Investigation of the fetch effect using onshore and offshore vertical LiDARs

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Abstract

An ongoing offshore wind measurement campaign using dual vertical light detection and ranging (LiDAR) devices is underway at the Hazaki Oceanographic Research Station (HORS) as part of an investigation into determining the optimal distance from the coast for a nearshore wind farm development from a meteorological perspective. This measurement campaign is being conducted from a 427 m long pier located near the Hazaki Wind Farm in the central Japan. The relationship between wind speed increasing ratios and fetch length, which is the distance wind has traveled over water, is being continuously analyzed via LiDAR observations taken at heights from 40 to 200 m. The results obtained thus far show that coastal wind blowing from land to sea gradually increases as the fetch length increases, raising by approximately 20% at a fetch length of about 2 km. It was also found that the wind speed increase at a 2 km fetch length is equivalent to the effect of a 50 to 90 m vertical height increase.

Keywords: LiDAR, HORS, Coastal winds, Fetch length, Wake, Atmospheric stability

1. Introduction

An ongoing coastal wind measurement campaign using light detection and ranging (LiDAR) devices is being conducted at the Hazaki Oceanographic Research Station (HORS), operated by the Port and Airport Research Institute since October 2015 in Japan's Ibaraki Prefecture (Fig. 1) in an effort to obtain hub height wind speeds for a new Japanese offshore wind atlas project. The observations obtained in this project are being used to evaluate a mesoscale model.

Recently, an additional vertical LiDAR device has been installed at the research platform in order to investigate coastal wind modifications along with the internal boundary layer in greater detail. It is thought that the increase in wind speeds traveling over water, which is known as the fetch length effect, might be of interest to engineers, as well as scientists, working in the renewable energy industry because it is highly relevant to the development of effective offshore wind farms.

To date, only a few previous studies [1-3] have looked at this complicated problem. According to these studies, onshore wind speeds increased between 5% and 45% over long marine fetch lengths, but wind speed increases over fetch lengths less than a few kilometers, which appear to be more important for nearshore wind farm developments, have yet to be thoroughly investigated, primarily due to the lack of appropriate observations necessary for such analyses.

With this point in mind, this study will attempt to illustrate the increase in wind speeds as a function of the fetch length, which is something that has not yet been shown in any previous studies, by analyzing LiDAR observations in order to determine an optimal coast-to-wind farm distance from a meteorological perspective, thereby assisting in considerations related to nearshore wind farm developments.

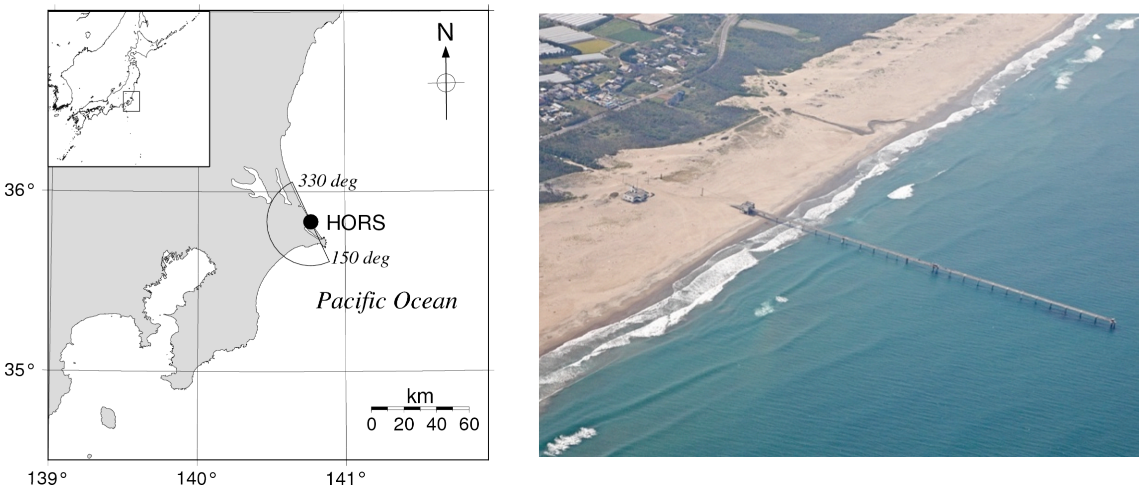

Fig. 1: Location and orientation (left) and photograph (right) of the HORS research platform.

