Delaware Sea Grant Data Activity

Understanding downwind effects

Grade Level: High School

Lesson Time: 60 minutes

Required Materials:
- This packet only

STEM Connections
Science – Wind energy
Technology – LIDAR instrument and wind speed sensors
Engineering – Wind turbine placement; construction; materials
Math – Calculating distance and wind direction from unique sources

Next Generation Science Standards
HS-ESS3-4
HS-PS3-3

Energy Literacy Principles
1.1; 1.3; 1.4; 1.8; 2.3; 4.1; 4.4; 4.5; 4.7; 5.3; 5.4; 5.6

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Summary

Since the first wind-powered generator was invented in 1888, humans have been creating and installing more efficient wind turbines all over the world. Wind farms are composed of many wind turbines, connected together and oriented so they maximize their electricity output. Wind farms can be placed on mountains, in fields, even in the ocean. But just like we hide behind walls, trees, or people to block wind on a chilly day, do "blocked" downwind wind turbines receive less wind than the turbines in front them? Explore real data to answer this question.

Activity Use

This activity can be used as part of a:
- Meteorology unit
- Renewable energy unit
- Climate change/Human impact unit

Objectives

After completing this activity, students will be able to:
- Describe wind wakes and their effect on downwind wind turbines
- Interpret wind rose figures
- Measure distance and wind direction using data visualizations

Vocabulary

downwind, downstream, downwind, wake, wind rose, wind turbine

Invitation

Imagine yourself somewhere outside—a wide-open sports field watching friends compete or maybe downtown watching a holiday parade—it's cold and windy! Sure, you could abandon ship and head inside or get in the car, but you need to stay outside and support your community. Despite layering your warmest clothes, that wind is still bone-chilling. You decide to take action to block the wind and get behind something—anything—you can find. Suddenly, you see a good friend at the event, she's super tall and wearing her big poofy winter coat. Perfect! You go over to say "hi" and stand downwind of her. While the feeling slowly returns to your face and hands and you start actually enjoy the event you are watching, you start to think about why standing here next to your tall friend is helping. You see the wind is still blowing all around you, but you don't feel it as much. Coincidentally, you just finished learning about wind farms in school, and wonder, "huh, how is a downwind wind turbine impacted by an upwind turbine?"

Essential Question

How is the atmosphere and a downwind wind turbine(s) impacted by an upwind wind turbine?

Introduction

Wind energy

Using the wind to help humans is not a new technology. People have been using wind-powered sailboats since roughly 5,000 BC. In 200 BC China, wind-powered pumps were used to move water, and wind mills used to grind grain date back to 500-900 AD Persia. We then see bigger, more efficient wind-harnessing systems pop up all over the world, including China, the iconic Dutch windmills, and American farmland windmills, in the coming centuries to do similar tasks— grind grain and pump water.

Fast-forward to Cleveland, Ohio in 1888 when Charles F. Brush built what we believe to be the first electricity generating wind turbine (as opposed to a wind mill, which does not produce electricity), producing 12 kilowatts of electricity. This was followed in 1891 by Poul la Cour, a Danish scientists, inventor, and educator, who developed the first wind turbine with the ability to store power. Smaller, farm-scale wind turbines continue to grow in popularity until the 1930s when electricity was finally distributed out to rural areas via power lines. Oil shortages in the 1970s caused the reinvigoration of wind power, particularly in California, with larger-scale wind farms coming online in the 1990s and early 2000s.

Wind turbines and wind farms

In 2010, the University of Delaware installed a 2-megawatt wind turbine on its Lewes, Delaware campus (https://publicutility.ceoe.udel.edu/lewesturbine/). Not only has this wind turbine powered the small coastal campus and 100 homes in the city of Lewes, but it has also served as a research platform for numerous wind energy related research projects. Projects have included bird and bat interactions, metal corrosion, wind turbine tower vibration, component performance, and down-wind effects. This wind turbine has also served as the central figure in social science research on the public perceptions of wind energy, and visual and auditory impacts of wind turbines.

The average life of a wind turbine is approximately 25-years. Some wind turbines, depending on the materials that were used and the location, may last less than that, but most should last longer. A wind turbine built high on a mountain top is not subjected to the brutal saltwater and salt-air that an offshore wind turbine must endure. Therefore, through research such as the corrosion study on the Lewes turbine, better materials are being used now than 10- or 20-years ago.

