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Application of the spectral correction method to reanalysis data in south Africa

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ABSTRACT

In connection with applying reanalysis data for extreme wind estimation, this study investigates the use of a simple approach that corrects the smoothing effect in numerical modeling through adding in missing spectral information for relatively high, mesoscale frequencies. This approach, called the spectral correction method, has been applied in the wind energy community for estimating the design winds. Two particular aspects are examined, firstly the diurnal spectral peak and then the meso-microscale interface. Both aspects provide challenges for the application of the method, and the purpose of this study is to evaluate the applicability of the method to the relevant region. The impacts from the two aspects are investigated for interior and coastal locations. Measurements from five stations from South Africa are used to evaluate the results from the spectral model $S(f)=af^{-5/3}$ together with the hourly time series of the Climate Forecast System Reanalysis (CFSR) 10 m wind at 38 km resolution over South Africa. The results show that using the spectral correction method to the CFSR wind data produce extreme wind atlases in acceptable agreement with the atlas made from limited measurements across the country to a temporal resolution of 1 h. However, the modeled data tend to underestimate the diurnal peaks in the coastal areas, with a resultant underestimation of the 1:50-year wind speed. Measurements, even of limited length, could improve the estimate. Lastly, the validity of using the spectral model into higher frequencies is limited by the spectral gap between the meso- and microscale.

1. Introduction

This paper investigates a series of issues in obtaining a map of the 50-year wind for an area using numerical model data. The 50-year winds here refer to the requirements in international design criteria; they are 1 h or 10 min values, at a height of 10 m, corrected to a homogenous surface with a roughness length of e.g., 5 cm, namely, the so-called standard condition (Eurocode, 1995; Miller, 2003; Mann et al., 2004; Larsén et al., 2013c).

The spectral behaviors of wind time series in the mesoscale range have been studied for decades, in experiments (Nastrom and Gage, 1985; Gage and Nastrom, 1986; Högström et al., 1999; Wikle et al., 1999; Larsén et al., 2013a), theory (Lindborg, 1999; Lindborg et al., 2010) and numerical modeling (Tung and Orlando, 2002; Skamarock, 2004). There have been interests in the implications of the mesoscale spectral studies on wind engineering, regarding the estimation of extreme wind values (Harris, 2008, 2010; Baker, 2010). The spectral correction method was developed by Larsén et al. (2012) to correct the smoothing effect embedded in the mesoscale modeling, to eventually estimate extreme winds using model data. In Larsén et al. (2012), this smoothing effect was shown as the tapered-out power spectrum in the mesoscale range, reflecting the missing wind variability for the scales from about half a day to higher time frequencies. A brief introduction to the spectral correction method is given in this paper in Section 3; the core of this method is to add in the missing variability by replacing the power spectrum calculated from the modeled wind time series in the mesoscale range with the corresponding spectrum from measurements, starting at frequency fc and ending at frequency fh, if measurements are available. This approach is applicable where even measurements as short as a few months are available. In the absence of available measurements, a spectral model was recommended for $fc \le f \le fh$, with f the frequency

$$S(f)=af^{-5/3} \tag{1}$$

where S(f) is the power spectrum as a function of f, and a is a coefficient. The $-5/3$ dependence of the power density on f in a log–log scale, or in most studies on the wave number k, describes the mesoscale spectral behavior that has long been investigated in numerous experimental and theoretical studies (e.g., Gage and

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Nomenclature

A	dimensionless parameter used in the geostrophic drag law
B	dimensionless parameter used in the geostrophic drag law
f	frequency
f_c	the starting (lower) frequency for replacing the modeled spectrum
f_h	the ending (higher) frequency for replacing the modeled spectrum
f_{cor}	the Coriolis parameter
$E(k)$	power density as a function of wave number k
G	the geostrophic wind
k	wave number
h	mean elevation within a grid box area of 36 km^2
m_0	the zero-order spectral moment
m_2	the second-order spectral moment
q	the spectral bandwidth parameter
s_o	speed-up coefficient caused by orography
s_r	speed-up coefficient caused by roughness change
$S(f)$	power spectrum as a function of frequency f
SE	the smoothing effect
T	the integral time scale
T_0	the basis period of one year
T_a	the averaging time
τ	time
u_{mod}	modeled wind speed at height z
u_z	wind speed at height z
$\overline{U}$	mean wind speed
$\overline{U}_{max}$	the mean annual maximum wind speed
$\overline{U}_{max,1}$	the mean annual maximum wind speed without spectral correction
$\overline{U}_{max,2}$	the mean annual maximum wind speed after the replacement of spectrum in the range of f_c and f_h
U_0	the mean background wind speed
U_{50}	the 50-year wind with the spectral correction
$U_{50,M}$	the 50-year wind without the spectral correction
u_*	the friction velocity
z	height in m
z_0	roughness length
κ	von Kármán constant
ρ	the autocorrelation coefficient of a time series
ω	the radian frequency $\omega = 2\pi f$
σ	the standard deviation of the wind speed time series
σ_h	the standard deviation of the elevation at 3 km resolution within a grid box of 36 km^2