2. Experimental setup

The measurement setup, shown in Fig. 2, is a 427 m long pier constructed at a height of 6.81 m above sea level at the HORS station. Vertical wind speed profiles from 40 to 200 m in altitude are measured at 20 m intervals with two WINDCUBE WLS7 LiDAR devices, the specifications of which are described in Gottschall et al. (2010) [4] in detail. One WINDCUBE (hereafter referred to as LiDAR#1) is installed at the top of the pier, and the other (LiDAR#2) is located on the roof of a 3.5 m tall observational hut located at the foot of the pier. The two LiDAR devices are exactly 400 m apart. A sonic anemometer is also used for surface wind and flux measurements. In addition, seawater temperature observations at a depth of 2 m are recorded at the halfway point of the pier.

Since the region has a rectilinear coastline and is surrounded by flat terrain, this research platform provides an ideal site for investigating variations in wind speed related to the fetch length effect. Additionally, since a straight coastline from 150 to 330° runs through this region, observed winds at the top of the pier can be easily distinguished into winds coming from sea or land sectors.

Note that some winds observed by both LiDARs, blowing from between 165 and 215°, were influenced by the nearby 1.25 MW Hazaki Wind Farm turbines, which have hub heights of 64.5 m. Briefly, we categorized the winds with wind directions between 335 and 145° as offshore winds (sea to land), winds with directions between 165 and 215° as wake zones, and winds with directions between 215 and 325° as onshore winds (land to sea).

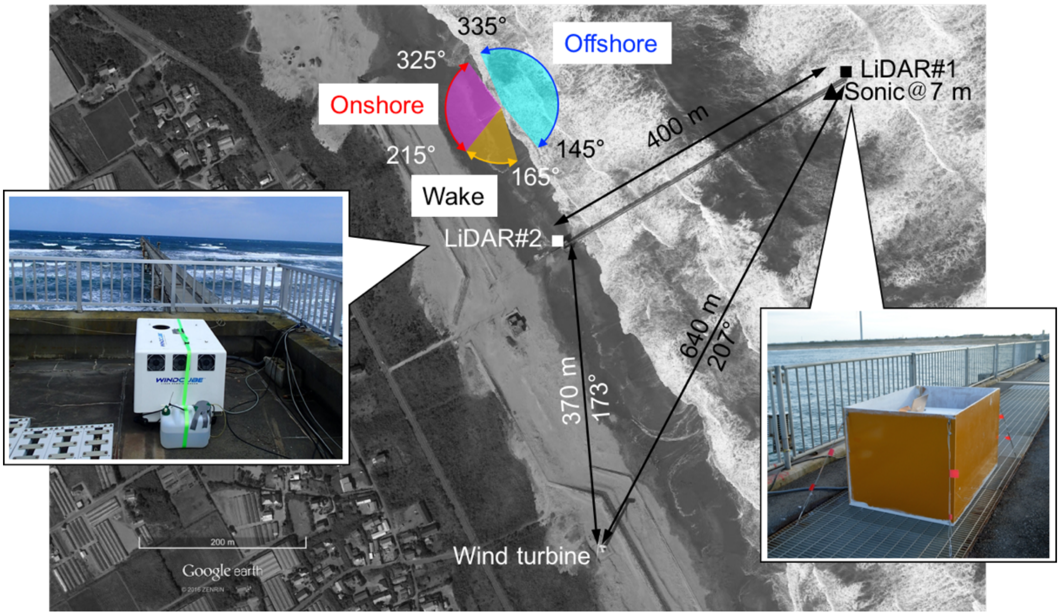

Fig. 2: Experimental setup

Measurements using the two vertical LiDAR devices began in March 2016. Prior to the actual measurement campaign, LiDAR#2 was located at the top of the pier for two weeks in order to investigate differences between the two instruments. Comparisons of 10-minute mean wind speeds obtained from the two LiDARs at heights of 40, 120, and 200 m above the pier for the period from March 7 to 21, 2016 are shown in Fig. 3.