Unlike the singular wind turbine at the University of Delaware, most wind turbines are built in systems called wind farms. Whether it is located on a mountain, in a field, or in the ocean, wind farms utilize an economy of scale, where it is actually less expensive to build many of something at once versus fewer. The turbines are connected together and the power is delivered via one main line to a sub-station which is connected to the electrical grid.

In the United States, areas conducive to wind farms are leased to companies who build the farm. In order to maximize their investment, these companies place as many wind turbines as possible on the lease area. Extensive studies are carried out to not only determine the environmental impacts of the wind farm, but also the optimal arrangement of the turbines to maximize energy output, and get the best return on their investment. As wind turbine technology changes and we see larger wind turbines, fewer turbines fit in the lease area. However, these larger machines are more efficient at capturing wind and generating more electricity, so fewer wind turbines are needed to produce the same amount of electricity as more, smaller, less-efficient wind turbines.

Downstream atmospheric impacts

As mentioned above, when siting a wind farm, companies maximize the lease area by installing as many wind turbines as possible, allowing proper spacing between wind turbines, in case of an accident. Extensive research goes into the optimal arrangement of wind turbines, including evaluating annual wind patterns in order to maximize electricity generation. Looking at annual wind patterns, you can determine if a line, cross, grid, arcs, or a fan, is the optimal arrangement (Fig. 1).

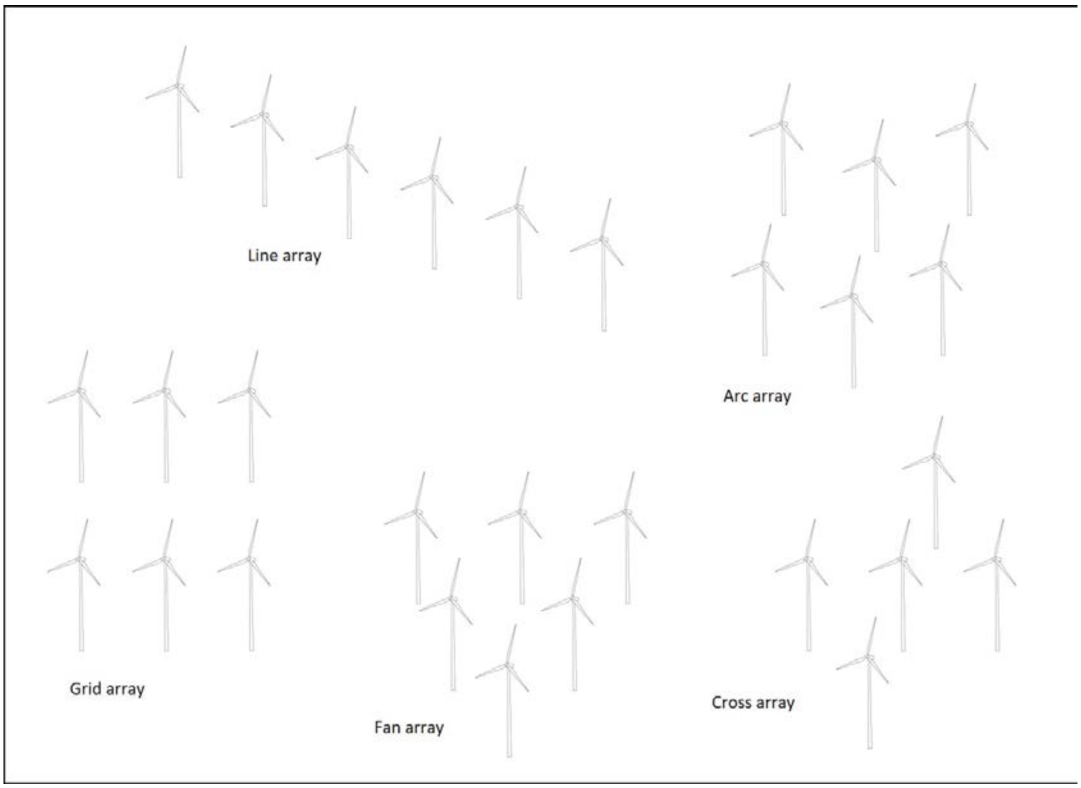


Figure 1. Five types of wind farm orientation.

