Delaware Sea Grant Data Activity

Offshore windfarms' impact on onshore precipitation

Grade Level: High School

Lesson Time: 60 minutes

Required Materials:
- This packet only

STEM Connections
Science – Wind energy; meteorology
Technology – Meteorological sensors (wind speed, precipitation)
Engineering – Wind turbine placement; construction
Math – Percent-change; compare data with like units

Next Generation Science Standards
HS-ESS2-5
HS-ESS3-1
HS-ESS3-4
HS-LS2-7
HS-PS3-3

Energy Literacy Principles
1.1; 1.3; 1.4; 1.5; 1.8; 2.3; 3.6; 4.1; 4.5; 4.7; 5.3; 5.6; 6.4

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Summary

Large-scale offshore wind farms have been shown to decrease onshore wind speeds and precipitation intensity. Students will analyze real computer model and observational data to understand the downstream atmospheric effects of offshore wind farms.

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 how wind turbines may affect offshore and onshore precipitation intensity
- Graph and interpret basic data
- Calculate percent-change

Vocabulary

downwind, downstream, convergence, divergence, surface roughness, onshore, offshore

Invitation

Wind turbines have impacts on the atmosphere downwind of (behind) the structure(s). These impacts are multiplied with the more wind turbines installed on a wind farm. If you build an offshore wind farm big enough, would the farm decrease the intensity of rain falling on the land behind the farm? Could a large enough wind farm stop a hurricane from coming onshore?

Essential Question

Can offshore wind farms noticeably change the onshore wind speed and precipitation intensity?

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 precipitation impacts

Scientists have long hypothesized, but only recently shown that wind turbines have an impact downstream, i.e. a wind turbine changes atmospheric conditions downwind of the turbine and on a larger scale, a wind farm. The wind turbines remove kinetic energy from the air flow and increases turbulence downstream. Using computer models, scientists have also shown that wind speed decreases and precipitation increase just upwind of a wind farm, due to the formation of a convergence zone, where air moves up into the atmosphere. Conversely, on the downwind side of a wind farm, a divergence zone is formed, where air sinks down to the surface. In a computer model-based experiment published in 2014 (Jacobson, et al.), scientists demonstrated that a wind farm with 70,000 wind turbines could actually reduce hurricane-force winds by 50% and decrease storm surge by up to 72%.

Computer models versus observational data

Using high-powered computers, scientists can run repeated, controlled simulations called computer models. Computer models use carefully coded, large data sets to deliver outputs which are then analyzed and interpreted by scientists. This is how weather forecasts are created.

Also important to understanding the environment and relationships are observational data. Unlike computer models, which use observed data to run simulations, observational data is often considered more accurate because it is measured and recorded in real-time. The more observational data we have, the better and more accurate our models become.

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. In this activity, students will graph and analyze computer model data representing the change in Houston, Texas precipitation intensity from Hurricane Harvey (August 2017) if the hurricane had encountered different sized wind farms in the Gulf of Mexico prior to landfall.

Case ID	Number of turbines	Installed electricity capacity (megawatts)	72-hour precipitation reduction in Houston, TX (%)	Description
Control	0	0	0	Control
SWF	28,197	210,000	9.54	Small Wind Farm
MWF	33,363	250,000	15.29	Medium Wind Farm
LWF	74,619	560,000	15.37	Large Wind Farm
MWF-WS	22,242	170,000	12.08	MFW area, but with Wide inter-turbine Spacing
MWF-TS	59,312	440,000	21.17	MFW area, but with Tight inter-turbine Spacing
MWF-Z0	0	0	10.41	MFW area, but with NO wind turbines, but instead, increased surface roughness over the area

Table 1. Computer model data from Pan, et al. 2018.