The number of samples, mean wind speeds, biases, and root mean square differences (RMSD), along with the correlation coefficients between the observations, are also described in the figures. Although their differences increase slightly as the heights increase, it was found that the instrumental differences between the two LiDAR devices were negligibly small. Therefore, we can confirm that no unreasonable offsets that might lead to misunderstandings were included in the observed wind speeds.

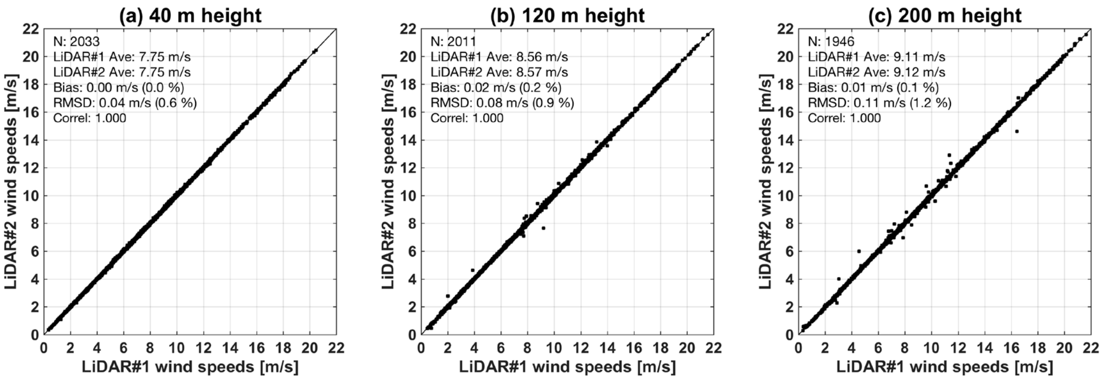

Fig. 3: Comparison of LiDAR wind speed observations from the pier-top LiDAR installation levels of 40, 120, and 200 m heights for the period from March 7 to 21, 2016.

The two LiDAR system measurement campaign started on March 22, 2016 and was ongoing as of September 29, 2016. In this study, observations for the period from March 22 to September 11 are utilized for investigating the relationships between the wind speed increasing ratio and the fetch length effect. Fig. 4 shows the data acquisition ratio of 10-minute wind speeds for LiDAR#1 and LiDAR#2 at nine levels.

The acquisition ratio for LiDAR#1 was found to be clearly lower than that for LiDAR#2, which had 90% data availability for all heights. An electricity supply problem associated with high air temperatures occurred at the pier top for roughly one month from the end of June to the end of July. This is the primary reason why LiDAR#1 showed the lower availability than LiDAR#2, even though instrumental differences were small, as shown in Fig. 3.

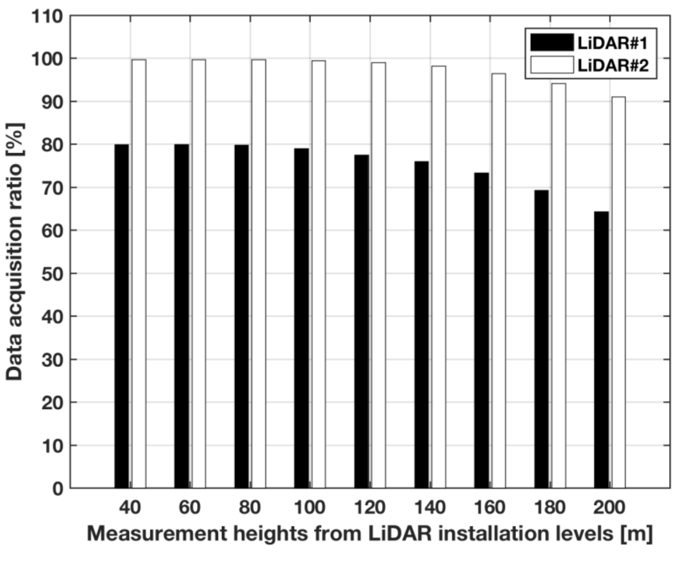

Fig. 4: Data acquisition ratio for the period from March 22 to September 11, 2016.

