Accuracy assessment of offshore wind observations partially compensated by MCP method considering data availability

Kota Enoki[1]
Takeshi Ishihara[2]
[1] PhD. Obayashi Corporation, Japan
[2] Prof. The University of Tokyo, Japan

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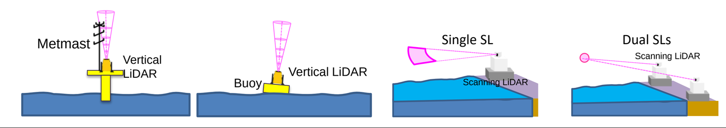
1. Introduction

In Japan, most of offshore promotion area for bottom fixed turbines are in the near-shore areas where the offshore wind speeds are not uniform. Therefore, the dual scanning LiDAR system (DSL) is widely used to measure mean wind speed and wind direction as well as turbulence (**Table 1**). However, the availability of data obtained from DSL tends to be lower than the criteria used to determine whether Key Parameter Indicators (KPIs) are met, which are proposed by the Carbon Trust in Offshore Wind Accelerator project (**Table 2, 3**). Therefore, the missing data must be complemented to achieve high availability.

A common complementation framework is based on the MCP (Measure – Correlate – Predict) method. The uncertainty of the MCP method can be examined using the constructed prediction function. However, it is not clear how to evaluate the final dataset consisting of the observed data and the data predicted by the MCP method.

In this study, a set of formulas is proposed to evaluate the KPIs, such as the coefficient of determination (R^2), slope and offset of linear regression for the partially complemented dataset and is validated using the on-site measurement.

Table 1. Offshore wind measurement technologies.

Type of platform	Bottom fixed	Floating	Onshore	
Type of LiDAR	VL	VL	SL×1	SL×2
Image				
Wind speed	○[3]	○	○[6]	○
Turbulence	○	△[4]	×[8]	○
Post-processed data availability	> 95 %	> 85～90 %[5]	> 90 %	> 80 %
References	Ishihara et al. [1]	Yamaguchi and Ishihara [2]	Mano et al. [6]	Watanabe et al. [7]

VL: Vertical LiDAR. SL: Scanning LiDAR.
○: Applicable. △: Applicable with motion compensations. ×: Inapplicable.

KPIs for evaluation of wind measurements[9]

Table 2. KPIs for accuracy of LiDAR system.

Acceptance criteria	Wind speed		Wind direction		
	Slope	R^2	Slope	Offset	R^2
Minimum	0.97-1.03	> 0.97	0.95-1.05	±10 °	> 0.95
Best practice	0.98-1.02	> 0.98	0.97-1.03	±5 °	> 0.97

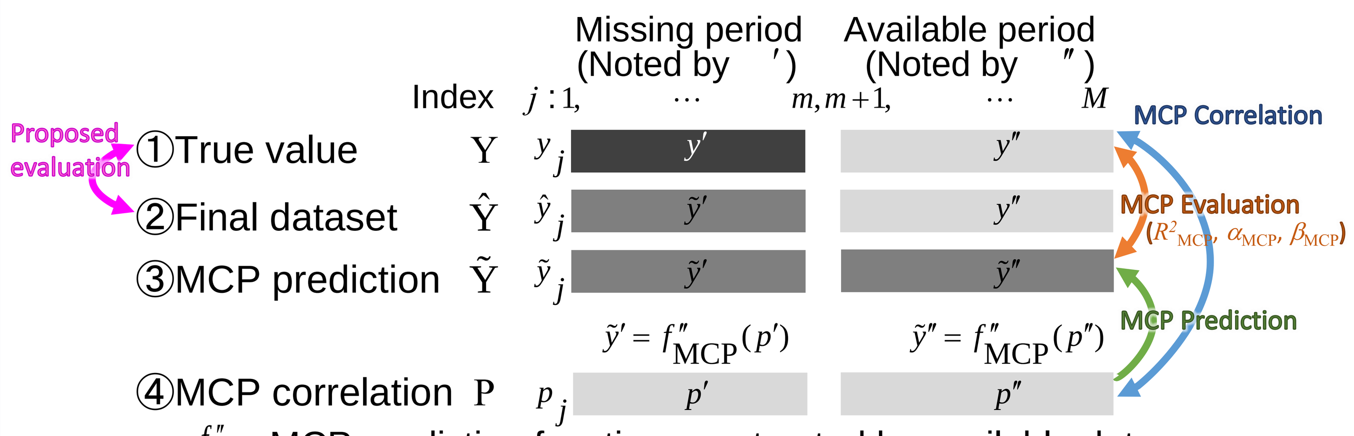
Table 3. KPIs for reliability of LiDAR system.

