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Evaluating anemometer drift: A statistical approach to correct biases in wind speed measurement

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ABSTRACT

Recent studies on observed wind variability have revealed a decline (termed "stilling") of near-surface wind speed during the last 30–50 years over many mid-latitude terrestrial regions, particularly in the Northern Hemisphere. The well-known impact of cup anemometer drift (i.e., wear on the bearings) on the observed weakening of wind speed has been mentioned as a potential contributor to the declining trend. However, to date, no research has quantified its contribution to stilling based on measurements, which is most likely due to lack of quantification of the ageing effect. In this study, a 3-year field experiment (2014–2016) with 10-minute paired wind speed measurements from one new and one malfunctioned (i.e., old bearings) SEAC SV5 cup anemometer which has been used by the Spanish Meteorological Agency in automatic weather stations since mid-1980s, was developed for assessing for the first time the role of anemometer drift on wind speed measurement. The results showed a statistical significant impact of anemometer drift on wind speed measurements, with the old anemometer measuring lower wind speeds than the new one. Biases show a marked temporal pattern and clear dependency on wind speed, with both weak and strong winds causing significant biases. This pioneering quantification of biases has allowed us to define two regression models that correct up to 37% of the artificial bias in wind speed due to measurement with an old anemometer.

1. Introduction

Near-surface (i.e. ~10-meter height) wind speed has declined on average −0.140 meter per second per decade ($m\,s^{-1}\,dec^{-1}$) over continental surfaces in the last 30–50 years (McVicar et al., 2012); a phenomenon termed "stilling" for the first time by Roderick et al. (2007). The drivers behind this weakening in observed wind speed have been partly attributed to: (i) changes in land surface friction force because of forest growth, urbanization and other land use changes (Vautard et al., 2010; Bichet et al., 2012; Wever, 2012); (ii) decadal variability of atmospheric circulation (Lu et al., 2007; Azorin-Molina et al., 2014, 2016); (iii) increase of aerosol emissions and greenhouse gas concentrations (Jacobson and Kaufman, 2006; Xu et al., 2006); (iv) decrease of the spatial variance in both atmospheric pressure and air temperature (Kim and Paik, 2015); (v) positive trends in available soil water (Shuttleworth et al., 2009); (vi) astronomical changes (Mazzarella, 2007); and (vii) instrumental issues including technological improvements of wind sensors, maintenance and calibration issues, shifts in measurement sites, and time intervals at which data is stored (Wan et al., 2010; Azorin-Molina et al., 2017a). However, the causes of stilling remains uncertain as all these issues are likely occurring simultaneously with varying spatio-temporal variance. Moreover, some studies have recently claimed that this terrestrial stilling has broken in some regions (Kim and Paik, 2015; Dunn et al., 2016; Azorin-Molina et al., 2017b). Therefore, further research to assess and, particularly, improve the attribution of wind speed trends and cycles is strongly needed.

Among the instrumental artefacts related to the loss of cup anemometer performance, Pindado et al. (2014) pointed out three issues that affect the accuracy of wind speed measurements: (i) wear and tear with the internal anemometer bearings (i.e., degrading its rotor) and, secondarily, the mass addition of dirt to the cups (i.e., changing its aerodynamics); (ii) rotor damage due to severe storms, hail or lightning; and (iii) failure at the opto-electronic output signal system. The first impact

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of anemometer drift (i.e., bearings malfunctions) has only been superficially discussed as a possible cause of stilling (Wan et al., 2010; Azorin-Molina et al., 2014), and because of its complexity, to date, no research has attempted to quantify and minimize the contribution of anemometer degradation to the stilling phenomenon. Pindado et al. (2014) noted that the gradual drift of cup anemometers occurred due to instrument ageing and results in a progressive and artificial decrease of measured wind speed over time because of the reduction in the rotational speed. This degradation (i.e., increase of friction) has most impact in weak winds and, consequently, increases the periods of observed calms (Pindado et al., 2014). In theory, National Weather Services apply a maintenance program to periodically inspect and/or recalibrate cup anemometers to ensure accuracy of instruments. However, because of the limited metadata about field calibration of cup anemometers (e.g., frequency of recalibrations, etc.; Azorin-Molina et al., 2014), and even assuming that annual inspections are conducted, as recommended by the World Meteorological Organization (WMO, 2008), anemometer ageing is a concern when analyzing long-term wind speed variability and trends. Therefore, anemometer drift is hypothetically a partial cause of the stilling that deserves to be assessed and corrected. This study fills this knowledge gap.