3. Results and discussion

A 10-minute wind speed occurrence frequency breakdown and a wind rose calculated from LiDAR#1 observations at a height of 80 m above the pier are shown in Fig. 5. In terms of atmospheric stability, neutral to stable stability conditions prevailed at the research platform for the measurement period of spring to early autumn. Fig. 6 shows air and water temperature time-series for the period from January to June 2016. After the end of March, it was found that the air temperature was usually higher than the seawater temperature.

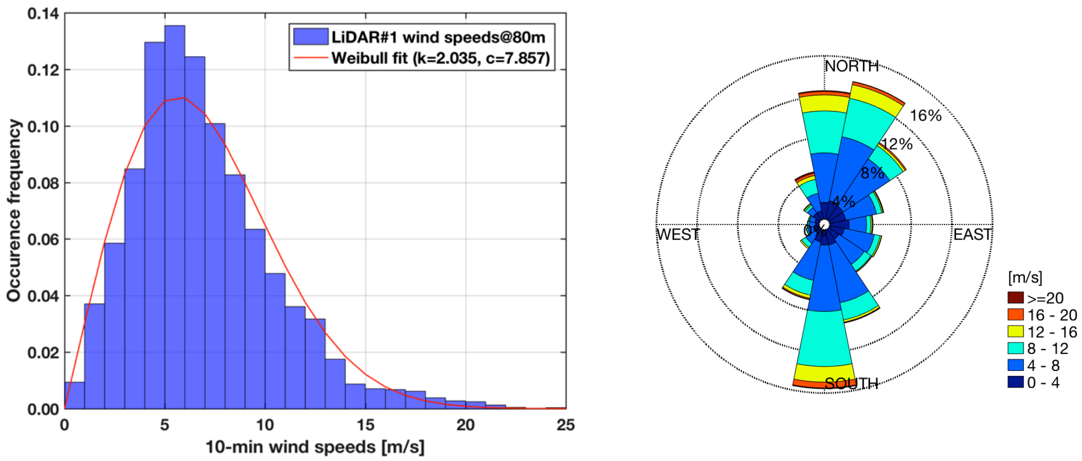

Fig. 5: Occurrence frequency of 10-minute wind speeds (left) and a wind rose (right) at a height of 80 m above the pier for LiDAR#1.

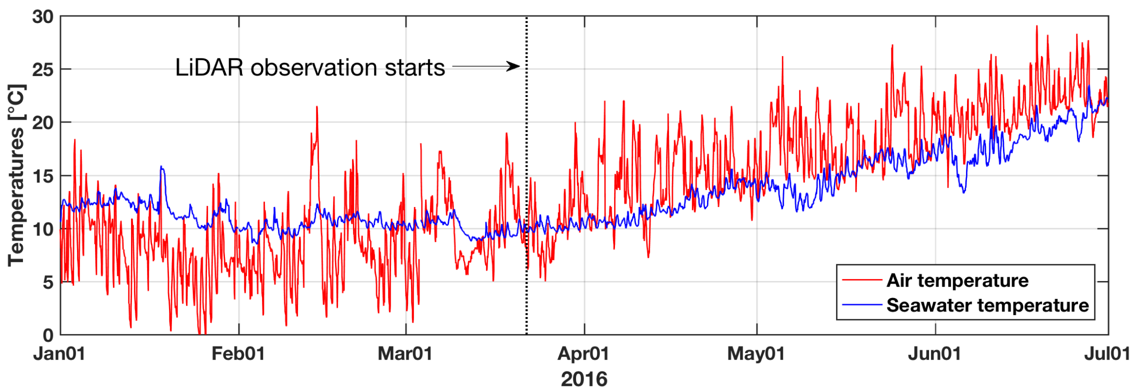

Fig. 6: Comparison of air and seawater temperatures at a 2 m depth from January to June 2016.