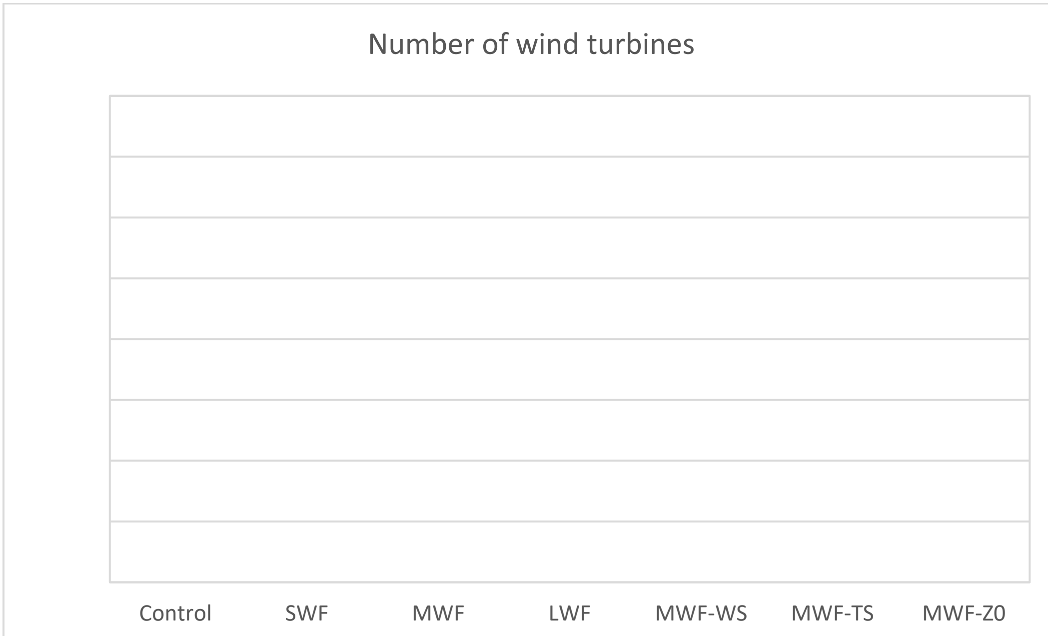

Figure 1. Number of wind turbines in the seven project cases. Students should graph the data found in Table 1 as a column graph.

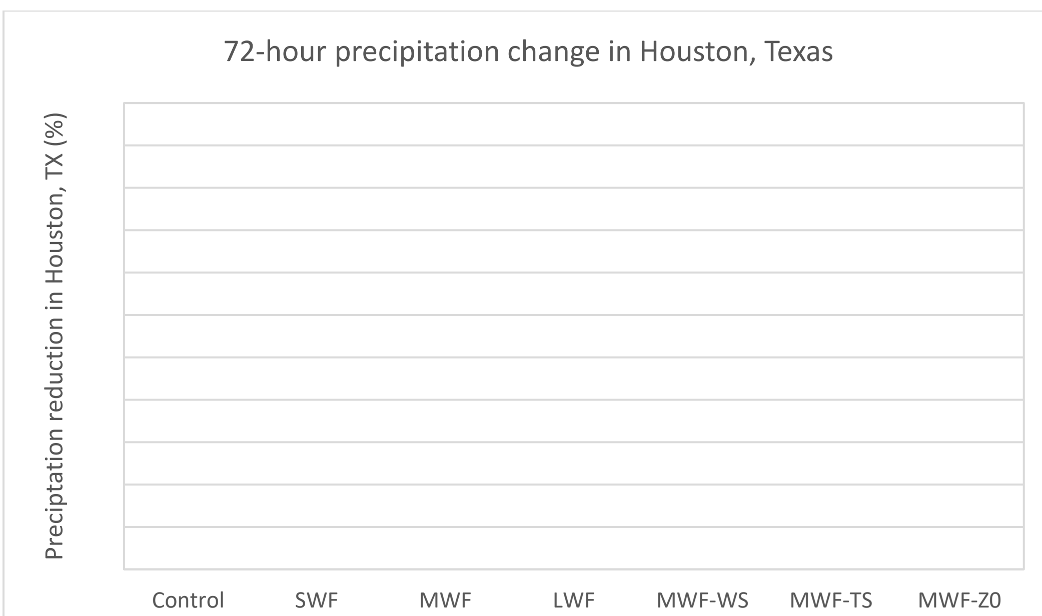

Figure 2. The 72-hour reduction in precipitation intensity in Houston, TX, in the seven project cases. Students should graph the data found in Table 1 as a line graph.

