Biases in wind speed measurements due to anemometer changes

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ABSTRACT:

This research presents a case study of the biases and discontinuities that were introduced in observed long-term mean wind-speed and gust data-series due to anemometer changes in a meteorological station in northern Spain, operated by the Spanish State Meteorological Agency: San Sebastian-Igueldo. Field and wind-tunnel experiments with predefined conditions have been presented in the literature, however this research uses a real case study to assess the impact of anemometer changes on wind speed measurements due to three factors being: (i) the 3-cup anemometer model (SEAC *vs.* THIES companies); (ii) sensor height (~19.95 m *vs.* ~20.45 m) and (iii) sensor age (20-years old *vs.* new). Our results show (a) substantial biases in the measured wind speed and daily peak wind gusts, with the new THIES anemometer reporting stronger surface winds than the old SEAC anemometer; (b) opposing biases under weak (negative) and moderate-strong (positive) winds; and (c) significant breakpoints in the long-term wind data-series, which highlight the importance of data homogenization. National Weather Services and climate assessment groups will benefit from these findings since errors in wind speed and gust measurements can be minimized by implementing systematic observation protocols. Robust anemometer observations provide a basis for accurate quantification of the magnitude of changes and the variability of surface winds.

KEY WORDS: Surface wind measurements; anemometer changes; biases; breakpoints

1. Introduction

In situ anemometer measurements are important for: (i) assessing wind changes and variability, such as the "stilling" (Roderick et al., 2007) and the "reversal" (Zeng et al.,

2019) phenomena of surface winds that has been observed over the last 50–60 years; (ii) wind energy prospecting for use in the renewable energy industry (Pindado et al., 2011); and (iii) developing wind-speed grids for use in numerous socioeconomic and environmental applications (McVicar et al., 2008; Zhou et al., 2022), to name but a few. The reliability of raw anemometer measurements has been discussed and confidence levels are low for both land and ocean surface wind speed trends, owing to uncertainties in the datasets and measures that are generally used (IPCC, 2021). Recently, a few quality control and homogenization approaches have been proposed to minimize systematic instrumentation errors and to correct inhomogeneities in wind speed measurements (Wan et al., 2010; Azorin-Molina et al., 2014; Minola et al., 2016; Lucio-Eceiza et al., 2018a, 2018b; Azorin-Molina et al., 2019; Turner et al., 2019). These errors and inhomogeneities can be due to station relocations, anemometer height changes, instrumentation malfunctions, instrumentation model changes, inconsistent sampling and averaging intervals, and observed environment changes (Pryor et al., 2009; Azorin-Molina et al., 2014).

The World Meteorological Organization (WMO, 2021) and the Parallel Observations Science Team recommends that old and new sensors are compared when a transition is made, as examples: (i) when a meteorological observing network changes from a conventional to an automatic network; and/or (ii) when other changes are made, such as changes to sensor heights, anemometer types, or station relocation. However, this comparison is not implemented as standard practice by National Weather Services and there are few comprehensive station diaries that report changes which have occurred in measurement systems over the years (Azorin-Molina et al., 2014). The periodic maintenance of weather stations (e.g., via yearly inspections as recommended by the WMO, 2021), and addressing instrumentation issues are both challenging aspects of weather observation which are essential for ensuring the quality and continuity of long-term climate records thus providing a solid basis for assessing and attributing changes and variability.

This paper reports a unique case study of the biases and breakpoints that were introduced in long-term mean wind speed and gust measurements by changes to the anemometer type, height and age by the Spanish State Meteorological Agency (AEMET; http://www.aemet.es/ ; last accessed 31 January 2023). The data used herein show systematic biases and discontinuities that can be introduced in wind measurements, similar to what was found by Wan et al. (2010). These data are particularly valuable as they represent a real case study with no predefined conditions, which is in direct contrast to designed field (Azorin-Molina et al., 2018) or wind-tunnel experiments (Safaei Pirooz et al., 2020).

