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Stochastic spatio-temporal model for wind speed variation in the Arctic

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ABSTRACT

A spatio-temporal transformed Gaussian field has been proposed to model wind variability in the northern North Atlantic, but it does not accurately describe the extreme wind speeds attributed to tropical storms and hurricanes. In Rychlik and Mao (2018), this model was generalized by adding certain number of random components to model rare events with extreme wind speeds or severe storms, and was named the hybrid model.

In this study, these models are further developed and validated to properly describe the variation of wind speeds in the Arctic area. In most locations, the transformed Gaussian field is a sufficiently accurate model. However, in some regions, e.g., the Laptev and Beaufort Seas, this model severely underestimates the frequencies of extreme wind speeds. Therefore, the hybrid model is further improved to add Poisson distributed random storm events to describe the wind variation in these regions, and is named as the Poisson hybrid model. There are also locations, e.g., along the east coast of Greenland, where the frequencies of high wind speeds are severely overestimated by the transformed Gaussian model. It is shown that this model can be used to estimate the long-term distribution of wind speeds, predict extreme wind speeds and simulate the spatio-temporal wind fields for practical applications.

1. Introduction

Strong winds over the oceans can create dangerous metocean conditions for ships and offshore engineering activities, such as oil and gas drilling rigs or renewable energy installations. As sea ice declines, human activities in the Arctic Ocean are increasing, the Arctic shipping is attracting increasing number of sailing ships, and Arctic offshore development is also increasing. All these activities bring very urgent demands for the development of reliable models for wind and wave loads. Statistical properties of wind speed vary in terms of geographic location and season. The median and other statistics, e.g., standard deviation and return values, are important parameters describing the wind climate. These statistics of wind speed in the Arctic have recently been presented in, e.g., Hughes and Cassano (2015) and Kislov and Matveeva (2016). For practical engineering applications such as estimating the average wind energy that could be harvested at a fixed location, the long-term (yearly) wind speed distribution is needed. In this case, a Weibull distribution often gives a good description of observed wind speeds (Takle and Brown, 1978). Other models have been also proposed (e.g., recently by Drobinski (2015)) to describe the wind speed variability if the Weibull model is not sufficient accurate. It is shown that the Weibull distribution often underestimates the frequency of very high wind speeds in the Arctic. Another useful wind characteristic is the expected frequency of episodes of wind speed exceeding a given value; see Appendix A for details. The frequency is often called the crossing frequency. A ratio of these two characteristics gives an estimate of the expected duration of a storm.

Both the long-term distribution and the crossing frequency are one-dimensional characteristics that change "slowly" across locations and seasons. However, there are practical engineering problems that require multivariate characteristics, e.g., the joint distribution of wind speeds at distinct locations and times. For example, these distributions are needed to evaluate the wind statistics encountered by a sailing vessel (Mao and Rychlik, 2016), and for predicting ship speeds (Mao et al., 2016). In such cases, spatio-temporal models often based on well understood transformed Gaussian models can be used to describe these wind statistics. Such models can be used to evaluate frequencies and distributions of various wind storms' characteristics (Brodtkorb et al., 2000; Podgórski and Rychlik, 2016). The popular transformations proposed by Brown et al. (1984), Winterstein (1988) etc., are frequently used in engineering literature. For example, the exponential transformation proposed by Brown et al. (1984) was successfully used in Mao and Rychlik (2016) to model wind speed distributions in the North Atlantic. At offshore locations of the Arctic, the modified Winterstein's

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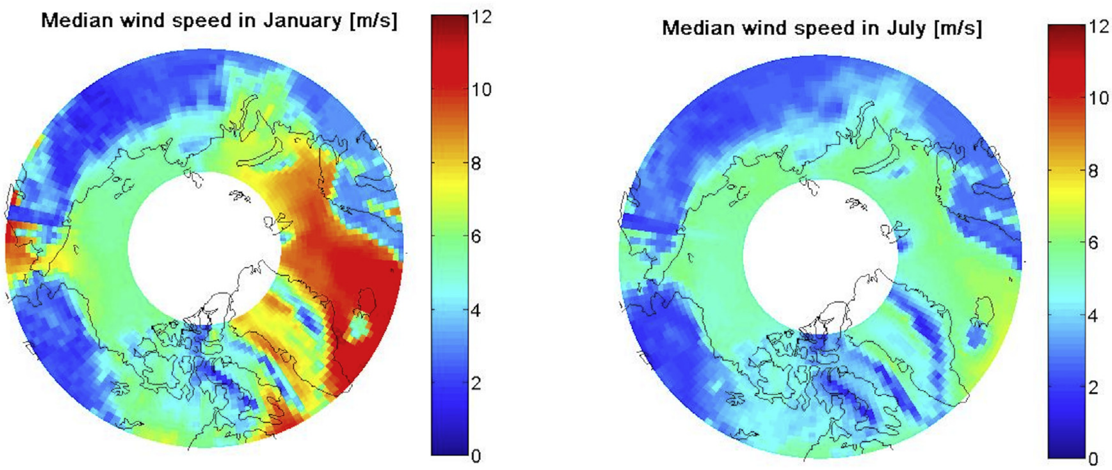

Fig. 1. Seasonal and geographic variability of the median wind speed in the Arctic area.

transformation gives more accurate predictions of extreme winds, while the Brown's exponential transformation works better in inland locations. In approximately 8% of the Arctic area, the transformed Gaussian models underestimate the extreme wind speeds.