Stage	System data availability		Post – processed data availability	
	Monthly	Overall	Monthly	Overall
Pre-commercial	≧90 %	≧95 %	≧80 %	≧85 %
Commercial	≧95 %	≧97 %	≧85 %	≧90 %

2. Proposal of equations for evaluation of MCP

2.1 Proposal

The final dataset consists of the data in the available period y'', and complemented data predicted from the nearby observation using the MCP method in the missing period $\tilde{y}'$. In this study, equations for evaluation of the final dataset against true value are proposed.



f''_{MCP} : MCP prediction function constructed by available data.
$R^2_{Avail}, \alpha_{Avail}, \beta_{Avail}$: R^2, slope, offset of dataset ② against ①.
$R^2_{MCP}, \alpha_{MCP}, \beta_{MCP}$: R^2, slope, offset of dataset $\tilde{y}''$ against y''.

Figure 1. Definition of variables and periods in this study.

2.2 Mean and std. dev. of final dataset

The mean and standard deviation of final dataset as a function of the data availability ζ of the observation are derived as **Equation (1) and (2)**.

Mean: $$\bar{y} \simeq \bar{\hat{y}} = \zeta \bar{y}'' + (1-\zeta)\bar{\tilde{y}}' \quad \cdots \text{Eq. (1)}$$

Std. dev.: $$\sigma_y^2 \simeq \sigma_{\hat{y}}^2 = (1-\zeta)\sigma_{\tilde{y}}'^2 + \zeta(1-\zeta)(\bar{y}'' - \bar{\tilde{y}}')^2 + \zeta\sigma_y''^2 \quad \cdots \text{Eq. (2)}$$

2.3 Derivation of formulas

R^2_{Avail}, α_{Avail} and β_{Avail} are derived from their definitions, assuming the mean and std. dev. during the missing period are close to those in the available period for the MCP, the proposed equation can be simplified as shown in **Equation (3) to (5)**.

Proposed equations

R2: $$R^2_{Avail} = 1-(1-\zeta)(1-R^2_{MCP}) \quad \cdots \text{Eq. (3)}$$

Slope: $$\alpha_{Avail} = 1-(1-\zeta)(1-\alpha_{MCP}) \quad \cdots \text{Eq. (4)}$$

Offset: $$\beta_{Avail} = (1-\zeta)\beta_{MCP} \quad \cdots \text{Eq. (5)}$$

Derivation of formulas

In case of high data availability, it is acceptable to assume following conditions.

Approximations ① $\bar{\hat{y}} \sim \bar{y}' \sim \bar{\tilde{y}}' \sim \bar{y}'' \sim \bar{\tilde{y}}''$ ② $\sigma_{\hat{y}}^2 \sim \sigma_y'^2 \sim \sigma_{\tilde{y}}'^2 \sim \sigma_y''^2$

$$R^2_{Avail} = 1 - \frac{\sum_{j=1}^{M}(y_j - \hat{y}_j)^2}{\sum_{j=1}^{M}(y_j - \bar{y})^2} = 1 - \frac{m \sum_{j=1}^{m}(y_j - \bar{\tilde{y}}')^2 m^{-1} \sum_{j=m+1}^{M}(y_j - \tilde{y}_j)^2}{M \sum_{j=1}^{M}(y_j - \bar{y})^2 M^{-1} \sum_{j=m+1}^{M}(y_j - \bar{\tilde{y}}'')^2}$$