2. Anemometer transition case study

2.1. Weather station and wind climatology

When a new sensor was commissioned, the Basque Regional Office of the AEMET measured wind speed and gusts using the conventional and modern anemometers simultaneously (for details see subsection 2.2.). Weather observation maintenance notes for 5 Sep 2016 state: "*For at least 5 years from today, the conventional SEAC anemometer will record data in parallel so that it can be compared with the new THIES anemometer for the purpose of continuity of the climatological series*". This is an uncommon practice for weather measuring systems i.e., conventional sensors are more often replaced by modern devices without any parallel observations recorded (there are some exceptions, e.g. the China Meteorological Administration (CMA) states that station relocations should involve 1–2 years of parallel observations for data correction;

CMA, 2012). To our knowledge, the San Sebastian-Igueldo Station (AEMET synoptic Id. 1024E; 43.31º N and 2.04º W) is one of few parallel wind data-series that are available and appropriate for assessing biases and breakpoints due to anemometer changes. The station is located in Monte Igueldo, a hilly area at 251 m above sea level and ~1 km from the Atlantic shore (Bay of Biscay) in northern Spain (Figure 1a).

The wind climatology at this station is dominated (around 80% of the time) by winds blowing from the N (summer), NW–W (spring and autumn) and S (winter), with a mean annual wind speed of ~5 m s^{-1} (Gomez-Piñeiro et al., 1993) and a marked seasonality (Azorin-Molina et al., 2016). The highest daily peak wind gust recorded across the Iberian Peninsula was measured at the San Sebastian-Igueldo Station, at 51.9 m s^{-1}, and this is also the area with the highest mean wind gust speed, at 13.9 m s^{-1} (Azorin-Molina et al., 2016). Gusty winds are mainly associated with Atlantic extratropical cyclone systems during the cold season (November–April).

2.2. Anemometers and parallel wind speed measurements

Azorin-Molina et al. (2014) reported that long-term wind-speed data-series were measured in Spain using the anemograph universal 82a before the mid-1980s and the 3-cup *Sociedad Española de Aplicaciones Cibernéticas SA* (SEAC) anemometer SV5 after the installation of automatic weather stations (AWS) in the mid-1980s. In the last 2 decades, the THIES CLIMA wind transmitter compact (also the first class model) was introduced in the AEMET climate monitoring network. Technical specifications for both the SEAC SV5 (SEAC hereafter) and THIES CLIMA wind transmitter compact (THIES hereafter) anemometers are summarized in Table 1, and pictures of the transition at the Igueldo Station are shown in Figure 1b.

This study quantifies the biases and discontinuities in the long-term mean wind speed and daily peak wind gust data-series due to anemometer changes that occurred on the 5 Sep 2016 to the model (SEAC *vs.* THIES), the sensor height (~19.95 m *vs.* ~20.45 m above the ground) and the instrument age (~20-years old since 14 Nov 1997 *vs.* new after the change). Both cup anemometers were mounted on top of a 6 m tower located on the roof of the AEMET's building, ~15 m above the ground; with the SEAC anemometer placed ~0.50 m below the new THIES one (see Figure 1b). The SEAC and THIES anemometers were connected to a datalogger which monitored the output frequency. Mean wind speed data-series (hereafter WS, in m s^{-1}) were stored at hourly intervals (from 10 min means), and daily peak wind gusts (hereafter DPWG, in m s^{-1}) as the 3 s average highest record within 24 h, i.e., from 0000 to 2400 h UTC.

Paired raw wind speed data-series from the old and new system are available for a ~5-year field experiment from 5 Sep 2016 to 4 May 2021. For unknown reasons, AEMET stored the hourly 10-minute maximum value instead of the mean hourly value for WS measured by the SEAC after 7 Nov 2017, so the parallel data-series are only comparable for a little over a year and constitute 8,969 10-minute measurements. For DPWG, the parallel data-series cover the whole period, although we removed some outliers and there were some missing data, leaving a total of 1,357 paired data points. Descriptive statistics are shown in supplementary Tables S1 and S2 and show that these data are a reasonable sample from which to quantify the biases in WS and DPWG measurements introduced by this real anemometer transition. We evaluated the statistical significance of the differences calculated as [THIES - SEAC] measurements of WS and DPWG using the Wilcoxon–Mann–Whitney test (Siegel and Castelan, 1988) at $p < 0.05$ and $p < 0.01$. This is a non-parametric statistical hypothesis test based on ranks, and so does not require the samples to be normally distributed for both parameters (see the Kolmogorov-Smirnov test statistic; Chakravarti et al., 1967).