In an effort to better understand the downwind effects of wind turbines on the atmosphere—including wind speed and direction—University of Delaware scientist, Dr. Cristina Archer, and colleagues deployed a series of sensors downwind of the Lewes turbine, in the turbine's wake. Once they collected and analyzed the data, they published the peer-reviewed research paper, "The VERTEX field campaign: observations of near-ground effects of wind turbine wakes" in 2019, in the Journal of Turbulence, Volume 20, Issue 1: Special Issue on Wind Energy (https://www.tandfonline.com/toc/tjot20/current).

In the Data Analysis section below, students will analyze some of the data from research projects focused on downwind impacts, and develop their own conclusions.

Data Analysis

Using the information from the Introduction and the data provided below, answer the following questions.

Part 1. Observation of downwind effects. Below are three images of the *Horns Rev 1*, 160-megawatt offshore windfarm, located in the North Sea, off the coast of Denmark. Figure 1a shows the windfarm in clear conditions. In Figures 1b and 1c, you see the windfarm under a unique meteorological condition on February 12, 2008, where the wind turbines created clouds downwind.

a)

b)

c)

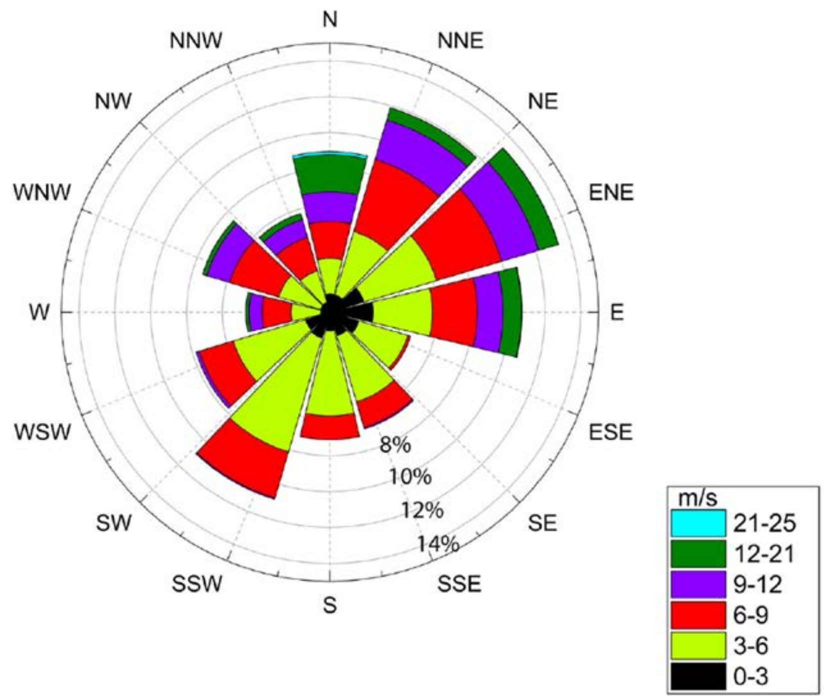
1. Based on Figure 1a, please describe the wind farm.

2. Looking at Figure 1b, please describe what you see. List questions you have after looking at the photograph.

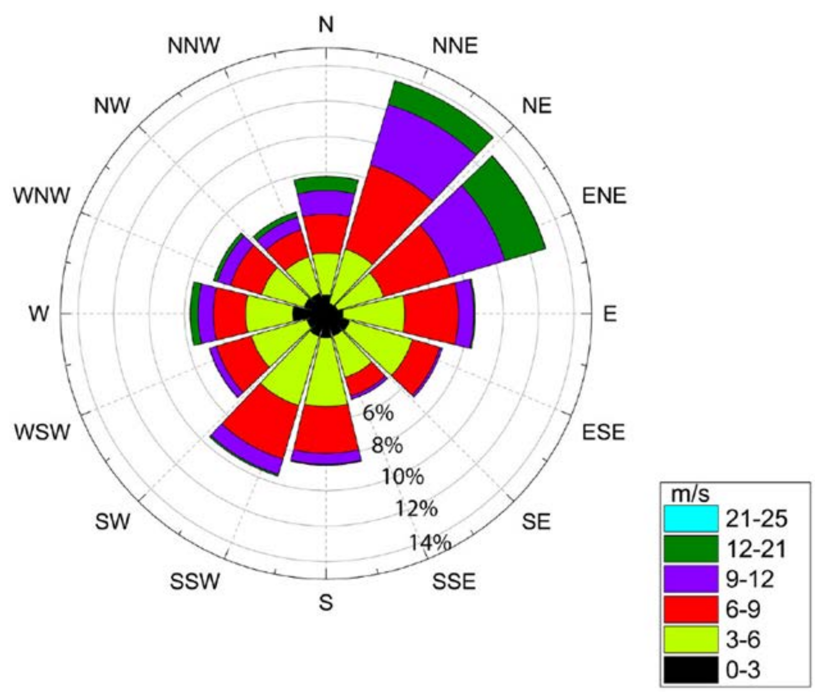
3. Looking at Figure 1c, do you notice anything different in this photograph?

