OCS Study
BOEM 2022-005

Supporting National Environmental Policy Act Documentation for Atlantic Offshore Wind Energy Development Related to Microclimates

U.S. Department of the Interior
Bureau of Ocean Energy Management
Office of Renewable Energy Programs

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BOEM	Bureau of Ocean Energy Management
NOAA	National Oceanic and Atmospheric Administration
OCS	Outer Continental Shelf
U.S.	United States
UTC	Coordinated Universal Time

Executive Summary

Offshore wind energy is a valuable resource to reduce greenhouse gas emissions, primarily carbon dioxide, and reduce the effects of climate change. Efforts to expand offshore wind energy to combat the effects of climate change are increasing along the Atlantic Outer Continental Shelf in the United States. Sales of offshore wind leases are increasing, along with the development of leases along the Atlantic coast. Accompanying this growth in development is the public interest in wide-ranging aspects about wind energy and the effects offshore wind has on the environment.

Recently, questions have been raised regarding microclimates within offshore wind farms and how these phenomena may affect the local climate and the overall global climate. Wind energy developers and scientists have studied microclimates generated by turbines and the associated downwind turbulence for decades to improve wind farm layout efficiency and energy production. More recently, research has been focused on the downwind effects of wind turbines on climate. The purpose of this white paper is to explain how microclimates are formed within offshore wind facilities and show that while microclimate effects are important for planning purposes, the effects are negligible onshore and to the overall climate.

1 Introduction

Offshore wind energy is a valuable resource to reduce greenhouse gas emissions and reduce the effects of climate change. Historically, traditional energy generation has impacted the Earth's climate from greenhouse gas emissions, primarily from combustion of fossil fuels. These effects have been studied and documented over many years by climate scientists, chemists, and other researchers (Wiser, et al., 2011). Growing efforts to expand offshore wind energy to combat the effects of climate change are increasing along the Atlantic Outer Continental Shelf (OCS) in the United States (U.S.).

Offshore wind has been in production in Europe since the 1990s, the first federal onshore wind development in the U.S. began operation in 1982, and the first commercial offshore wind development on the Atlantic OCS began generating electricity in 2016 (Wind Europe, 2021; Bureau of Land Management, N.D.; Orsted, 2021). Research and studies concerning wind energy both on and offshore have been conducted to better understand the effects of wind energy development on the environment. The Bureau of Ocean Energy Management (BOEM) is engaged in varying stages of processing over a dozen offshore wind leases on the Atlantic OCS.

Recently, questions have been raised regarding wake effects and localized climatic conditions, or microclimates, within offshore wind farms and how these phenomena affect the local climate and the overall global climate. Therefore, the purpose of this white paper is to explain how microclimates are formed within offshore wind farms and show that while microclimate effects are important for planning purposes, the effects are negligible onshore and to the overall climate.

2 Climate, Weather, and Wind Energy

Research has been conducted to study the influence of downwind windspeed reduction, or wake effect, on the arrangement of turbine arrays. This is when the leading row of turbines slows the wind force through the motion of the turbine blades, reducing the windspeed and increasing turbulence behind the turbine. Large wind farms arrange the subsequent rows of turbines to avoid the wakes from the turbines positioned upwind in the farm. Similarly, studies have been conducted within both onshore and offshore wind farms to observe and model the mixing of air masses occurring above, below, or within wind farms. Factors such as temperature, wind speed, humidity, atmospheric pressure, and air flow are measured with instruments within wind farms, on aircraft, or from satellite data. Other components such as drag, surface friction, turbulence, and wind direction are also factored into equations. The data collected is applied by scientists to create models to help the industry plan wind farms and is also used to gain a greater understanding of how wind farms, both large and small, may affect the local climate. (Frandsen, et al., 2004; Platis, et al., 2018; Musial, 2018; Meyers & Meneveau, 2012; Deutsche Windguard, 2018)

The Atlantic coast is influenced by numerous meteorologic factors, including hemispheric prevailing winds, the Gulf Stream, seasonal fluctuations from warming and cooling of the land surface, and storm events. Generally, winds come from the west in the central and north Atlantic and shift seasonally from northwest in winter to southwest in summer. Sea breezes, where the cooler air over the ocean is pulled shoreward as the hotter air rises above the land, occur in the warmer summer months. The reverse scenario may occur at night when air over the ocean water is warmer than the air over land, called a land breeze. Below 30 degrees south, equatorial influences will pull the winds from the east and can influence weather in the southeastern U.S. (National Oceanic and Atmospheric Administration (NOAA), ND,a; NOAA, ND,b; NOAA, ND,c)