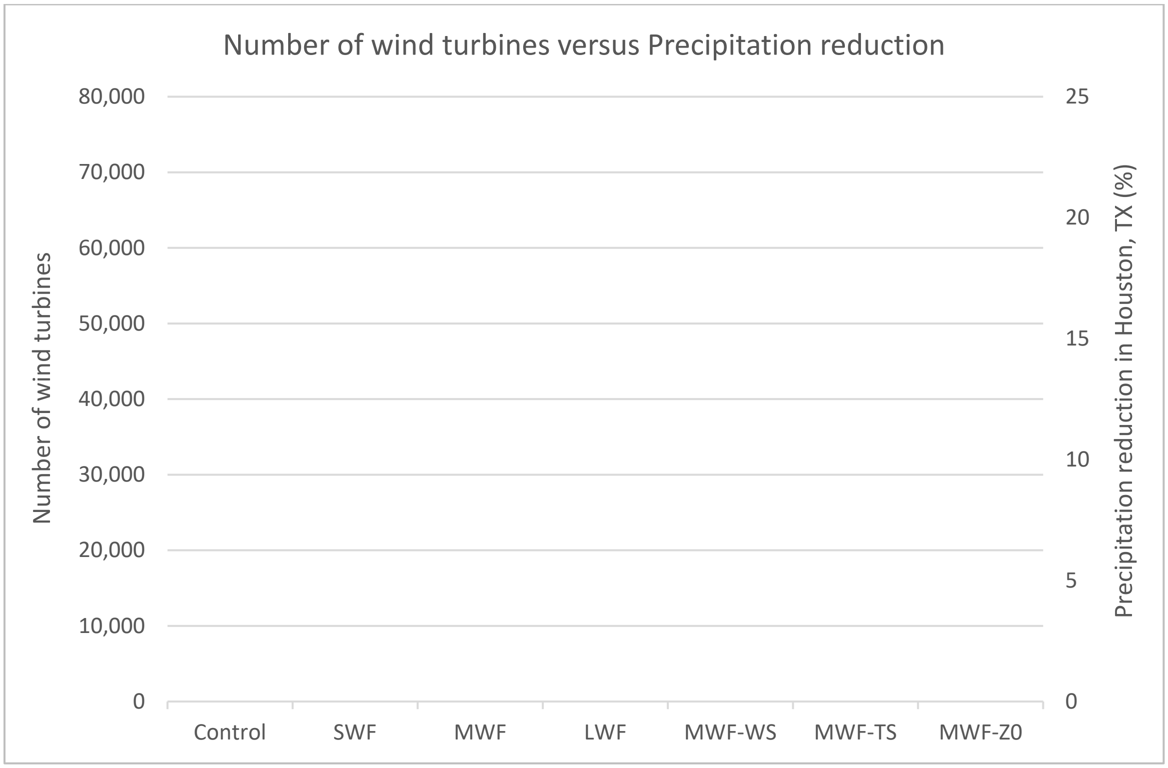

Figure 3 (OPTIONAL). If students prefer, they can plot both data sets on one graph; the y-axis values have been provided. If choosing this graphing option, the "Number of wind turbines" should be represented by a column graph, and the "Precipitation reduction" should be represented by a line graph.

Based on Figures 1 and 2 (or Figure 3), answer the following questions.