Part 2. Analysis of wind rose diagrams. Below are two "wind rose" graphs that display wind direction, wind speed, and frequency. The roses are based on data collected at 49-meters high on a specially designed meteorological data tower. The displayed data were collected from August 26-November 1, (a) during the VERTEX experiment in 2016, and (b) during a two-year period (2008-2010) prior to the UD-Lewes wind turbine's installation. Figure is from C.L. Archer, et al., 2019.

a) VERTEX



b) 2008-2020



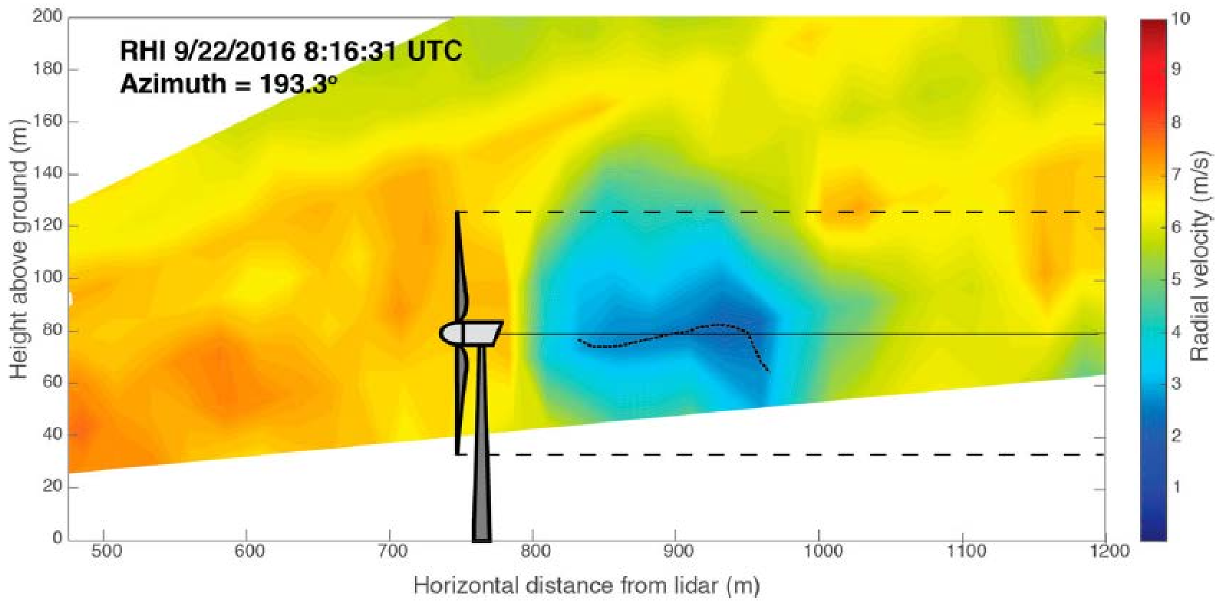
1. What is the predominant wind direction in both graphs? Explain your answer.

2. What direction was the wind blowing when the highest wind speed was measured? Northerly

3. In Figure 1(a), approximately how much of the time span did the wind blow out of the northeast/east-northeast (NE/ENE) at 12-21 meters per second?