Since large differences cannot be seen between the two LiDAR observations with respect to time-series and other basic statistics (results not shown), we will focus on the wind speed ratio between the LiDAR observations. Note that since there is a 3.5 m height difference between their installation levels due to the building height, observations are vertically interpolated onto the same levels using a logarithmic function in order to calculate wind speed ratio at the same height before analysis.

The wind speed ratio for LiDAR#1 to LiDAR#2 as a function of wind direction is shown in Fig. 7. The bin-average and standard deviation were calculated within 5° intervals and plotted in red based on 10-minute observations. In Fig. 6, two peaks with ratios of about 115 to 120% in bin-average can be seen around wind directions of 155 and 325°, which nearly coincide with the directions of the coast.

For these directions, winds measured by LiDAR#1 on the pier top had a long marine fetch length, while those measured by LiDAR#2 were entirely onshore. This result suggests that the fetch length effect can result in an increase in offshore wind speeds of up to 115 to 120% while travelling over water for a long distance. On the other hand, the trough at around 200° might be attributable to the wake from a nearby wind turbine, which has a hub height of 64.5 m and a rotor diameter of 62 m.

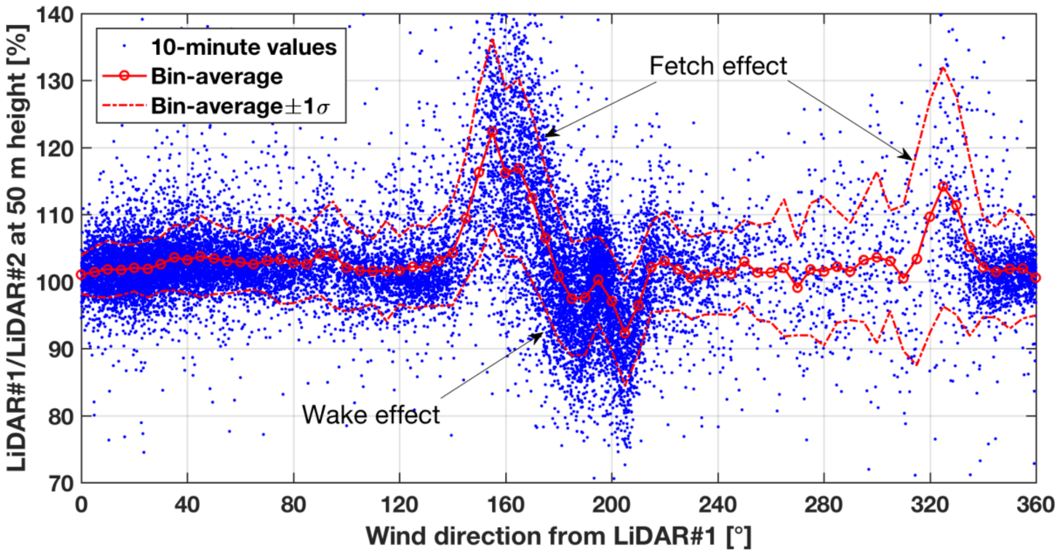

Fig. 7: LiDAR#1 to LiDAR#2 wind speed ratio at 50 m height above mean sea level (MSL) as a function of wind direction. For LiDAR#2, only wind speeds more than 2 m/s were used for our analysis.

The strength of the wake and fetch effects was found to depend significantly on the height when the same relationships are illustrated with different heights. Fig. 8 shows the same relationships as Fig. 7, but with all heights exhibited. From Fig. 8, it can be seen that the variations dependent on wind directions found at a 50 m height become ambiguous as the height increases, but that the wake effect around a direction of 200° disappeared for the heights above 130 m. Moreover, the increase in wind speeds around wind directions of 155 and 325°, which might be associated with the fetch length effects, ultimately declines to a few percentage points at a height of 207 m.