2.3. Application of Climatol to homogenize the WS and DPWG data

Herein, we used the same approach adopted by Azorin-Molina et al. (2018) and Azorin-Molina et al. (2019) to quality-control and homogenize the monthly WS and DPWG data-series, respectively. To summarize, we used the Climatol package v.3.1.2 (Guijarro, 2018; https://CRAN.R-project.org/package=climatol ; last accessed 31 January 2023) based on the Standard Normal Homogeneity Test (SNHT; Alexandersson, 1986), to detect inhomogeneities that were introduced in the wind data-series due to this transition case study at the San Sebastian-Igueldo Station. Nearby stations were used as reference series and the normal ratio normalization was applied to the data as advised when the variable has a skewed probability distribution (Guijarro, 2018). See the references above for full details about this approach.

3. Results

3.1. Biases in the WS and DPWG data-series

The box-plots in Figure 2 summarize the annual, seasonal and monthly biases in the WS and DPWG measurements from the SEAC and THIES devices; descriptive statistics are shown in supplementary Tables S1 and S2. The changes to the anemometers introduced mean biases of 0.19 m s^{-1} and 0.47 m s^{-1} in the WS and DPWG data-series, respectively, with the THIES reporting greater speeds than the SEAC. These biases are statistically significant for both parameters and all time-scales according to the Wilcoxon–Mann–Whitney test at $p < 0.01$. When compared with the annual mean measurements from the SEAC, the new THIES measurements increased WS and DPWG by 5.2% and 4.0%, respectively. There is a marked seasonal cycle in the biases, with the largest differences in winter (WS 0.26 m s^{-1}, DPWG 0.63 m s^{-1}) and lowest differences in summer (WS 0.12 m s^{-1}, DPWG 0.25 m s^{-1}), while differences in spring and autumn are similar (WS ~0.18 - 0.20 m s^{-1}, DPWG 0.48 m s^{-1}). The highest mean biases were recorded in February (WS 0.38 m s^{-1}, DPWG 0.73 m s^{-1}), and the lowest mean biases were in August (WS 0.05 m s^{-1}, DPWG 0.13 m s^{-1}). This seasonal pattern also occurs in the standard deviations, except for the extreme biases that were recorded in September for WS (5.28 m s^{-1}) and in December for DPWG (4.72 m s^{-1}). Moreover, the hourly biases for WS in Figure 3 show a noticeable daily cycle, with the lowest mean bias at 12 h UTC (0.11 m s^{-1}), and the largest mean bias at 3 h UTC (0.25 m s^{-1}). The histograms in Figure S1 and the scatterplots in Figure S2 clearly show the positive biases that were introduced due to the transition of the anemometers.

3.2. Biases as a function of wind speed

Wind speed has a significant effect ($p < 0.05$) on both the sign and magnitude of the biases. As shown in the scatterplots for WS (Fig. 4a) and DPWG (Fig. 4b), the stronger the wind speed is the larger the biases are. This means that, under moderate to strong surface winds, the sign and magnitude of the biases tend to be positive and larger, relative to under weaker wind speeds, when biases are generally negative and have smaller magnitude (i.e., under weak wind conditions, the old SEAC sometimes recorded greater wind speeds than the new THIES). This behaviour is clearly visible in the box-plots that show the biases as a function of different wind-speed ranges. For WS (Fig. 5a) and DPWG (Fig. 5b), the lowest ranges show negative values for both the mean and the median, whereas the sign and magnitude of the biases increase as the surface winds become stronger for all other categories. The mean and median biases tend to be stable, or even to slightly decrease, for the strongest wind-speed ranges. Lastly, the spread of the middle half of the distribution measured by the interquartile range (IQR; the difference between the 75th and 25th percentiles of the biases) is also shown in the box-plots and tends to increase for both WS and DPWG as surface winds become stronger, showing that the biases are dispersed under strong wind speeds.