1. Do you notice any trends in the data?

2. Which Case had the most wind turbines?

3. Which Case had the largest reduction in precipitation?

4. Please explain how the Case that had the second highest number of wind turbines had such a higher reduction in precipitation.

5. Case MWF-Z0 had no wind turbines yet reduced precipitation at similar amounts to cases with 22,000-28,000 wind turbines. Based on these data, what can you infer about surface roughness?

Part 2. Figure 4 below is from Al Fahel and Archer, 2020. Use this series of two figures to answer the questions. The black arrows indicate air flow (wind); U_x is wind speed at different locations; and the blue water drops represent generalized precipitation intensity, not a specific amount. The spirals behind the wind turbines represent turbulence caused by the wind farm. “Conv.” is the convergence zone; “Div.” is the divergence zone.

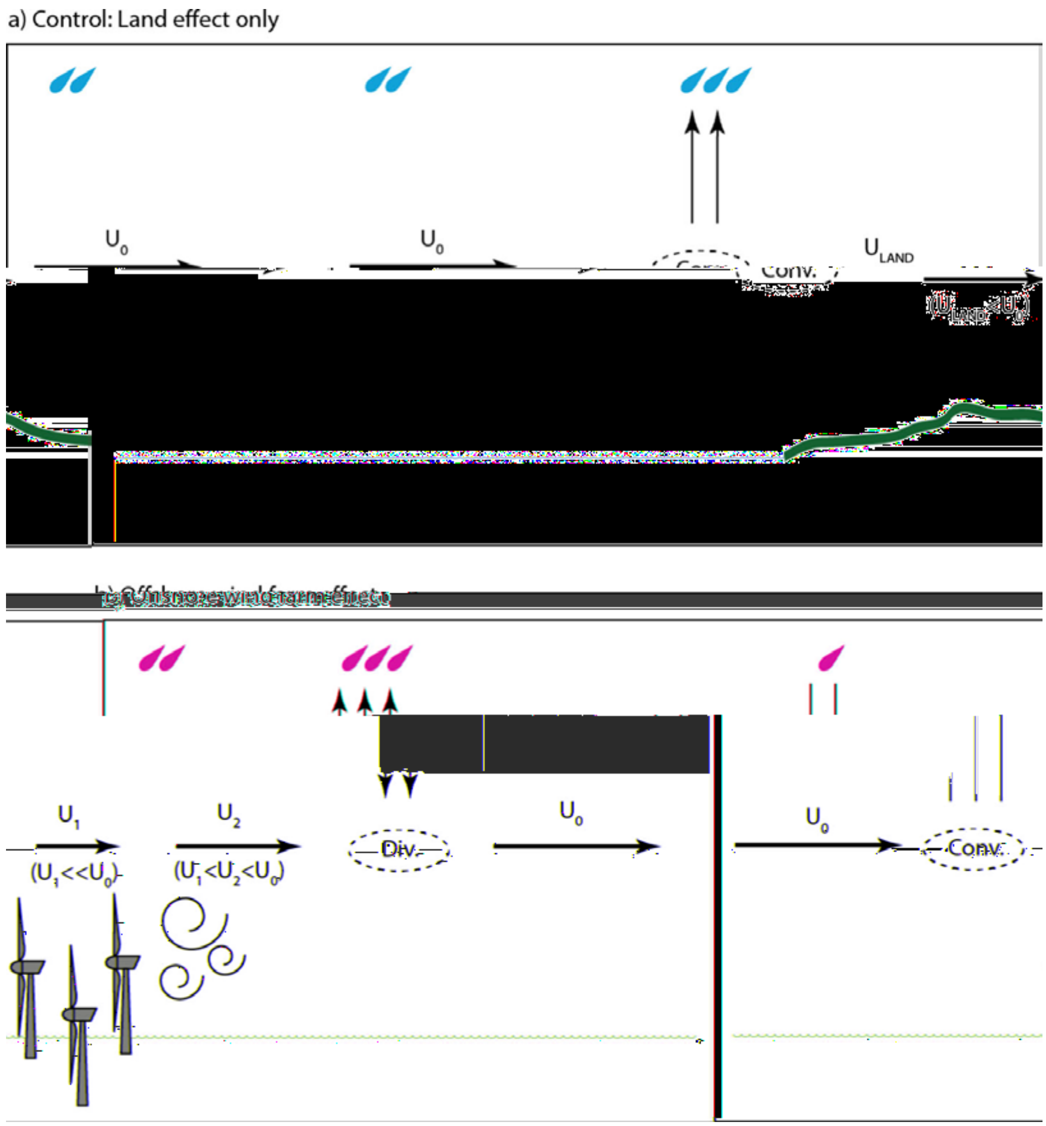

Figure 4. Sketch of the effects of divergence and convergence on precipitation for (a) the land effect only (control case), by which the sea–land transition causes convergence and enhanced precipitation at the shore due to changes in surface roughness, and (b) the offshore wind farm effect, by which the wake recovery causes divergence and reduced precipitation past the farm, near the shore. In reality, both effects a and b overlap and the net effect at the shore is, likely, lower precipitation than in (a). From Al Fahel and Archer, 2020.

6. In your own words, please explain the difference between figures 4a and 4b.

7. What do you think would happen to the precipitation intensities if there were six wind turbines in Figure 4b?

Part 3. Use Table 2 to answer the following questions.

	Walney, UK	**Burbo Bank (Crosby), UK**
Build out years	2010-2014, 2018	2005-2007, 2014-2017
Number of wind turbines	327	57
Electricity production capacity	1,026 megawatts	348 megawatts
Distance from shore	~12 km	~7 km