In this study, the Poisson hybrid model is proposed to model the wind variation in the Arctic. In this model, the daily wind speed variation is modelled by the transformed Gaussian field, and a Poisson number of random components is then added to model the rare events of extreme wind speeds. The Poisson hybrid model is compared with the previously proposed hybrid model in Appendix C. Various transformed Gaussian models are briefly presented in Section 2, and Section 3 presents some details of the Poisson hybrid model. Based on the proposed Poisson hybrid model, the Rice's method can be used for predicting extreme wind speeds and estimating the long-term wind distribution in the Arctic regions. Section 4 briefly reviews how to use the model to estimate the long-term wind speed distribution and the crossing frequency, and to derive 100- or 1000-year return values (the extreme wind speeds). The accuracy of the model is validated in Section 5 by comparing the wind speed characteristics observed in the data with those evaluated from the fitted model. Section 6 presents examples of simulating spatio-temporal wind fields by the proposed Poisson hybrid model. Conclusions, the reference list and four appendixes close the paper.

2. Various transformed Gaussian models for wind speed variability

Transformed Gaussian and hybrid models can be fitted to various data sources, e.g., the wave heights measured from satellites (Baxevani et al., 2005, 2008). In this study, the wind speed (referring to the 10-min average wind speed with a unit of m/s) is investigated with these models. The hindcast wind data over 26 years (1990–2015) with a 0.75-degree and 6-h resolution from the ECMWF ERA-Interim reanalysis dataset (Dee et al., 2011) are used. The distribution of wind speed in a large geographic region such as the Arctic depends on the season and geographic location $\mathbf{p} = (t_\mathbf{p}, x_\mathbf{p}, y_\mathbf{p})$. However, at shorter scales of hours and kilometers, the wind speed can be considered stationary for a period of approximately one month and in a region of several degrees in diameter.

Then, the wind speed variation can be described by a transformed Gaussian model using monotonic transformation $x = g(w)$ if the field

$$X_\mathbf{p}(t, x, y) = g(W(t_\mathbf{p} + t, x_\mathbf{p} + x, y_\mathbf{p} + y)) \tag{1}$$

has standard Gaussian distribution. The local transformed Gaussian model is fully defined if the transformation g and the correlation structure of the Gaussian field $X_\mathbf{p}(t, x, y)$, i.e.,

$$\rho(t, x, y) = E[g(W(t_\mathbf{p}, x_\mathbf{p}, y_\mathbf{p})\cdot g(W(t_\mathbf{p} + t, x_\mathbf{p} + x, y_\mathbf{p} + y)],$$

are specified.

2.1. Exponentially transformed Gaussian model

In Rychlik and Mao (2018), the Brown's exponentially transformed Gaussian model was proposed to model the wind speed W in the neighbourhood of a location $\mathbf{p}$, viz.

$$W(t_\mathbf{p} + t, x_\mathbf{p} + x, y_\mathbf{p} + y)^{a_\mathbf{p}} = m_\mathbf{p} + \sigma_\mathbf{p} X_\mathbf{p}(t, x, y), \tag{2}$$

Normally, the exponent a is of the range $0 < a_\mathbf{p} < 2$. When a is very small, the extreme wind prediction based on this transformation becomes very sensitive; i.e., even small estimation errors in a may cause big errors in predicted extreme wind speeds. Empirically, by setting $0.4 < a_\mathbf{p} < 2$ can limit this problem without affecting the accuracy of the transformation model. Then the Brown's exponential transformation can be also written as

$$g(w) = (w^{a_\mathbf{p}} - m_\mathbf{p})/\sigma_\mathbf{p}. \tag{3}$$

The parameters $a_\mathbf{p}$, $m_\mathbf{p}$ and $\sigma_\mathbf{p}^2$ are estimated by the method of moments. All parameters defining the model depend on the location $\mathbf{p}$ and are estimated "pointwise". For a given location $\mathbf{p}$, the transformation exponent a is first estimated to satisfy the criterion that the skewness of W^a be zero; then, m, σ^2 are set equal to the mean and variance (monthly) of the transformed wind speeds W^a. It should be noted that for the applications in which the model is used to predict extreme wind speeds by the model, the parameters are smoothed over a spatial neighbourhood with a radius of approximately 3°. The parameter $m_\mathbf{p}$ can be evaluated from the median wind speed. For example, Fig. 1 presents the median wind speeds in January and August in the Arctic, and Fig. 2 shows the variability of parameter $a_\mathbf{p}$. The variability of the standard deviation of the transformed wind speed $\sigma_\mathbf{p}$, which varies in both time and space, is presented in Fig. 3.

The exponential transformation has been successfully applied in the North Atlantic. However, in many Arctic locations, the exponential transformation does not work well; i.e., the distribution of $g(w)$ is not Gaussian, while the kurtosis of the exponentially transformed wind speeds often exceeds the Gaussian threshold (three), leading to an underestimation of the frequency of high wind speeds. Therefore, in this study, the Brown's exponential transformation is superposed with the Hermite transformation proposed by Winterstein (1988). This transformation is a monotonic cubic polynomial that is calibrated such that the first four moments (mean, variance, skewness and kurtosis) of the transformed model are equal to the moments of the data.