2.1 Horns Rev Examples

Two very visible but atypical displays of wake effect occurred in the North Sea off the coast of Denmark. These cases are often cited as concerning examples of microclimates that could possibly occur along the Atlantic coast. Notably, these offshore wind farms are located off the west coast of Denmark, where the wind generally moves across the sea toward land. (Hasager, et al., 2017)

The Horns Rev 1 offshore wind farm in the North Sea was photographed on February 12, 2008, at 10:10 Coordinated Universal Time (UTC), showing fog wakes trailing the leading row of moving turbines. This sparked the curiosity of scientists to understand what climatological factors were at the source of the condensation behind the spinning blades. In this instance, a unique phenomenon of cold humid air was situated above a warm marine layer. As the turbines rotated, the cold humid air was pulled downward into the warmer air close to the sea, creating condensation into a swirling trail of fog that drifted downwind in the wake of the spinning blades. Figure 1 shows the fog event at Horns Rev 1. (Hasager, Rasmussen, Pena, Jensen, & and Rethore, 2013; Hasager, et al., 2017; Emeis, 2010)

Figure 1. Horns Rev 1 Visible Fog Wake
(Hasager, Rasmussen, Pena, Jensen, & and Rethore, 2013) © Vattenfall, Horns Rev 1 owned by Vattenfall. Photographer: Christian Steiness

Eight years later, another fog wake phenomena took place at Horns Rev 2, located less than 20 km from Horns Rev 1. However, many different meteorological conditions were at the source of this occurrence. Simplified, in this case, warm humid air was pulled down toward cooler air near the sea level, which mixed and created fog in the wake of the leading rows of turbines. A similar effect occurs when people exhale in cold weather. Warm humid air from a person's lungs hits the colder dry air where the water vapor briefly condenses into a fog. Although the upwind turbines display the fog wakes, the downwind turbines' mixing of the upper warm air layer causes a drying condition within those wakes. This situation is often measured in onshore wind farms. Figure 2 shows the Horns Rev 2 fog and dry wakes from January 25, 2016, at 12:45 UTC. (Hasager, et al., 2017)

Figure 2. Horns Rev 2 Visible Wakes
(Hasager, et al., 2017)

In both cases, numerous additional factors such as the presence of cloud or fog layer, prevailing winds, and atmospheric instability led to the wake fog formation. These events are known due to photographs taken from helicopters enroute to offshore locations, duration of the events is uncertain. Because of the many factors contributing to these rare events, persistence of visible wakes are likely to last only minutes to possibly hours. Research has determined that if even one factor of the wake formation were to change, no visible wakes would be present. (Joulin, et al., 2020; Hasager, et al., 2017; Hasager, Rasmussen, Pena, Jensen, & and Rethore, 2013)

These two visible examples display that localized microclimates are present in wind farms. Studies and research from both onshore and offshore wind farms, in combination with complex modeling, also provide evidence that microclimates are created within wind farms. (Hasager, Rasmussen, Pena, Jensen, & and Rethore, 2013; Hasager, et al., 2017; Wang & Prinn, 2010)

2.2 Onshore and Offshore Wind Microclimates

In 2004, research by Keith, et al., concluded that microclimates within large scale onshore wind farms were present (Keith, et al., 2004). These areas are created by mixing air layers, often moving warmer air or humidity, which leads to localized warming in the wakes within the wind farms, generally at night (Figure 3). This research was misinterpreted by journalists and the general public to imply that wind farms cause warming temperatures. In reality, in the case of localized warming, the turbines pull warmer air from where it rises overnight[1] and mixes the warm air with the cooler air at the ground surface, resulting in a downwind wake of warmer air. This warmer wake is a redistribution of existing warm air, not a net warming of the atmosphere (Stromberg, 2014).

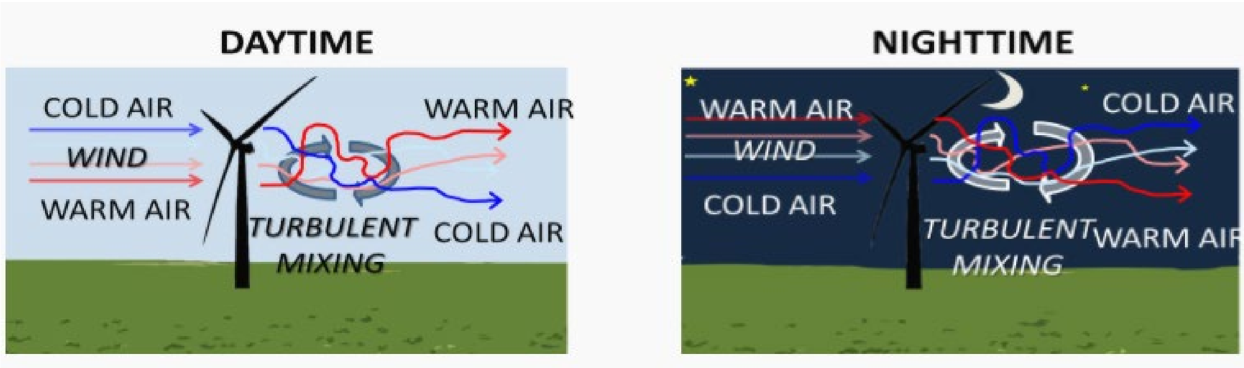

Figure 3. Mixing of Air Layers – Day and Night
(Cervarich, 2021)

