Land–Sea Contrast of Nearshore Wind Conditions: Case Study in Mutsu-Ogawara

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Abstract

To develop offshore wind energy, we investigated nearshore wind conditions, notably the land–sea contrast, using the coastal area of Mutsu-Ogawara, Aomori Prefecture as a case study. We found that wind conditions were substantially different between onshore (MT-A1) and offshore (MT-B) sites, even when the latter were only 1.5 km apart. The mean wind speed at 55 m above sea level at MT-B was higher than that at the onshore site by up to 20% monthly and 12% annually. For winds from the landward side, the Iref value (turbulence intensity at a mean wind speed of 15 m/s) at MT-B was 37% lower than that at MT-A1. Because such high wind speeds and low turbulence conditions are preferable for the operation of wind turbines, an offshore wind farm would have advantageous wind conditions, even if placed close to the coastline. Moreover, we found that the land–sea contrast is caused not only by mechanical factors, such as roughness length, but also by thermodynamic factors such as seasonal variations of atmospheric stability over land and sea.

1. Introduction

To develop an offshore wind farm, it is important to precisely understand the wind conditions at the candidate site. In Europe, offshore wind farms are mostly installed far from coastlines; hence, they are minimally affected by land (Rodrigues et al. 2015). In contrast, because of the surrounding deep seas, the installation of offshore wind farms in Japan has started in nearshore shallow waters (Sayigh and Milborrow 2020), which is greatly affected by the land. Therefore, a reliable method for wind resource assessments, that is applicable to nearshore areas, is required for wind energy development in Japan.

For offshore wind resource assessments in Japan’s coastal waters, the first task is to clarify the characteristics of nearshore wind conditions, especially for areas within several kilometers of a coastline. It is necessary to determine the space-time structure and mechanism of wind speed and turbulence distributions, which are controlled by factors such as land–sea breeze circulations, internal boundary layers, land–sea differences in surface roughness, and atmospheric stability (Hsu 1988; Nassif et al. 2020).

However, it is difficult to observe offshore wind conditions at the wind turbine hub height, which is more than 100 m. Thus, studies that examine the differences in wind speed between onshore and offshore sites located in a particular coastal area, such as Nagai et al. (2003) and Shimada et al. (2018), are very limited in Japan. Moreover, there are very few comparative studies that investigate wind shear and turbulence intensity differences between onshore and offshore sites, which are important parameters for wind turbine design; one such study was conducted by SethuRaman and Raynor (1980). Our research aims to clarify the characteristics of nearshore wind conditions, especially their land–sea contrast, using in-situ observation data from two onshore and offshore meteorological masts (met masts) and a vertical LiDAR (light detection and ranging) in Mutsu-Ogawara, Aomori Prefecture.
3. Differences between onshore and offshore wind conditions

The mean wind speed and turbulence intensity are two of the most important parameters for evaluating the business viability of a wind farm and determining the design strength of a wind turbine; thus, the parameters between onshore and offshore sites are discussed in this section. The comparison is made separately for sea-sector winds (wind direction: 0−180°) and land-sector winds (180−360°), with the sector separation being defined by the wind direction at the offshore site MT-B.

3.1 Wind speed

Figure 2 shows the monthly mean wind speeds, and Figs. S1–S3 in the supplementary materials illustrate the monthly and annual wind roses at 55 m ASL at MT-B. The wind roses revealed that the predominant wind direction is westerly or west-northwest, which means that most of the winds blow from the land, except in warm season, when easterly wind blows such as “Yamase” (Kanno 1997).

Although MT-B and MT-A1 are only 1.5 km apart, wind speed is clearly higher at MT-B. The annual mean wind speed at MT-B was higher than that at MT-A1 by 12%, and the monthly mean wind speed reached a maximum of 20% in December. In Figs. 2(b) and (c), the monthly mean wind speed is depicted separately for the land and sea-sector winds. It is clear that the land-sector winds lead to greater differences in wind speed between onshore and offshore sites than sea-sector winds. The wind speed differences between MT-B and MT-A1 were mainly due to mechanical effects such as the land–sea contrast of roughness length and the windbreak zone on the windward side. Westerly winds that decelerated because of a high roughness length and the windbreak zone at MT-A1, accelerated over the sea, reaching MT-B with 10%−20% greater speeds.