(m/M: $1-\zeta$; $\sigma_y'^2\sigma_y^{-2} \sim 1$; $1-R^2_{MCP}$)

$$\alpha_{Avail} = \frac{\sum_{j=1}^{M}(\hat{y}_j - \bar{\hat{y}})(y_j - \bar{y})}{\sum_{j=1}^{M}(\hat{y}_j - \bar{\hat{y}})^2} = (1-\zeta)\frac{\sigma_y'^2}{\sigma_{\hat{y}}^2}\alpha'_{y,\hat{y}} + \zeta\alpha''_{y,\hat{y}}\frac{\sigma_y''^2}{\sigma_{\hat{y}}^2} + (1-\zeta)\zeta\frac{(\bar{y}'' - \bar{\tilde{y}}')^2}{\sigma_{\hat{y}}^2}$$

($\frac{\sigma_y'^2}{\sigma_{\hat{y}}^2} \sim 1$; $\alpha'_{y,\hat{y}}$: α_{MCP}; $\alpha''_{y,\hat{y}} = 1$; $\frac{\sigma_y''^2}{\sigma_{\hat{y}}^2} \sim 1$; $(\bar{y}'' - \bar{\tilde{y}}')^2 \sim 0$)

$$\beta_{Avail} = \bar{y} - \alpha_{Avail}\bar{\hat{y}} \simeq (1-\alpha_{Avail})\bar{\hat{y}} = \sigma_{\tilde{y}}'^2\sigma_{\hat{y}}^{-2}\bar{\hat{y}}\bar{y}''^{-1}(1-\zeta)(\bar{y}'' - \alpha_{MCP}\bar{y}'')$$

($\sigma_{\tilde{y}}'^2\sigma_{\hat{y}}^{-2} \sim 1$; $\bar{\hat{y}}\bar{y}''^{-1} \sim 1$; β_{MCP})

3. Verification of equations for evaluation of MCP

3.1 On-site measurement

Figure 2 and **Table 4** show an overview of the observations by the VL and the met mast used for verification. The location is about 150 m inland from the coastline of the Sea of Japan in Akita Prefecture. The observation period was one year, during which the VL showed good agreement with the mast at a horizontal distance of 15 m. The correlation of wind speed and wind direction by the VL and mast are shown in **Figure 3**.

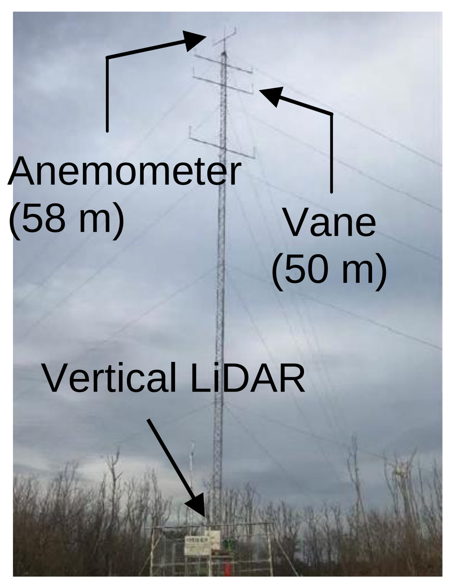


Figure 2. Met mast and vertical LiDAR.