The assessment of cup anemometer working health is challenging (Siegel and Lee, 2011) as damaged or used instruments can produce reasonable wind speed measurements (Pindado et al., 2014). Previous studies assessing the behavior of anemometers in measuring wind speed have focused on: (i) the number of cups and arm length (Marvin, 1932); (ii) the aerodynamic of cups (Marvin, 1934); (iii) the frequency system to record data (Charnock and Pierce, 1959); (iv) the over-estimating errors in fluctuating winds (Deacon, 1951); (v) the impact of environmental-climatic conditions (Kimura et al., 2001); (vi) the loss of performance of wind speed sensors and the deviations of calibration coefficients (Pindado et al., 2012); (vii) anemometer condition diagnosis problem (Sun et al., 2012); (viii) the study of the geometry of cups to improve the uniformity of anemometer rotation and reduce degradation due to ageing (Pindado et al., 2014); and (ix) the errors of cup anemometer rotational speed (Martinez et al., 2016), among other instrumental issues. Many recent anemometer performance studies were performed to assess the impact of measurement accuracy on the wind energy sector (i.e., wind turbine power performance; Pindado et al., 2014). However, interest in advancing a comprehensive attribution of the stilling phenomenon also has other scientific, socioeconomic and environmental impacts (Azorin-Molina et al., 2017a), particularly because the impact of wind speed on atmospheric evaporative demand (e.g., McVicar et al., 2012; Limjirakan and Limsakul, 2012) and air pollutant concentrations (e.g., Tong et al., 2017), among others.

The aims of this study are to: (i) assess divergences in measuring wind speed due to the cup anemometer drift (i.e., wear on the bearings); and (ii) define statistical approaches to correct biases in wind speed measurement due to the artificial decline signal produced by anemometer-bearing ageing. Our ultimate goal is to improve the long-term assessment of wind speed trends. The paper is structured as follows: Section 2 describes the experimental design and methodology; Section 3 deals with the results of the intercomparison addressing objective (i) above; Section 4 proposes and assesses two statistical approaches to minimize errors addressing objective (ii); and Sections 5 and 6 discusses and summarizes the findings of this research, respectively.

2. Experimental design, paired data and statistical analyses

2.1. Cup anemometers and experiment setup

The first hemispherical cup anemometer was invented by John Thomas Romney Robinson in 1846 (Robinson, 1847), and consisted of four cups-arms instead of three that Patterson (1926) designed some decades later to improve its response and aerodynamics. The standardized three-cup anemometer is still the most widely used wind measuring instrument for the wind energy sector (i.e., production forecast and wind mill performance control; Pindado et al., 2015) and in meteorological applications (WMO, 2008). Due to its simplicity, it is inexpensive when compared to sonic or propeller devices, shows an accurate linear response in the usual range of wind speed (i.e., 4–16 m s^{-1}) (Kristensen, 1998), and it can operate under extreme weather conditions (Makkonen et al., 2001). Therefore, almost all long-term wind speed time series have been measured by cup anemometers (McVicar et al., 2012) and assessing the drift due to the wear and tear on the internal bearings of three-cup anemometers is of key importance.

Table 1
Technical specifications of the SEAC SV5 cup anemometer used in this study.

General and electrical features	Specifications
Measuring system	Opto-electronic pulse generator (20 pulses/meter)
Measurement range	0.0 to 65.0 m s^{-1}
Threshold sensibility	0.2 m s^{-1}
Resolution	0.05 m s^{-1}
Accuracy	± 2.0%
Transducer type	LED phototransistor
Power supply	5 to 12VDC
Power consumption	300 mW
Dimensions	**Specifications**
Weight	0.30 kg
Height (cup wheel included)	235 mm
Case diameter	55 mm
Cup wheel diameter	120 mm
Material	Injected aluminium with anticorrosive paint

The cup anemometer chosen for this intercomparison study was the 3-cup *Sociedad Española de Aplicaciones Cibernéticas SA* (SEAC; http://www.seac.es/; last accessed 1 November 2017) anemometer SV5. This SEAC SV5 anemometer has been in continual operation in most automatic weather stations (AWS) of the Spanish Meteorological Agency (AEMET) since the mid-1980s (Azorin-Molina et al., 2014). Technical specifications regarding the SEAC SV5 are summarized in Table 1 along with pictures shown in Fig. 1a. For the intercomparison, two SEAC SV5 were used: (i) one new anemometer purchased from SEAC (hereafter 'SEAC-new'); and (ii) one anemometer rescued from an AWS after some years of operation (hereafter 'SEAC-old'). The SEAC-old was delivered to SEAC to replace: (i) the 3-cups and arms; and (ii) the opto-electronic output signal system, with new ones. The used bearings were not subject to any maintenance and/or replacement to assess the impact of anemometer drift on wind speed measurements when compared to SEAC-new; i.e., both anemometers only differ in the age of the bearings. Furthermore, before the paired-anemometer experiment, wind tunnel tests (see Fig. 1b) were performed by SEAC to ensure the optimal performance of the SEAC-new against a reference anemometer, and prove the rotor response of the SEAC-old. Test results in the tunnel estimated that the SEAC-old underestimated wind speed below the threshold of 3 m s^{-1}, whereas it showed an almost linear response to the reference anemometer above 7 m s^{-1}; parallel wind speed data performed in the tunnel tests were not recorded and, therefore, cannot be shown.

The experiment consisted of mounting the two anemometers 9 m above ground-level i.e., almost on top of a 10 m meteorological tower in Villena (Alicante; south-eastern Spain; 38°37′42.41″N and 0°56′05.25″W; 497 m above sea level; and ~50 km from the Mediterranean shore; see Fig. 1c). Both cup anemometers were separated by a distance of 1.5 m, with the horizontal mast oriented from 95° (i.e., where SEAC-old is located) to 275° (i.e., where SEAC-new is placed). The field site is located in a valley within the Prebetic System Mountains (Fig. 2a), representing a cold semi-arid climate (BSk)