Average wind speed, pre-wind farm*	13.4 knots	17.8 knots
Change in wind speed, post-wind farm construction*	*a) - 1.1 knots*	*b)*
Percent change in wind speed*	- 8%	- 8%
Average precipitation intensity, pre-wind farm*	0.727 mm/hour	0.773 mm/hour
Change in precipitation intensity, post-wind farm construction*	- 0.080 mm/hour	- 0.080 mm/hour
Percent change in precipitation intensity*	*c)*	*d)*

*At land-based weather station, not at the actual wind farm

Table 2. A comparison between offshore wind farms at Walney, UK and Burbo Bank (Crosby), UK. Pre-farm refers to data collected prior to the wind farms being built. Post-wind farm refers to data collected after the wind farm was built.

8. Using the data available in Table 2, complete the missing data in boxes (b) through (d) by using and calculating percent-changes in wind speed and precipitation intensity. Box (a) has been completed for you.

9. Based on the data in Table 2, did the wind farms change the onshore wind speed and precipitation intensity? Provide evidence for your claim.

10. Did the larger windfarm have a larger impact on the wind speed and precipitation intensity? Provide evidence for your claim.

Discussion Questions

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

1. The MWF and LWF had nearly the same reduction in precipitation despite the large difference in their respective number of wind turbines. What are the advantages and drawbacks to building the medium size wind farm compared to the large wind farm?

2. Figure 4 represents the difference between the absence and presence of an offshore wind farm. How might the figure look if both scenarios were inland, instead of a coastal environment?

3. If the Walney wind farm was built today, it would include fewer, larger, more-efficient wind turbines. How do you think that would impact the downstream wind speed and precipitation intensity at the onshore weather station? Provide evidence for your claim.