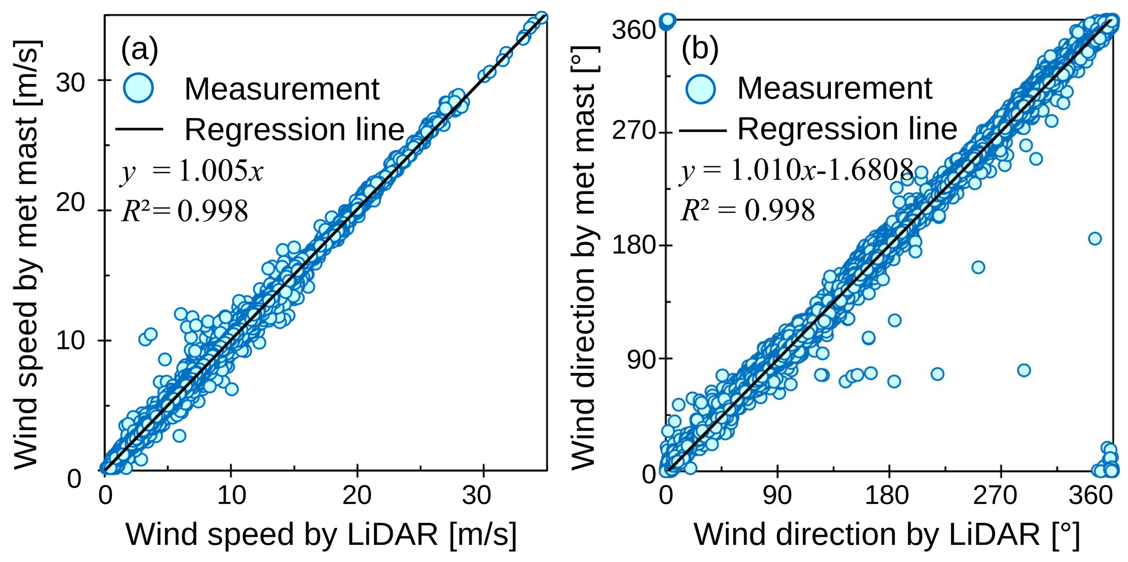


Figure 3. Comparison of (a) 10 min. mean wind speed at 58 m and (b) wind direction at 50 m obtained from the met mast and the vertical LiDAR.

Table 4. Summary of on-site measurements.

Observation	Met mast	Vertical LiDAR
Location	N 40.05025 °, E 139.93232 °	
Measured items	Mean and standard deviation of wind speed and mean direction in 10 minutes	
Instruments	Anemometer (NRG Class1). Vane (NRG 200M)	Vertical LiDAR (Leosphere Wind Cube V2)
Heights	58m (Wind speed), 50m (Direction)	40/50/58/70/90/110/130/140/150/170/190m

3.2 Methodology

As for the validation, the observation at 58 m by the VL is taken as the true value. Observations at 90, 150 and 190 m are used as the reference data for complementation. **Table 5** shows data availability, statistical indices of the reference data against true value. R^2 decreases as the reference altitude increases.

Table 5. Statistics of wind data at different heights against those at the target height 58 m.

Height [m]	Availability [%]	Statistical indices against 58 m						
		Mean wind speed		Mean wind direction			Std. dev. of wind speed	
		Slope	R^2	Slope	Offset	R^2	Slope	R^2
190	96.44	1.094	0.866	0.927	21.65	0.937	1.013	0.786
150	98.33	1.077	0.913	0.953	14.11	0.965	1.002	0.849
90	99.16	1.038	0.981	0.983	5.30	0.994	1.003	0.942
58	99.21	1.000	1.000	1.000	0.00	1.000	1.000	1.000

Validation cases to examine the applicability of proposed equation for various data availabilities and statistical properties of complementation are prepared as follows.

a) Case setup at 58m height

- Target timeseries observation is divided into 10 segments.
- The availability groups of 10, 20, …, 90% (Total 9 groups) are defined.
- For each availability group, ①~⑩ of timeseries with different window are defined. Then, observation of target point with various missing period are generated for 900 cases in total.