Nastrom, 1986; Lindborg, 1999; Larsén et al., 2013a). In these studies, the spectral slope changes from $-5/3$ in the mesoscale to -3 towards synoptic and planetary scales. Generally speaking, the "mesoscale" ranges from a couple of kilometers to a couple of hundreds of kilometers, between the "microscale" and "macroscale". Examples of typical mesoscale meteorological phenomena include convective systems and hurricanes (Orlanski, 1975). The typical durations of mesoscale phenomena vary from minutes to hours. From the perspective of the power spectrum, the mesoscale range is characteristic of the $-5/3$ slope in a log–log coordinate (Eq. (1)) (e.g., Gage and Nastrom, 1986; Lindborg, 1999; Larsén et al., 2013a). In higher frequencies, the mesoscale range is followed by a "spectral gap" (der Hoven, 1956; Courtney and Troen, 1990; Baker, 2010) and microscale spectrum (e.g., Kaimal and Finnigan, 1994). There are no fixed boundaries for this mesoscale range at the low and high frequency ends, since the boundaries depend on the types of meteorological phenomena that are active. In the absence of measurements, identification of the interfaces between different ranges (micro- to mesoscale, and meso- to macroscale) is important for the application of the spectral correction method, since f_c and f_h need to be defined.

In Larsén et al. (2012), f_c was parameterized with the scale of the dominant local weather through the integral time-scale T. Conventionally, this scale is calculated as $T = \int_0^\infty \rho(\tau) d\tau$, with τ the time and ρ the autocorrelation coefficient (Pope, 2000; Kristensen et al., 2002; Larsén et al., 2013a, 2013b). Measurements in Denmark show that T is about 0.6 days for winter months and 0.8 days for summer months (Larsén et al., 2013a). On the other hand, f_h is related to the location of the "spectral gap". Whereas it is important, but relatively easy to find f_c for a particular modeled dataset used here (Section 3.2), one major focus of this study is to investigate the sensitivity of f_h in the vicinity of the interface of the meso to micro scales, in other words, the "resolvable scales" in connection with the spectral correction method.

It was argued in Larsén et al. (2012) that, in principle, this method can also be applied to global reanalysis data. However, the coarser resolution of the global reanalysis data indicates larger uncertainty in the mean wind as well as the zero- and second-order spectral moments calculated from a spectrum with $f > 1$ year^{-1}, with both used in the calculation of the smoothing effect of mean annual maximum wind (see Eq. (2) in Section 3). Outputs from high resolution mesoscale models are therefore preferred. However, a high resolution mesoscale model data is not always available and computationally expensive to obtain. Therefore, the considerable amount of global reanalysis data offers an attractive alternative.

In line with one of the goals in the Wind Atlas of South Africa (WASA) project, namely, to improve the existing extreme wind atlas (1h values over standard condition) based on limited measurements, in our previous study, Larsén et al. (2013b), various global reanalysis data sets were investigated in the application of the spectral correction method. These include the Climate Forecast System Reanalysis (CFSR) data (Saha et al., 2010a, 2010b), NCEP/NCAR (National Center for Environmental Prediction/National Center for Atmospheric Research) reanalysis and ERA-40 (European Center for Medium-Range Weather Forecasting Reanalysis) data. These global reanalysis products can compensate for the limitations of estimations from measured data, which could be compromised by quality, record lengths, and and spatial coverage. In Larsén et al. (2013b) it was found that the CFSR winds, with much higher temporal and spatial resolution (1 h and 38 km, respectively), outperform the NCEP/NCAR and ERA-40 data and together with the generalization process (Badger et al., 2010; Larsén et al., 2013c), they produce an extreme wind atlas at the standard condition (at 10 m, with a roughness length of 5 cm, see Section 4.3) that conform the best with the results from the measured data. In Larsén et al. (2013b), the spectral correction was done uniformly for all grid points with $f_c = 1.1$ day^{-1} and $f_h = 12$ day^{-1} using Eq. (1), thus correcting the estimate to an effective resolution of 1 h.

In the development of the spectral correction method in Larsén et al. (2012), the focus was mostly on offshore conditions, in order to avoid the issues other than the smoothing effect of the various mesoscale models, e.g., the differences caused by the land schemes in the models. However, here, we are primarily interested in interior and coastal land conditions. There are a variety of terrain