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

Al Fahel, N., Archer, C.L. Observed onshore precipitation changes after the installation of offshore wind farms. *Bull. of Atmos. Sci.& Technol.* **1,** 179–203 (2020). https://doi.org/10.1007/s42865-020-00012-7

Jacobson, M., Archer, C. & Kempton, W. Taming hurricanes with arrays of offshore wind turbines. *Nature Clim Change* **4,** 195–200 (2014). https://doi.org/10.1038/nclimate2120

Pan, Y. Yan, C., & Archer C.L. Precipitation reduction during Hurricane Harvey with simulated offshore wind farms. Environ. Res. Lett.13 084007 (2018) https://doi.org/10.1088/1748-9326/aad245

Standards

Next Generation Science Standards

HS-ESS2-5 Plan and conduct an investigation of the properties of water and its effects on Earth materials and surface processes.
HS-ESS3-1 Construct an explanation based on evidence for how the availability of natural resources, occurrence of natural hazards, and changes in climate have influenced human activity.

HS-ESS3-4 Evaluate or refine a technological solution that reduces impacts of human activities on natural systems.
HS-LS2-7 Design, evaluate, and refine a solution for reducing the impacts of human activities on the environment and biodiversity.
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.
1.5 Energy comes in different forms and can be divided into categories.
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.
3.6 Humans are part of Earth’s ecosystems and influence energy flow through these systems.
4.1 Humans transfer and transform energy from the environment into forms useful for human endeavors.
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.
5.6 Energy decisions are influenced by environmental factors.
6.4 Earth has limited energy resources.

Offshore windfarms' impact on onshore precipitation – HIGH SCHOOL

****TEACHER ANSWER KEY****

Part 1. Comparison of computer model data

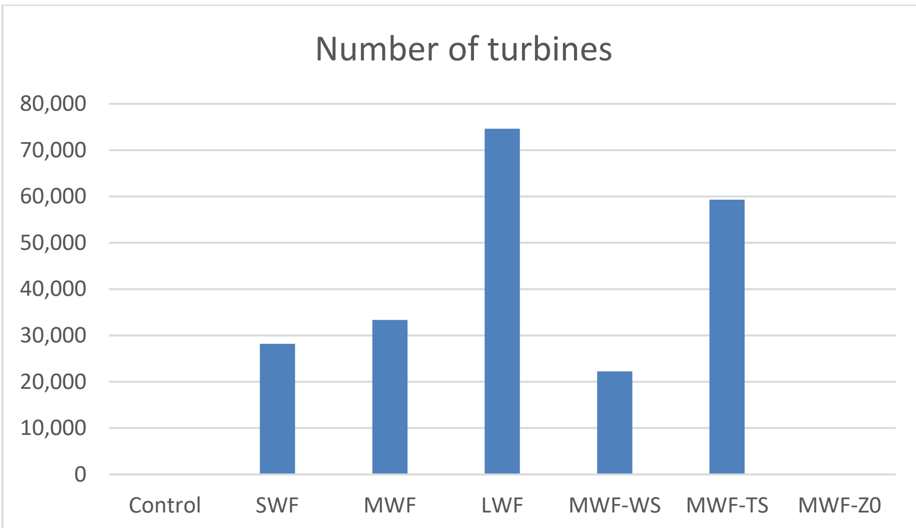

Figure 1.