In contrast with the land-sector wind, the sea-sector wind exhibited much smaller differences between onshore and offshore sites. This result indicates that the offshore wind profile is advected directly to the onshore site MT-A1. However, it was also observed that the onshore−offshore wind speed differences became larger in the cold season, exhibiting the maximum difference in November. This was probably due to thermodynamic effects on the internal boundary layer, which are discussed in Section 4.
3.2 Turbulence intensity

Because turbulence substantially impacts the fatigue load of wind turbines, it is necessary to understand the turbulence intensity at the planned site. The turbulence intensity $I$ is obtained by dividing the standard deviation $\sigma$ by the mean wind speed $\bar{u}$ in 10 minutes in IEC 61400-1 (2019), which relates design requirements of wind turbines, as follows:

$$I = \frac{\sigma}{\bar{u}}, \quad \sigma = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (u_i - \bar{u})^2}$$

where $u_i$ is the instantaneous wind speed (sampling rate of 1 Hz) and $n$ is the number of data points in 10 minutes. The average and 90-percentile values calculated for wind speed bin are used for wind turbine design.

Figure 3 shows the turbulence intensity measured at the offshore site MT-B (upper) and the onshore site MT-A1 (lower). Figures on the left and right are for the land-sector wind and sea-sector wind, respectively. The curves labeled as IEC (A: Higher turbulence – C: Lower turbulence) indicate the wind turbine categories for turbulence characteristics designated by IEC 61400-1 (2019) and $I_{ref}$ represents the reference value of turbulence intensity at the wind speed of 15 m/s.

4. Discussion in terms of atmospheric stability

4.1 Warm and cold seasons

Figure 4 shows four temperature time series in the study area—sea surface temperature at buoy (blue), air temperature at Odanosawa JMA observation station (red), air temperature (dark green) and land surface temperature (pale green) at site MT-A2. The four lines show 30-day moving averages for each temperature.
August, the air temperature on land was slightly higher than the SST. Assuming that air temperature does not change significantly between the onshore and offshore sites owing to the short distance, the above situation meant that stable (or neutral) conditions prevailed over the sea during this period. In April and May 2018, the land surface temperature was higher than the air temperature. This means that unstable conditions prevailed over the land during this period. Conversely, during September to March, the air temperature became colder than the SST and strong unstable conditions prevailed over the sea. Meanwhile, the difference between air and land surface temperatures observed in February and March 2018 indicated that stable conditions (air temperature > land surface temperature) prevailed over the land during this period.

The estimated seasonal mean atmospheric stability is thus summarized in Table 1. Here, the periods from April to August and from September to March are referred to as “warm season” and “cold season,” respectively.

### 4.2 Vertical wind shear

Figure 5 shows mean wind speed profiles for June 2017–May 2018, measured using LiDAR at the onshore site VL, which are displayed separately for the land and sea-sector winds. The wind shear is expressed by the exponent $\alpha$ and the reciprocal number $N (= 1/\alpha)$, defined as,

$$V(z) = V(z_r) \left( \frac{z}{z_r} \right)^\alpha$$  \hspace{1cm} (2)

where $V(z)$ is the wind speed at height $z$ and $z_r$ is the reference height (IEC 61400-1, 2019). Comparing the wind shear between the land and sea-sector winds, it was obvious that land-sector wind exhibited greater wind shear than sea-sector wind. This result can be explained in terms of mechanical factors, such as the difference in the roughness length between the land and sea surfaces. In addition, the windbreak forest canopy likely affected the land-sector wind, especially in the lower part of the profile, adding to the vertical shear.

Furthermore, differences in wind shear were compared between the warm and cold seasons. The sea-sector wind was found to have a lower shear in the cold season ($N = 11.31$) than in the warm season ($N = 6.75$). This high seasonal difference indicates that the vertical shear of the sea-sector wind largely depended on atmospheric stability over the sea. Considering the seasonal variations in atmospheric stability listed in Table 1, the lower shear in the cold season was caused by unstable stratification, and the relatively higher shear in the warm season was due to neutral to stable conditions. In contrast, the land-sector wind showed almost the same value of $N$ for the warm ($N = 2.86$) and cold seasons ($N = 2.89$), despite the substantial difference in atmospheric stability between the two seasons (shown in Subsection 4.1). These results indicate that the vertical shear of the land-sector wind is governed by mechanical effects, such as surface roughness and canopy, rather than thermodynamic effects. This is probably due to a large friction velocity $u^*$ over rough surface, which leads to a larger Obukhov length $L$, that is, a neutral stratification.

