old WRF setup (top middle). With that, stronger red divergence occurs over the NJ WEA in the new WRF setup (top right). At 2000 UTC, the inland convergent line is no longer there in the new WRF, but there is an offshore convergent line extending from the Delmarva Peninsula eastward and offshore, just north of a red divergent line (middle right). At 2300 UTC, few differences are apparent, with somewhat weak and noisy convergence and divergence offshore, with perhaps a convergence zone offshore of SE NJ extending to the southeast in the new WRF (bottom right). More investigation is required to determine whether a coherent convergence zone actually propagated offshore with time during this synoptic-enhanced sea breeze case, which would be consistent with one of our hypotheses of how this type of sea breeze evolves offshore.

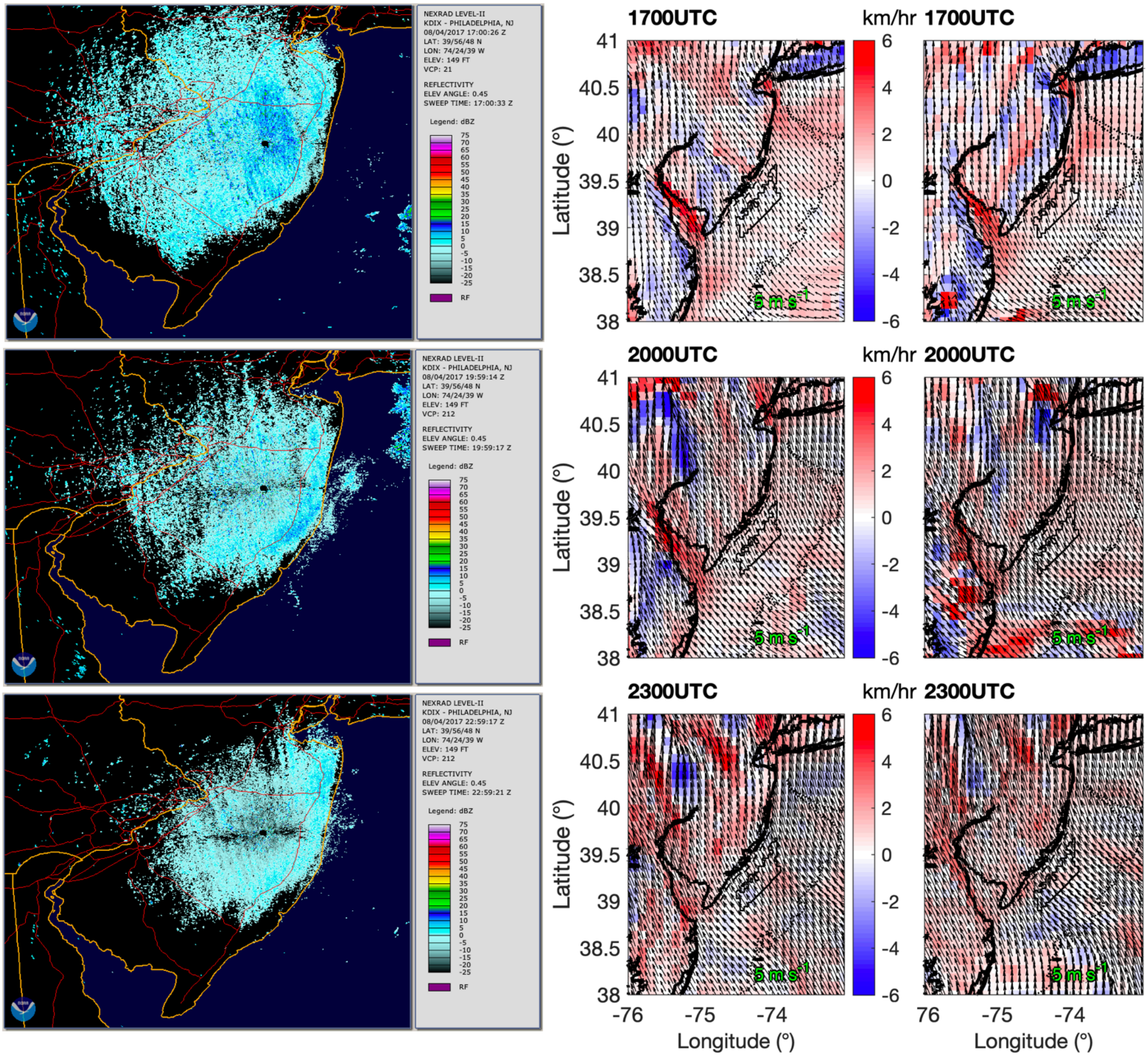

Figure 4: Same as Figure 1, but for synoptic sea breeze case on August 4, 2017.

Figures 1-4 show the results from the 2D particle trajectories and Lagrangian analyses. Figure 5 shows some preliminary results when the particles are allowed to move in three dimensions. Eight tracer trajectories across 30+ hours of simulation are shown. Note the differing horizontal and vertical axes on each panel. Large vertical motion can be seen in several of the trajectories, e.g. number 3 (~1400 m), number 4 (~600 m), number 7 (~800 m), and number 8 (~500 m). This large vertical motion of upwards of 1 km indicates that perhaps our assumption that the flow during our four sea breeze cases is mainly horizontal and not vertical is not fully valid. It was previously found that vertical velocities were *O*(100) times smaller than horizontal velocities during sea breeze cases analyzed by Seroka et al. (2018). The complete 3D trajectory and Lagrangian analyses of all four sea breeze cases will enable us to fully determine the validity of that assumption, and whether Lagrangian study of the sea breeze would indeed require three dimensions.