3.3. Detection of discontinuities in the WS and DPWG data-series

Figure 6 shows detected breakpoints for both the WS and DPWG data-series, showing that the changes in the 3-cup anemometer model, height gain and sensor age had an impact on the wind measurement series. Significant SNHT values were detected in October 2015 for WS (SNHT = 28.9; Fig. 6a) and DPWG (SNHT value = 27.1; Fig. 6c). These breakpoints predate the anemometer changes that occurred on the 5 Sep 2016, however it is well known in wind research (e.g., Azorin-Molina et al., 2014) that breakpoints can occur before or after the year-month of the changes that drive them. Lastly, Figures 6b and 6d show the reconstructions of the data-series for WS and DPWG, respectively, and the correction factors applied to the homogeneous subperiods. We used Climatol to apply a robust homogenization to remove the discontinuity that was introduced in the wind data-series due to the anemometer changes, and to quantify the sign, magnitude and statistical significance of changes to WS and DPWG more accurately (Utrabo-Carazo et al., 2022). Table 2 summarizes WS and DPWG trends at the San Sebastian-Igueldo Station, and the number of days for which DPWG exceeded the 90th percentile during 1961–2019. These show significant declining trends for almost at all time-scales, highlighting the importance of homogenizing wind-speed data-series.

4. Concluding remarks and discussion

There are many sources of error and uncertainty in meteorological (Aguilar et al., 2003) and wind measurements (Azorin-Molina et al., 2018). In this study, for the first time, we assessed a transition case study of the biases and discontinuities introduced to measurements of wind speed and gusts due to changes in the cup anemometer manufacturer, height and sensor age. This study provides a reference example of the sensitivity of wind measurements to anemometer changes, and the importance of following the WMO-established observation guidelines (WMO, 2021). This example is useful for National Weather Services and weather observation offices. Previous wind-tunnel and field experiments evaluated wind instruments under predefined (Safaei Pirooz et al., 2020) and real (Azorin-Molina et al., 2018) wind conditions, respectively, and this transition case study presents a further step in wind measurement intercomparison as it shows a real case study over a relative long period. Here, we found significant and positive biases due to anemometer changes. The THIES reported stronger WS and DPWG than the old SEAC; and the sign of the biases was opposite under weak (negative) and moderate-strong (positive) winds. We also found that there were significant breakpoints in the long-term wind data-series. The magnitude of the biases reported here is site-specific and cannot be extrapolated to anemometer changes at other stations, as has been done with the results of previous intercomparisons, e.g., for air temperature (Brunet et al., 2011). For this reason, we do not aim to define standard correction biases; however, this work illustrates the extent to which weather observing procedures impact wind measurements.

In this study, the biases in wind speed and gust measurements due to sensor performance represent an increase of around 4–5% with respect to the annual means.

This strongly influences estimates of other processes such as potential evapotranspiration and pan evaporation (McVicar et al., 2012), water resources (Vicente-Serrano et al., 2014), wind energy (Zeng et al., 2019), and the quantification of wind speed changes and variability (Azorin-Molina et al., 2017; 2018). The Parallel Observations Science Team (POST), supported by WMO, was looking across the world for climate records which simultaneously measure climate variables using conventional and modern automatic equipment. This kind of initiatives are crucial as transitions have an effect on the quality and homogeneity of climate data-series (Zahradníček et al., 2019), and the assessment and attribution of climate changes and decadal-scale variability (Venema et al., 2012).