Part 3. Analysis of wind wakes. Below are images (a, b, and c) from a LIDAR (Light Detection and Ranging) instrument, mounted at the U.S. Coast Guard Station in Lewes, Delaware, pointing toward the UD-Lewes wind turbine. The images are false-color, meaning a computer assigns respective data points a certain color on the heat scale (blues are lower velocity, reds are higher velocity). Answer the questions following each figure. Figures are from Archer, et al. 2019.

a) Vertical profile, September 22, 2016 at 8:16 am UTC (4:16 am EDT)



The above image is a vertical snapshot of the LIDAR data. The LIDAR instrument is mounted on the left side of the image. The wind direction is left to right. Using the figure above, answer the following questions.

1. What questions develop in your mind after looking at this data plot?

2. What is the hub-height (height above ground) of this wind turbine?

3. How long are the wind turbine blades?

4. How fast (in meters per second or m/s) is the wind blowing in front of the wind turbine?

    a. How fast is this wind speed in miles per hour (mph)?

5. What color indicates the wind wake?

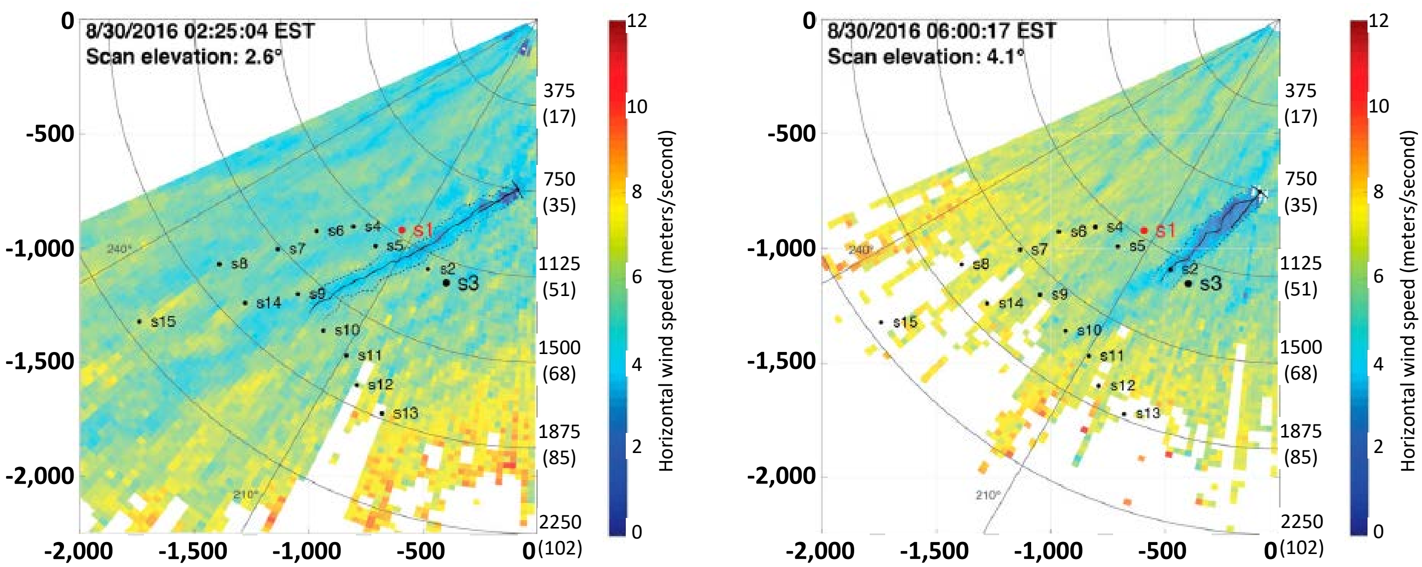
    a. How fast is the wind speed in the wind wake?

b. Approximately how long (distance) is the wind wake measured?

6. If you were building a wind farm based on these data, at least how far behind this wind turbine would you place a second wind turbine? Why?

BONUS: What does the term “azimuth” mean/measure?

b) Scanning LiDAR images from August 30, 2016.



The above images are looking down from the sky on the wind field. The LiDAR instrument is mounted in the top-right corner of each figure. The wind direction is top-right to bottom-left. The scale on the secondary (right) y-axis of each figure indicates the distance from the LiDAR in meters, with the measurement’s elevation above ground in the parentheses. Using the figures above, answer the following questions.