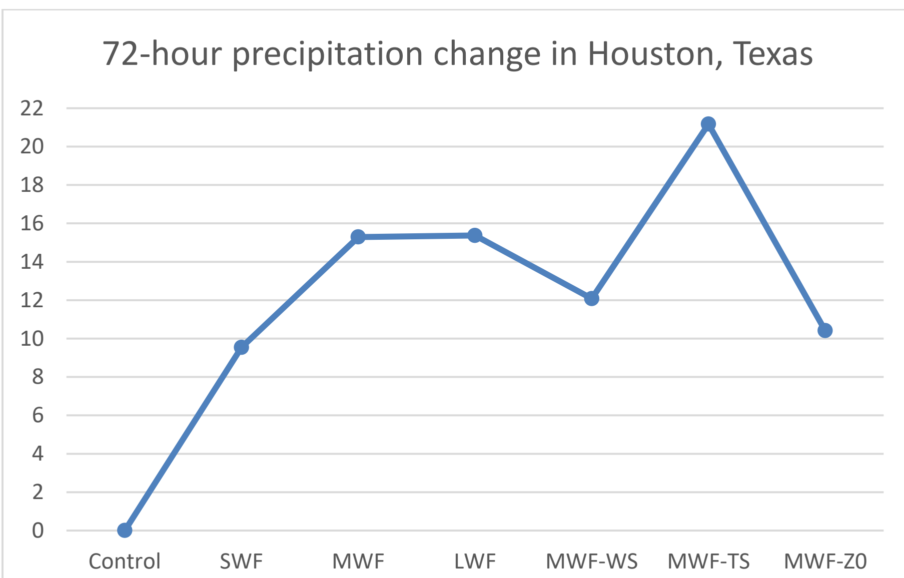

Figure 2.

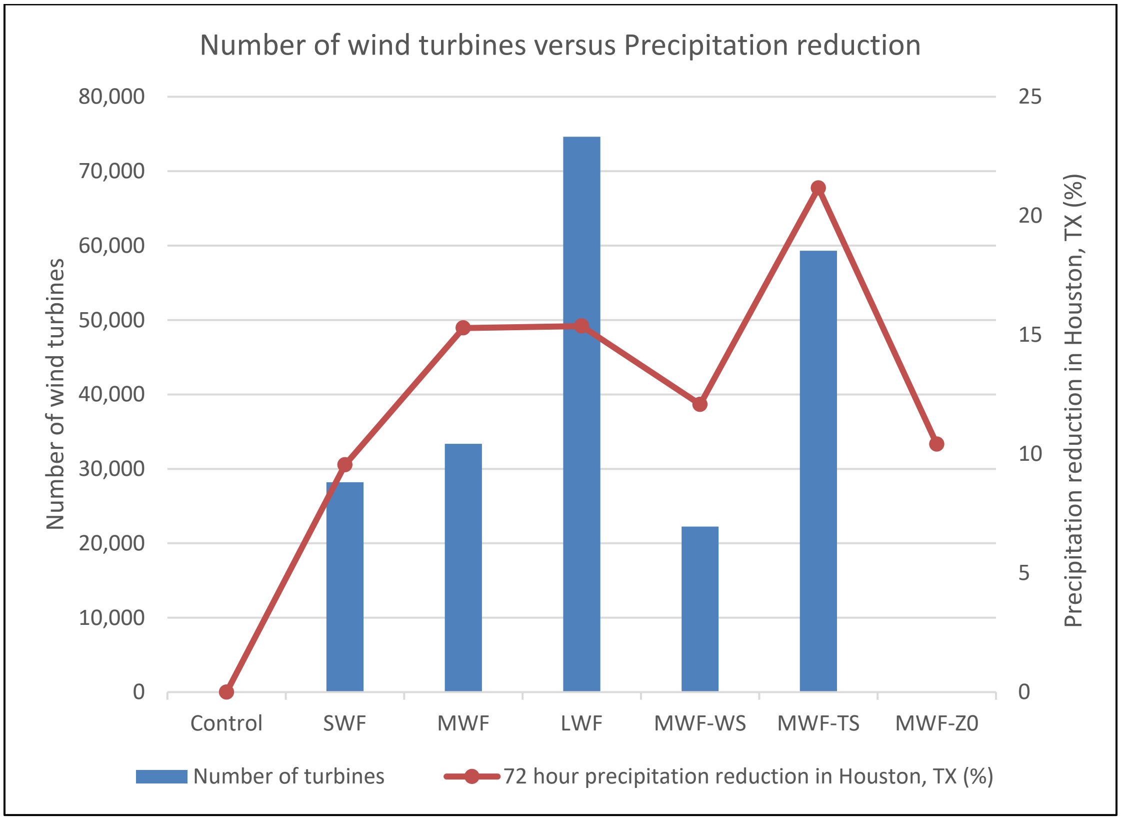

Figure 3 (OPTIONAL)