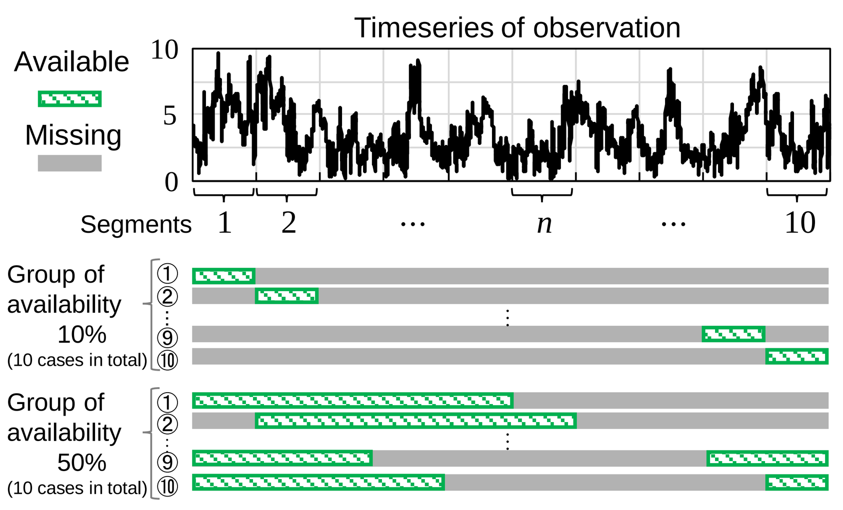


Figure 4. Examples of case setup of availability 10% and 50%

b) Complementation of missing data

- In each case, three final datasets are generated with different reference data at 90, 150 and 190 m.
- Using generated (Y) and reference (P) data in available period, MCP prediction functions for wind speed, direction and std. dev. of wind speed are constructed for each group.

Wind speed: $U_{\hat{Y}} = a(\theta_P)U_P + b(\theta_P)$

Wind direction: $\theta_{\hat{Y}} = \theta_P + \Delta\theta(\theta_P)$

Std. dev. of wind speed: $\sigma_{\hat{Y}} = c(\theta_P)\sigma_P + d(\theta_P)$

MCP prediction functions

c) Evaluation

- Indices of R^2, α, β are calculated by the true value and the final dataset.
- The predicted indices by proposed equations are compared to those obtained from the final dataset directly.

3.3 Verification results

a) Evaluation for mean and standard deviation

The annual mean and std. dev. estimated by Eq. (1) and (2), are compared with those calculated directly from timeseries, and estimated annual std. dev. are shown in **Figure 5**. Both agree well.

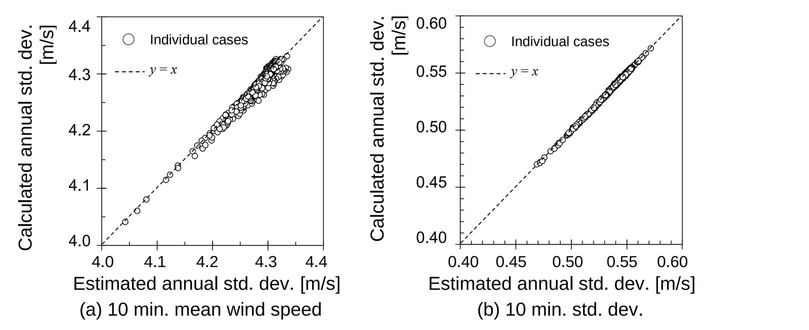


Figure 5. Comparison of the annual standard deviation of (a) 10 min. mean speed (b) 10 min. std. dev. obtained from timeseries and estimated by Eq. (2).

b) Results estimated by proposed formulas

Comparisons of the R^2, slope and offset calculated from the predicted and true timeseries of Y, and R^2_{Avail}, α_{Avail} and β_{Avail} evaluated by proposed formulas are shown in **Figure 6** for the 10-minute mean wind speed and in **Figure 7** for the mean wind direction. As the availability approaches 100 %, the estimated value approaches the actual value.

When the data availability before complementation is high, estimated values by the proposed formulas show good agreement with the actual values. When the correlation between the reference and target data is high, the estimated values agree well with the actual values.