1. What questions develop in your mind after looking at these data plots?

2. At what distance is the Lewes wind turbine from the LiDAR instrument?

3. How can you distinguish the wind turbine wake?

a. How much slower is the wind speed in the wake versus the surrounding area?

b. How long (distance) are the two wakes?

4. The y-axes both run North to South (top to bottom), and there are additional lines indicating 210˚ and 240˚ directions. Based on the angle of the wind wake, approximately what direction is the wind blowing at the two different times of the day?

5. The ground-mounted LiDAR instrument is angled up at the wind turbine, as indicated by the measurements on the secondary (right side) y-axis, in the parentheses (elevation above ground, in meters). Based on the two figures, what observation can you make about wind speed with increasing altitude? Provide data as evidence for your claim.

Discussion Questions

Students should defend their answers with evidence from the data above.

1. Based on the data you analyzed, do wind turbines have substantial downwind effects?

2. How can downwind effects be minimized?

3. What is the ideal wind farm configuration?

Assessment

Performance: Did the student actively participate in the independent and discussion portions of the activity, clearly demonstrating a grasp of the material? Was the student engaged during the activity?
Product: Did the student answer the data analysis questions coherently and provide evidence for their answers?

References

Cristina L. Archer, Sicheng Wu, Ahmad Vasel-Be-Hagh, Joseph F. Brodie, Ruben Delgado, Alexandra St. Pé, Steven Oncley & Steven Semmer (2019) The VERTEX field campaign: observations of near-ground effects of wind turbine wakes, Journal of Turbulence, 20:1, 64-92, DOI: 10.1080/14685248.2019.1572161

Standards

Next Generation Science Standards

HS-ESS3-4 Evaluate or refine a technological solution that reduces impacts of human activities on natural systems.
HS-PS3-3 Design, build, and refine a device that works within given constraints to convert one form of energy into another form of energy.

Energy Ocean Literacy Principles

1.1 Energy is a quantity that is transferred from system to system.
1.3 Energy is neither created nor destroyed.
1.4 Energy available to do useful work decreases as it is transferred from system to system.
1.8 Power is a measure of energy transfer rate.
2.3 Earth's weather and climate are mostly driven by energy from the Sun.
4.1 Humans transfer and transform energy from the environment into forms useful for human endeavors.
4.4 Humans transport energy from place to place.
4.5 Humans generate electricity in multiple ways.
4.7 Different sources of energy and the different ways energy can be transformed, transported, and stored each have different benefits and drawbacks.
5.3 Energy decisions can be made using a systems-based approach.
5.4 Energy decisions are influenced by economic factors.
5.6 Energy decisions are influenced by environmental factors.

Understanding downwind effects

****TEACHER ANSWER KEY****

Part 1. Observation of downwind effects

1. Based on Figure 1a, please describe the wind farm.

   Student answers will vary, but may include observations that the wind farm is rectangular*; composed of 80 turbines** (10 x 8); no land in site (at least in this picture); wind turbines are white; etc.

   * Note that the windfarm shape is not a perfect rectangle, as the corners are not 90-degrees.
   **Students may also infer that since *Horns Rev 1* is a 160-megawatt windfarm, and there are 80 wind turbines, that each turbine is a 2-megawatt machine.

2. Looking at Figure 1b, please describe what you see. List questions you have after looking at the photograph.

   Student answers will vary, but may include things like turbines creating clouds; wind wakes downwind/downstream of the lead row of wind turbines; clouds appear "thinner" downwind; blades are in different orientations; blade tips are red (why?); etc.

   The questions students have can be used for research projects or in the Discussion portion of this activity.

3. Looking at Figure 1c, do you notice anything different in this photograph?

   Student answers will vary, but may include any of the above. Of particular note in this photograph is that the wind wake cloud in the second row, forms behind the second turbine in the sequence. This most likely indicates that the first turbine in that second sequence is not currently active (working) for some reason (e.g. maintenance issue, etc.).

Part 2. Analysis of wind rose diagrams.

1. What is the predominant wind direction in both graphs? Explain your answer.

   Based on the figures, as indicated by the longer pie wedges, the predominant wind direction during the (a) data collection is north-northeast (NNE) to east-southeast (ESE), and during the (b) data collection, north-northeast (NNE) to east-northeast (ENE).