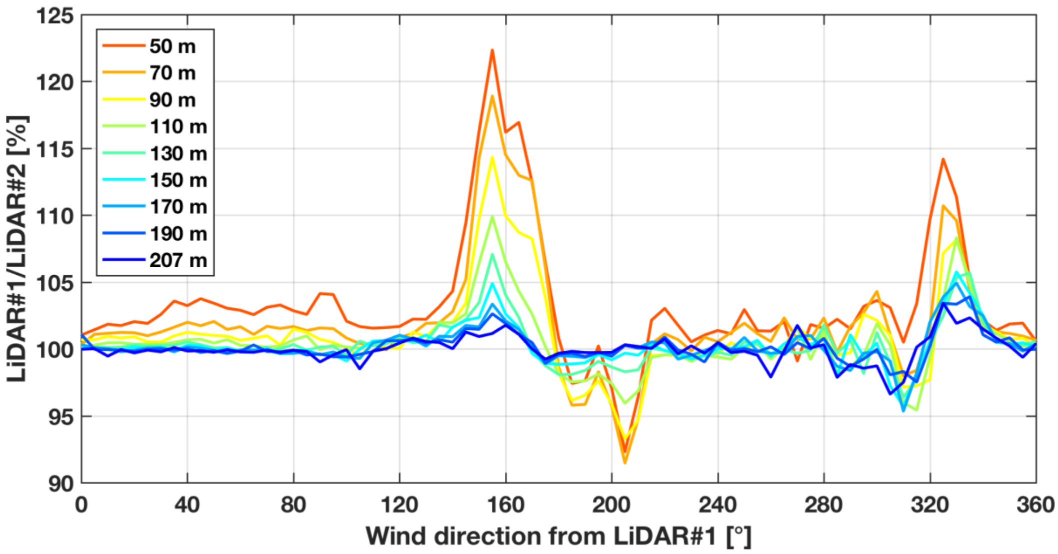

Fig. 8: Bin-averaged LiDAR#1 to LiDAR#2 wind speed ratio as a function of wind direction at heights of 50, 70, 90, 110, 130, 150, 170, 190, and 207 m above MSL.

Figs. 7 and 8 already include implications for investigating the relationship between wind speed increases and fetch length, but they are insufficient for understanding the relationship quantitatively. Accordingly, we next attempted to convert the relationships between wind direction and wind speed ratio to fetch length and wind speed. Since the test region has a rectilinear coastline, the fetch at the top of the pier can be simply defined as a function of wind direction θ as follows:

$$\mathrm{Fetch}(\theta) = L_{pier}/\cos(\theta\text{-}\theta_{pier}\text{-}180°). \quad (1)$$

Here, L_{pier} and θ_{pier} indicate the pier length of 427 m and the heading angle of 59°, respectively. Although the pier is only 400 m long, the fetch length effect for a few kilometers can be analyzed when the characteristics of site's rectilinear coastline are considered.

The wind speed ratio for LiDAR#1 to LiDAR#2 at 50 m height above MSL, as a function of fetch length, is shown in Fig. 9. As can be seen in the figure, the wind speed ratio drops twice for 400 to 650 m fetch lengths due to the turbine wake effects, and increases monotonically for 650 to 1200 m fetch lengths. Moreover, it slightly continues inclining to 120% at a fetch length of 1900 m, after which it appears to become almost constant.

In particular, we noted two interesting features with respect to the fetch length effect in the figure. One is that the offshore winds with short fetch of a few hundred meters or so seems to be strongly influenced by land obstacles such as wind turbines. The other is that the wind speed at a height of 50 m increased up to 120% while traveling over 2 km of water. Moreover, the fetch length effect appears to be saturated at distances exceeding 2 km.

Barthelmie et al. (1996) [1] showed that onshore wind speed at a height of 38 m could increase up to 120% over a long marine fetch length. The result obtained in this study is in near accordance with their result. On the other hand, in terms of the distance relationship to wind speed increases, different results can be found in Barthelmie and Palutikof (1996) [2], who showed that the increase in wind speeds persists for 20 km from a Moore model analysis [5], which is a primitive model for calculating coastal winds near the surface. The saturation distance for the wind speed increase shown in Fig. 9 is considerably shorter than that from their result, which is based on a simple computational calculation.