Further studies show mixing of air layers, depending on the location of the onshore wind farms, resulting in warming or less often, cooling within turbine wakes (Vautard, et al., 2014; Roy & Traiteur, 2010). Downwind turbulence from turbine wakes has been studied onshore to measure the distance and velocity of those wakes (Stergiannis, Caralis, van Beeck, & Runacres, 2021). Measured and modeled effects are shown to be very localized, with wake distances measured 3 to 6 miles downwind of the turbines onshore (Stergiannis, Caralis, van Beeck, & Runacres, 2021).

Offshore, similar mixing has been studied and modeled to show localized microclimates. Aside from very rare events, microclimates do not result in the unique visible wakes seen at Horns Rev 1 or 2. When turbines are spinning, they create downwind wakes, and in some cases, mixing of atmospheric layers. Research supports that although temperature or humidity is redistributed in the turbine wakes, this is not a net change of temperature or water vapor because of the turbines. The surface of the ocean is smoother than land, creating less resistance to slow downwind wakes, therefore allowing wakes to extend further than on land. Downwind turbulence wakes have been measured from zero to 43 miles and modeled up to 62 miles when multiple turbines interact together. Wakes tend to be shorter under stable wind conditions, with consistent wind speed and direction. (Wang & Prinn, 2010; Hasager, et al., 2017; Siedersleben, et al., 2018; Vautard, et al., 2014; Platis, et al., 2018)

In 2019, the average distance of planned U.S. offshore wind farms was about 29 miles from the coastline, although some projects may be located within 10 miles from shore (National Renewable Energy

[1] Warm air rises due to the expansion of molecules, making the air less dense. Cold air is denser due to the molecules moving more slowly, thus causing the colder air to sink and accumulate near the Earth's surface. (NOAA, 2016)

Laboratory, 2020). The prevailing winds on the Atlantic coast are generally directed away from shore, depending on the season (National Oceanic and Atmospheric Administration (NOAA), ND,a; NOAA, ND,b). Under normal circumstances, wakes from offshore wind farms will extend away from the coastline and further into the Atlantic Ocean. If the wind were blowing toward shore and the turbines were operating, in most cases, the distance to shore would be great enough to dissipate most wake turbulence before it reached shore. The event of fog wakes coming ashore would be extremely unlikely given the unique meteorological conditions needed to create this phenomena (Hasager, Rasmussen, Pena, Jensen, & and Rethore, 2013; Hasager, et al., 2017)

In the summer along the Atlantic coast, sea breezes are drawn inland off the cooler ocean toward the warmer, heated land mass. Sea breezes are a function of onshore warming of land, which heats more quickly than water. The warm air rises, pulling the cooler air from offshore, creating a cool breeze. This cycle creates low altitude winds traveling across the cooler sea inland in the afternoon when the land becomes increasingly heated by the sun. The opposite effect can occur if the coastal land cools below the sea temperature, drawing the cooler air onshore toward the ocean, called an offshore breeze. The underlying mechanism of a sea breeze is the temperature difference between the land and the water. The presence of wind turbines offshore would not interfere with the development of sea breezes, nor would they disrupt the wind being pulled onshore. (NOAA, ND,b)

3 Conclusion

The interest in offshore wind energy development on the Atlantic OCS is being spurred by concerns related to climate change and reducing greenhouse gases (primarily carbon dioxide) that have been linked to climate change. It is widely agreed that wind energy has the capacity to reduce greenhouse gases (Wiser, et al., 2011). Reducing carbon dioxide in the atmosphere through renewable energy production, such as offshore wind, will help reduce impacts to the global climate, protecting rising sea levels, loss of sea ice, and changes in temperatures on Earth (Miller & Keith, 2018). Research and models applied to the subject of microclimates caused by offshore wind farms show some localized changes in surface temperature, humidity, and windspeed downwind of active turbines. Overall effects of wind farms do not result in a net increase in temperature, but rather can cause localized redistribution of air masses. Although some small scale climatic shifts could occur offshore, sea breezes would not be disrupted by the presence of wind turbines offshore, and other climatic events such as those seen at Horns Rev 1 and 2 are extremely unlikely offshore the East Coast.

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BOEM's mission is to manage development of U.S. Outer Continental Shelf energy and mineral resources in an environmentally and economically responsible way.