Overall, the biases and discontinuities that we have found in this real transition case study are mainly due to the change in height, the removal of the drafting effect of the old sensor and the different technical specifications of these two anemometer models (see Table 1). In fact, the new 3-cup anemometer did not represent an improvement at all in terms of: (i) accuracy (SEAC ±2% *vs.* THIES ±3%); (ii) resolution (SEAC 0.05 m s^{-1} *vs.* THIES 0.1 m s^{-1}); and (iii) measurement range (SEAC 0.0 – 65.0 m s^{-1} *vs.* THIES 0.5 - 50 m s^{-1}). Therefore, the fact that the sign of the biases was opposite under weak (negative) and moderate-strong (positive) winds might be linked to the starting velocity at 0.5 m s^{-1} of the new THIES, which cannot measure low winds accurately. In addition, the different cup wheel diameter (SEAC 120 mm *vs.* THIES 44 mm) could be also behind the negative biases found at low speeds; due to inertia, the bigger cups of the SEAC could overspeed (Busch and Kristensen, 1976) more and take much longer to slowdown after a wind event passes, particularly in the afternoon-evening. Moreover, the seasonal cycle found with the highest (lowest) biases in winter (summer) might be related to the strongest (weakest) surface winds associated with Atlantic extratropical cyclone systems at Monte Igueldo during the cold season (Gomez-Piñeiro et al., 1993; Azorin-Molina et al., 2016)

New 2- and 3-axis sonic wind devices represent an improvement compared to mechanical cup anemometers assessed in this study, and greater effects may be anticipated as these can accurately measure weak wind speeds. Therefore, sonic devices can reduce the frequency of calm periods that are registered by cup anemometers, which are less sensitive to weak winds (Bowen, 2008). However, even though the high accuracy and excellent reliability and low maintenance of new sonic sensors, errors in wind measurements may also be associated with other factors, such as the data encoding issues. Dunn et al. (2022) concluded that encoding of calm periods could lead to up to a 30% overestimation of the observed increase in global wind speed (the so-called "reversal" phenomenon, Zeng et al., 2019). In addition, the use of different units can also introduce uncertainties to wind measurements (Azorin-Molina et al., 2017).

This transition case study also highlights the importance of recording and keeping accurate wind instrument metadata. In our study, this allowed us to check that the breakpoints found in both the WS and DPWG data-series were due to artefacts, and the metadata allows appropriate adjustments to be made to ensure consistency: "*As of 5 Sep 2016 at 07:00Z, the wind data from the Igueldo Observatory will be obtained from the new THIES program, since it has been observed that the SEAC anemometer underestimate the strongest wind gusts in comparison to other devices, due to dragging problems*". Fortunately, relative homogenization approaches such as the SNHT test can be used to detect artificial discontinuities (Venema et al., 2012) without the availability of instrument reports (Azorin-Molina et al., 2014). However, it remains challenging to quality-control and homogenize wind data, since these can vary rapidly in space and time (Azorin-Molina et al., 2019).

The data from the San Sebastian-Igueldo Station are an example of best-practice in surface weather observations, since a protocol was established for simultaneously measuring winds from the old and new wind devices for at least a 5-year period (see notes in section 2). However, probably due to technical issues, the new cup anemometer was not placed at the same level on the tower and was therefore not next to the old one (Azorin-Molina et al., 2018). Consistent sensor placement is also crucial for ensuring the continuity and quality of weather observations, and for a robust assessment of WS and DPWG changes and variability (Zahradníček et al., 2019).

Current research in our group focuses on quantifying how much technological advances are improving the accuracy of wind measurements made using new wind devices, relative to older devices. An intercomparison of the most common wind sensors used by National Weather Services across the world in both wind-tunnel and field experiments is being developed in New Zealand as a joint collaboration between CSIC, NIWA and the University of Auckland (see supplementary Figure S3 and Figure S4). This will help weather observers, scientists and engineers from the wind industry to understand the biases associated with new wind sensors before deploying them in the field. It should also be noted that practices such as performing periodic calibrations of wind instruments are crucial for error minimization (WMO, 2021).

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List of Tables

Table 1. Technical specifications for the SEAC and THIES cup anemometers used in this study.