2. What direction was the wind blowing when the highest wind speed was measured? Northerly

    a. What was the wind speed? 21-25 m/s

    b. Convert this wind speed from meters per second to miles per hour. Answers will vary based on the significant figures used. The correct answer should range from 46.9-56.3 mph.

3. In Figure 1(a), approximately how much of the time span did the wind blow out of the northeast/east-northeast (NE/ENE) at 12-21 meters per second? 12-13%

Part 3. Analysis of wind wakes.

a) Vertical profiles, September 22, 2016

1. What questions develop in your mind after looking at this data plot? Student answers will vary.

2. What is the hub-height (height above ground) of this wind turbine? Approximately 80 meters

3. How long are the wind turbine blades? Approximately 40 meters

4. How fast (in meters per second or m/s) is the wind blowing in front of the wind turbine? Approximately 6.5-8 m/s
    a. How fast is this wind speed in miles per hour (mph)? Approximately 14.5-18 mph

5. What color indicates the wind wake? Light to dark blue
    a. How fast is the wind speed in the wind wake? 2-3 m/s or 4.4-6.7 mph
    b. Approximately how long (distance) is the wind wake measured? 200 meters (800-1,000 meters from lidar)

6. If you were building a wind farm based on these data, at least how far behind this wind turbine would you place a second wind turbine? Why? Student answers will vary, but at a minimum—based on this plot alone, a second turbine should be placed at least 325 meters from the existing turbine (at the 1,100-meter mark of the x-axis), in order to avoid wake effects in the predominant annual wind direction.

BONUS: What does the term "azimuth" mean/measure? The azimuth is an angular measurement between the projected vector and a reference vector. In this case the azimuth of 193.3˚ indicates the LiDAR was pointing 193.3˚ off magnetic north (360˚ or 0˚), so just west of due south (180˚).

b) Scanning LiDAR images from August 30, 2016

1. What questions develop in your mind after looking at these data plots? Student answers will vary.

2. At what distance is the Lewes wind turbine from the LiDAR instrument? Approximately 750 meters

3. How can you distinguish the wind turbine wake? The blue color (approximate wind speed of 2-4 m/s) or lack of yellow "specks" in the wind field. Note: The dotted lines outline the wind wake, so students may cite those lines as well.

    a. How much slower is the wind speed in the wake versus the surrounding area? Approximately 2-4 m/s in the wake versus approximately 5-7 m/s in the surrounding area.

    b. How long (distance) are the two wakes? At 2:25 AM (left figure), the wake is approximately 937.5 meters long ((1875m-1500m)/2)+(1500-750m)). At 6:00 AM (right figure), the wake is approximately 562.5 meters ((1500m-1125m)/2)+(1125-750m))

4. The y-axes both run North to South (top to bottom), and there are additional lines indicating 210˚ and 240˚ directions. Based on the angle of the wind wake, approximately what direction is the wind blowing at the two different times of the day? *Remember that winds are named by the direction FROM which they blow. Therefore, at 2:25 AM (left figure): from approximately 70˚ or east-northeast (ENE), and at 6:00 AM (right figure): from approximately 60˚ or east-northeast (ENE).

5. The ground-mounted LiDAR instrument is angled up at the wind turbine, as indicated by the measurements on the secondary (right side) y-axis, in the parentheses (elevation above ground, in meters). Based on the two figures, what observation can you make about wind speed with increasing altitude? Provide data as evidence for your claim. The student's answer should include increasing wind speed data the further you move away from the LiDAR instrument, e.g. 4-6 m/s closer to the instrument and the ground (less than 35 meters above-ground-level), increasing to 8 m/s further away and higher in the atmosphere (51 meters above-ground-level) and higher.

Discussion Questions

1. Based on the data you analyzed, do wind turbines have substantial downwind effects?
   Wind turbines do have downwind effects. Whether or not they are substantial depends on what is being measured/accounted for. In the example demonstrated in this activity, the wind farm does have downwind effects, but their impact is minimal.

2. How can downwind effects be minimized?
   Wind farm orientation; distance offshore; distance between wind turbines; number of wind turbines

3. What is the ideal wind farm configuration?
   Student answers will vary. The ideal configuration depends on a number of factors. Look for students to provide reasonable/viable evidence for their claim.