### 4.3 Turbulence intensity

Figure 6 shows the turbulence intensity at the MT-B offshore site. The average values for each wind speed bin of 1 m/s are shown separately for the warm and cold seasons. Despite a slight difference in trends, both the land and sea-sector winds showed greater turbulence intensity in the cold season than in the warm season.

For the land-sector wind, the turbulence intensity was high in the cold season, and this was probably due to the effect of westerly winter monsoon. For the sea-sector wind, the turbulence intensity tended to be high in the cold season in the low to medium wind speed range, with no such difference in the high wind range. This difference between wind speed ranges is due to atmospheric stability, which generally becomes neutral as the wind speed increases. In other words, because the atmospheric stability at
sea tends to be unstable in the cold season at the offshore site (as listed in Table 1), the turbulence intensity is greater than in the warm season at low to medium wind speed ranges.

4.4 Summary of discussion

By comparing the wind conditions in the warm and cold seasons in this section, it was found that the land–sea contrast of wind conditions was caused not only by mechanical but also thermodynamic factors such as seasonal variations in atmospheric stability. For monthly mean wind speeds (Fig. 2), the difference between onshore and offshore wind speed increased in the cold season, which was related to atmospheric stability over land and sea (shown in Fig. 4 and Table 1). This relationship can be explained as follows: As shown in Fig. 5, while the vertical wind speed shear over land is governed by mechanical effects and does not change throughout the year, the vertical shear over the sea greatly depends on atmospheric stability. In the cold season, the predominantly unstable conditions over the sea caused a lower vertical shear and higher wind speed in the lowest part of the atmospheric boundary layer. Thus, the wind speed differences between onshore and offshore sites increased during the cold season. Conversely, in the warm season, the prevailing neutral to stable conditions over the sea caused a greater wind shear and lower wind speed, and the wind speed difference became smaller between the onshore and offshore sites. These results suggest that offshore wind resource assessment for a nearshore wind farm needs to carefully consider both the mechanical and thermodynamic effects caused by different surface conditions between land and sea.

5. Conclusions

This study investigated nearshore wind conditions, especially the land–sea contrast, in the coastal area of Mutsu-Ogawara, Aomori Prefecture, as a case study. Measurements from met masts and vertical LiDAR at land and sea sites in the Mutsu-Ogawara port were compared to determine the differences between onshore and offshore wind conditions. The main findings are summarized below.

First, wind conditions were largely different between onshore and offshore sites, which were 1.5 km apart. The mean wind speed at 55 m ASL at the offshore site was higher than that at the onshore site by up to 20% monthly and 12% annually. As for the turbulence intensity, the $I_{ref}$ value for the land-sector wind at the offshore site was 37% lower than that at the onshore site. Thus, it is concluded that an offshore wind farm would have suitable wind conditions, even if placed very close to the coastline.

Next, the factors that cause the land–sea contrast of wind conditions were examined. While the vertical wind shear over the land is governed by surface roughness and canopy, and remains unchanged throughout the year, the vertical shear over the sea depends on atmospheric stability. The results suggest that the offshore wind resource assessment for a nearshore wind farm needs to carefully consider both the mechanical and thermodynamic effects caused by different surface conditions between land and sea.

The analyses in this study were mainly based on measurements from the met masts. However, the hub height of a typical offshore wind turbine can exceed 100 m. Thus, remote sensing devices, such as scanning LiDAR (Shimada et al. 2020) and floating LiDAR (Carbon Trust 2020), which can measure wind speeds for several hundred meters, are promising tools for surveying offshore wind conditions. For this reason, the New Energy and Industrial Technology Development Organization (NEDO) Fixed Offshore Wind Farm Development Support Project (Establishment of Offshore Wind Resource Assessment Method) (2019-22FY) is now underway to verify the practical effectiveness of these remote sensing devices through intensive meteorological observations at Mutsu-Ogawara. This study provides preliminary research on wind conditions prior to the NEDO project.

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Supplements

Supplementary figures: Wind rose figures at the offshore site MT-B for the period from April 2017 to March 2018.

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