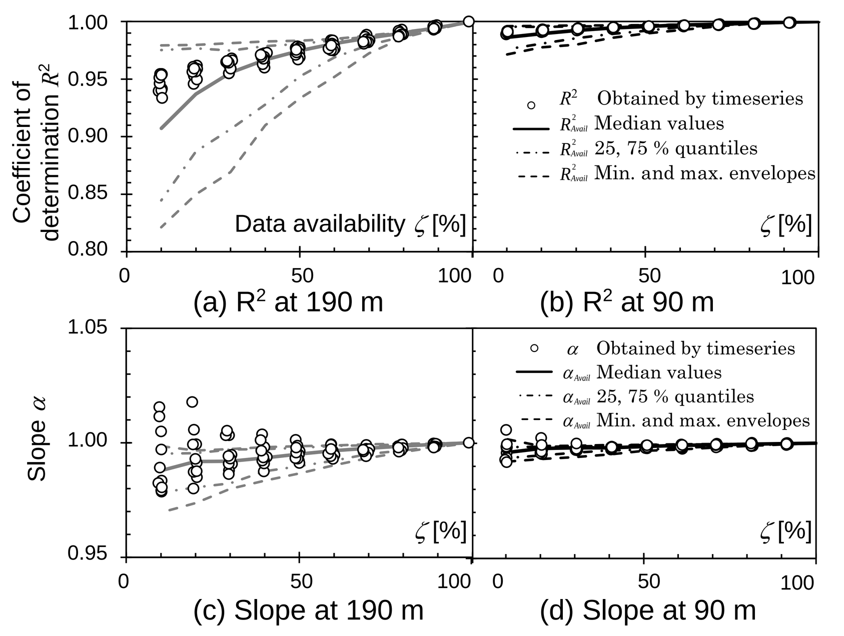


Figure 6. R^2, slope of timeseries (Symbols) and estimations by the proposed formulas (Lines) for 10 minutes wind speed. Left column (a), (c), (e) show data at 190m referred in MCP. Right column (b), (d), (f) present data at 90m.