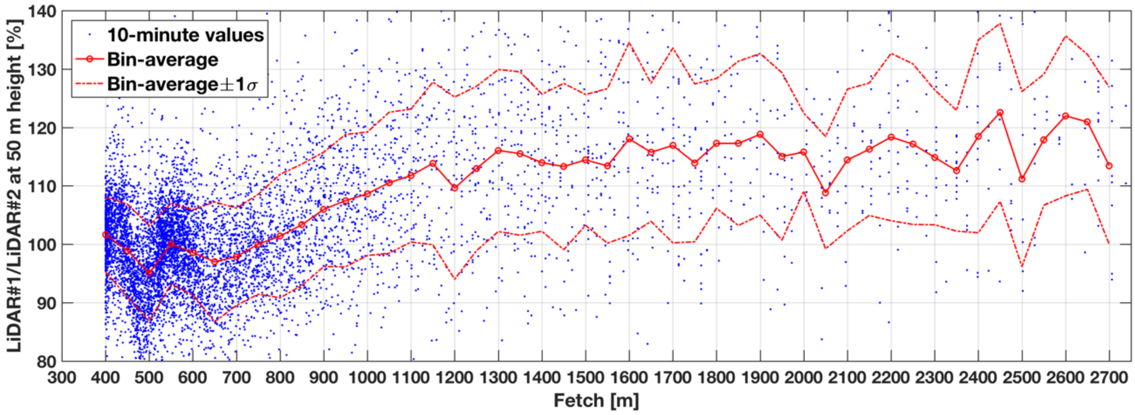

Fig. 9: Wind speed ratio as a function of fetch at a height of 50 m above MSL.

As expected from Fig. 8, the increase of wind speed ratio relevant to the fetch effect found in Fig. 9 becomes unclear as the height increases. The relationships between fetch length and bin-averaged wind speed ratio at heights of 50 to 207 m with an interval of 20 m above MSL are shown in Fig. 10. Due to the previously mentioned reduced data availability for levels higher than 50 m, the plots for 70 to 207 m heights are slightly less stable than those for the lower levels. However, it can unmistakably be seen that the wake and fetch length effects gradually decrease as the height increases. No clear fetch length-dependent difference is found above 130 m in height. Ultimately, the wind speed ratio at 207 m height seems to be independent of both the fetch length and the wake.

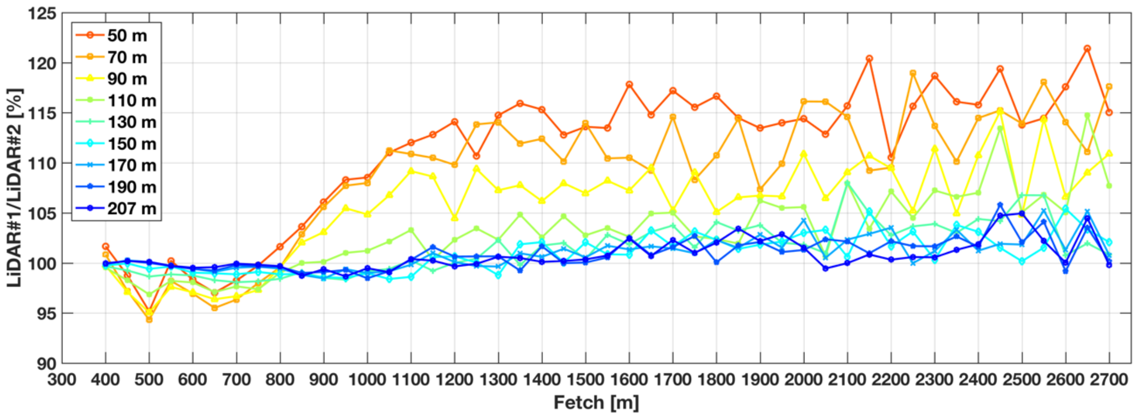

Fig. 11: Bin-averaged wind speed ratio as function of fetch at heights of 50, 70, 90, 110, 130, 150, 170, 190, and 207 m above MSL.

Our analysis of the LiDAR observations revealed that the 50 m wind speed increased up to 120% at a fetch of about 2 km. The question is then how attractive or effective this 120% speed increase from a wind resource usage perspective is. Since it is clear that wind speeds can increase independently of fetch length effects as altitude levels increase, we compared the increase in wind speed resulting from raising height to quantify the advantage of the fetch effect.