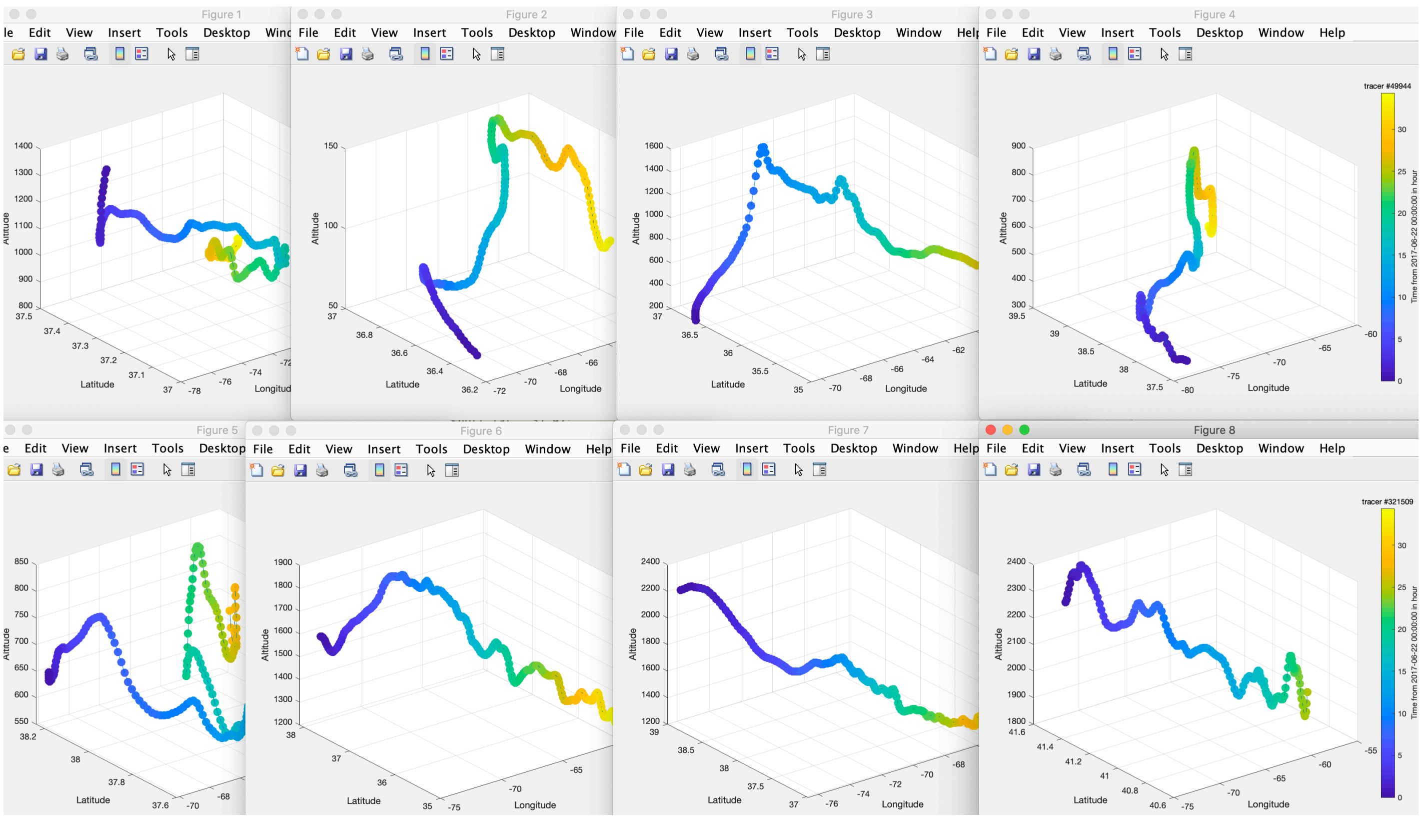

Figure 5: 3D Trajectories of 8 tracers from the preliminary 3D particle trajectory analysis. Note the different x-, y-, and z-axis in all panels.

4. CONCLUSIONS AND ONGOING/FUTURE WORK

Large differences between the old and new WRF setups were not found, which is a good result indicating that there has been consistency between our research-mode WRF simulations and the real-time RU-WRF model. One difference was the location of the corkscrew sea breeze front along the NJ coastline in the new WRF setup, versus a sea breeze front that propagated well inland in the old WRF setup, which is not validated by the weather radar observations. Another difference occurred in the synoptic sea breeze where a clear inland convergent line (front?) propagated somewhat inland of NJ in the new WRF setup (not apparent in the old WRF setup), and a clear convergent-divergent line couplet extending offshore from the Delmarva Peninsula in the new WRF setup. It remains to be seen whether that is within the noise of the Lagrangian analysis, or whether it is actually a signal of a sort of offshore frontal propagation during the synoptic-enhanced sea breeze, which was a hypothesis that we have had for years but have never been able to test until now.

Ongoing and future work includes completing the 3D trajectories and Lagrangian analysis using as similar a setup as possible to the 2D work, to complete the comparison between two and three dimensions. This will possibly include additional sea breeze cases of all sea breeze types (pure, corkscrew, backdoor, synoptic). We will also work to integrate the trajectories and Lagrangian RD analyses into the real-time RU-WRF system—the study here is a good start on that since we implemented a version of WRF that is similar to RU-WRF. The real-time RU-WRF/Lagrangian analysis system will enable a more useful predictive procedure for the offshore component of the sea breeze circulation. Finally, we will test WRF's wind turbine parameterization to examine potential sea breeze impacts on power production. This will enable us to simulate the effect of wind turbines on the boundary layer wind resource. We will potentially perform trajectory and Lagrangian analyses on these results—comparing scenarios with and without turbines to determine wake effects, power losses, etc.

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