1. Do you notice any trends in the data?
   Student answers may vary. Possible trends include:
   - Level precipitation reduction in MWF and LWF, and in SWF, MWF-WS, and MWF-Z0
   - There is an increase in precipitation reduction as you get larger windfarms, then diminishing returns
   - The second highest number of wind turbines resulted in the largest reduction in precipitation

2. Which Case had the most wind turbines? MWF-TS

3. Which Case had the largest reduction in precipitation? MWF-TS

4. Please explain how the Case that had the second highest number of wind turbines had such a higher reduction in precipitation.
   MWF-TS has tightly packed wind turbines, thus increasing the surface roughness and the amount of kinetic energy removed from the air flow, ultimately resulting in a larger divergence zone.

5. Case MWF-Z0 had no wind turbines yet reduced precipitation at similar amounts to cases with 22,000-28,000 wind turbines. Based on these data, what can you infer about surface roughness?

Surface roughness may have caused a stronger convergence zone ahead of the wind farm area, resulting in a higher precipitation intensity. This would cause a decrease in precipitation intensity due to the stronger convergence zone formed behind the wind farm area.

Part 2. Comparison of the effects of divergence and convergence on precipitation.

6. In your own words, please explain the difference between figures 4a and 4b.
   Student responses will vary. Answers may include, but are not limited to:
   - (b) has an offshore wind farm and (a) does not
   - We do not see a divergence zone in (a)
   - We see more uplifted air flow (three black arrows versus two) in (b) due to the wind farm

7. What do you think would happen to the precipitation intensities if there were six wind turbines in Figure 4b?
   We might expect the convergence zone and its impact double in size and have a bigger affect on precipitation intensity in front of the wind farm. This may also mean a larger/stronger divergence zone behind the wind farm and subsequently, even further reduction in precipitation intensity.

Part 3. Comparison of two wind farms' impacts on onshore wind speed and precipitation intensity.

8. Using the data available in Table 2, complete the missing data in boxes (b) through (d) by using and calculating percent-changes in wind speed and precipitation intensity. Box (a) has been completed for you.
   (b) *– 1.4 knots*; (c) *– 11%*; (d) – *10.35%*

9. Based on the data in Table 2, did the wind farms change the onshore wind speed and precipitation intensity? Provide evidence for your claim.
   Yes. Both wind farms decreased the onshore wind speed and precipitation intensity. In Table 2, we see negative average wind speeds and precipitation intensities after the wind farms were built.

10. Did the larger windfarm have a larger impact on the wind speed and precipitation intensity? Provide evidence for your claim.
    Despite the larger size of Walney, the data show a similar impact to that of the smaller Burbo Bank wind farm.

Discussion Questions

1. The MWF and LWF had nearly the same reduction in precipitation intensity despite the large difference in their respective number of wind turbines. What are the advantages and drawbacks to building the medium size wind farm compared to the large wind farm?
   Student responses will vary, but some examples include:
   - Advantages:
     - Less capital investment
     - Possible faster installation

    - Less environmental impact
- Drawbacks:
    - Less electricity generation
    - Potential higher cost of materials because you are purchasing less
    - Less underwater structure for reef building/habitat

2. Figure 4 represents the difference between the absence and presence of an offshore wind farm. How might the figure look if both scenarios were inland, instead of a coastal environment?
   Student responses will vary. Some examples may include:
    - Surface roughness will change depending on landscape/topography and development. This will change the size and strength of the convergence zone
    - Land-based wind farms tend to be smaller than offshore farms
    - Depending on wind farm configuration, due to landscape/topography/development, there may be more/less turbulence downstream of the wind farm

3. If the Walney wind farm was built today, it would include fewer, larger, more-efficient wind turbines. How do you think that would impact the downstream wind speed and precipitation intensity at the onshore weather station? Provide evidence for your claim.
   Student responses will vary, but they should provide reasonable/viable evidence for their claim.