Fig. 11 shows mean wind speed profiles (left) and the profiles normalized at the lowest level values (right) for the land sector (215° - 325°). The observations when all heights are available are used for the analysis. The normalized profile for LiDAR#2 shows that the 50 m wind speed increased up to 120% at a 90 m height. This indicates that the fetch length effect over a 2 km distance can be seen as equivalent to raising the height from 50 m to 90 m over land.

Furthermore, if the height is increased up to 130 m height, the value at 130 m increases to 140%. This is of particular note because as taller wind turbines complete development and become available, locating such turbines onshore in coastal areas could provide an acceptable alternative to nearshore wind farm developments in locations where sufficient space is available.

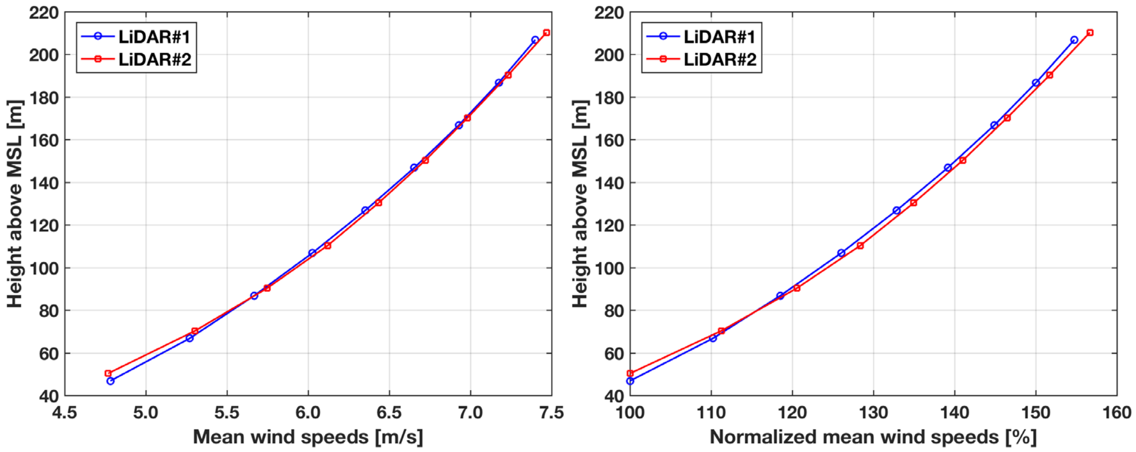

Fig. 12: Absolute (left) and normalized (right) mean wind speed profiles for land sectors (215° - 325°) for the period from March 22 to September 11, 2016 at HORS. The observations when all heights are available are used for the analysis.

4. Conclusions

In this paper, we report of the result of an ongoing coastal wind measurement campaign using two vertical LiDAR devices at a coastal research station (HORS) that is being conducted to investigate increases in wind speed with increasing fetch length from the coast. We began by describing the experimental setup and wind condition at HORS during the six-month measurement period used in this study, after which the increase in wind speed was examined from comparisons of observations recorded from the two vertical LiDAR devices.

The results showed that the 50 m wind speed in this region increased by a factor of up to approximately 1.2 when travelling over a long marine fetch length. In addition, observations taken at the top of the pier were found to be significantly influenced by onshore turbines that are located more than several hundred meters away. Moreover, the increase in wind speed as a function of fetch length was demonstrated via the rectilinear coastline characteristics of this region.

In our results, it was found that the 50 m wind speed on the coast increased monotonically over a 2 km fetch length and was found to reach a ratio of 120% at a 1900 m fetch length. In addition, the fetch length effect was shown to gradually moderate as the height increases. It was also found that the fetch length and wake effects from nearby wind turbines were negligible at heights more than 130 m.

Finally, the impact of the fetch length effect was compared with the height rising effect. In this measurement campaign, we obtained informative and valuable offshore wind observations. In our continuing research, we intend to install a scanning LiDAR to collect more detailed measurements and verify the reproducibility of a mesoscale weather research and forecasting (WRF) model [6] in order to facilitate more comprehensive understandings of coastal winds.

Acknowledgement

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