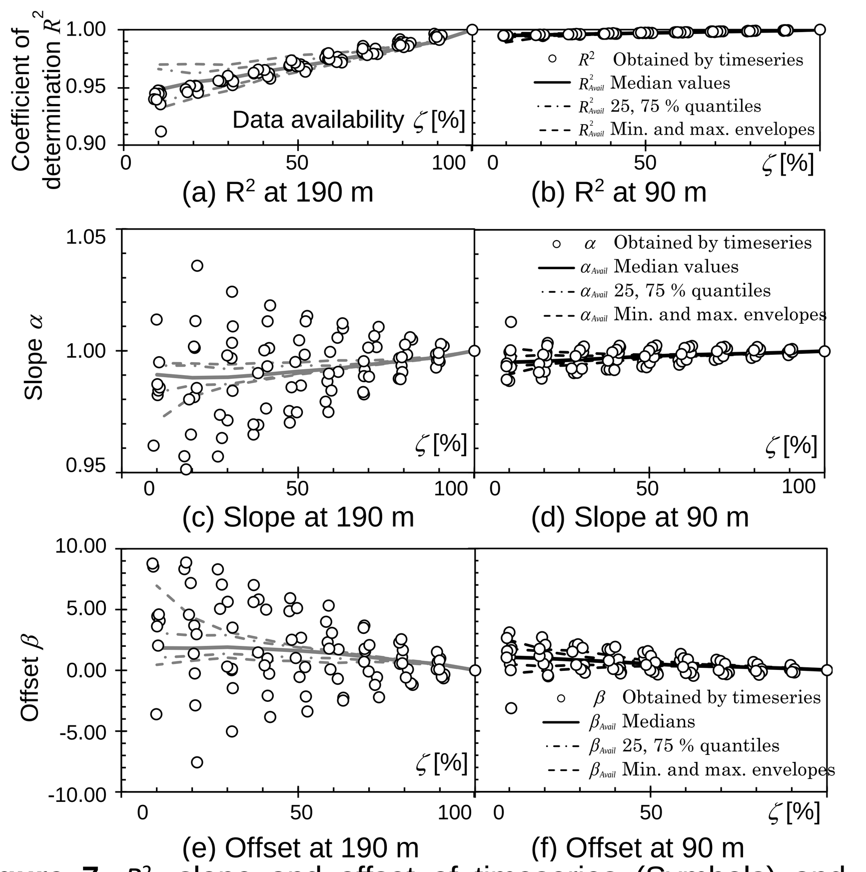


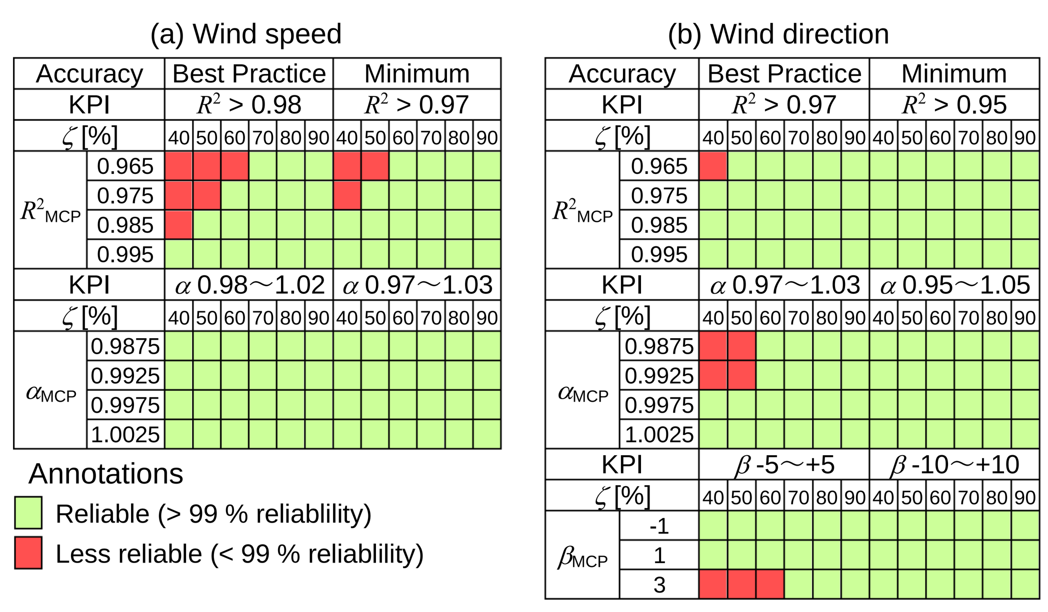
Figure 7. R^2, slope and offset of timeseries (Symbols) and estimations by the proposed formulas (Lines) for 10 minutes wind direction. Left column (a), (c), (e) show data at 190m referred in MCP. Right column (b), (d), (f) present data at 90m.

c) Certainty of proposed formulas

The bin method which analyzes the difference between true value and predicted value, is applied to examine certainty of the proposed equations. Assuming that the differences in the bins follow a normal distribution, 99% quantile is calculated. The predictability of KPI is defined as high (reliable) when the 99 % quantile of predicted values in a bin actually satisfied the criteria.

When the availability is higher than 60 % for both wind speed and direction, the result by the proposed equation has a confidence interval of 99 %, which indicates that the final dataset can be accurately evaluated by the proposed formulas.

Table 6. KPI estimated by proposed equations.



4. Conclusions

The formulas for evaluating the R^2, slope and offset of the data after complementation using the MCP method are proposed to consider the data availability of observations. Validations using the on-site measurements show that when the data availability before completion is high or when the correlation with reference data is high, the predicted KPIs by the formulas agree with the actual values, and the KPI of the final data set after completion by the MCP method can be accurately evaluated by the proposed formulas.

References

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