General and electrical features	SEAC - SV5	THIES – WIND TRANSMITTER COMPACT
Measuring system	Opto-electronic pulse generator	Opto-electronic (slotted disc)
Measurement range	0.0 to 65.0 m s^{-1}	0.5 to 50.0 m s^{-1}
Resolution	0.05 m s^{-1}	0.1 m s^{-1}
Accuracy	±2.0%	±3.0%
Power supply	5 to 12V DC	3.3 to 42V DC
Dimensions	**Specifications**	
Weight	0.30 kg	0.40 kg
Height (cup wheel included)	235 mm	165 mm
Case diameter	55 mm	50 mm
Cup wheel diameter	120 mm	44 mm
Material	The cup-star consists of plastic; the housing is made of injected aluminum with anticorrosive paint	The cup-star consists of synthetic (with fibre glass, PC-GF10); the housing is made of aluminum (AIMgSi1)

Table 2. Annual and seasonal trends for WS, DPWG and DPWG exceeding the 90th percentile at the San Sebastian-Igueldo Weather Station for 1961–2019. Statistically significant trends are defined as those $p < 0.10$ (in bold) and $p < 0.05$ (in bold and in parenthesis).

	Annual	**Winter**	**Spring**	**Summer**	**Autumn**
WS ($m\ s^{-1}\ dec^{-1}$)	**(-0.209)**	**(-0.409)**	**(-0.219)**	**-0.045**	**(-0.169)**
DPWG ($m\ s^{-1}\ dec^{-1}$)	**(-0.225)**	**(-0.423)**	**(-0.226)**	-0.054	-0.214
DPWG >90th Per. (days dec^{-1})	**(-3.863)**	**(-1.368)**	**(-0.927)**	**(-0.904)**	**(-1.182)**

List of Figures

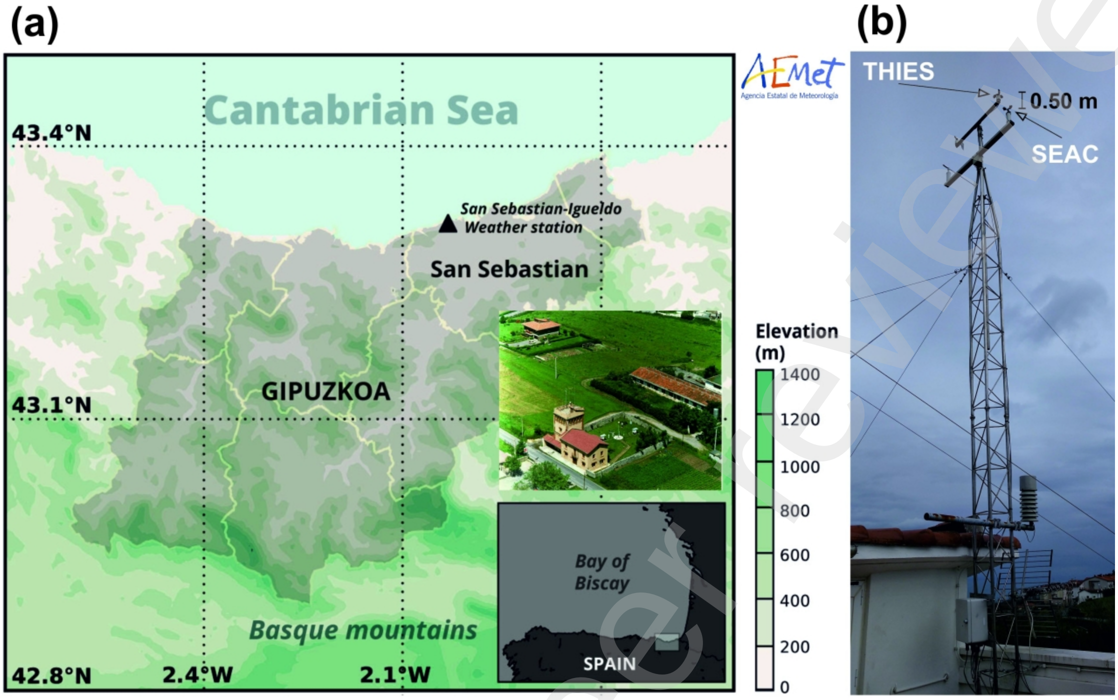

Figure 1. (a) Land-surface elevation of Gipuzkoa province, showing the location of the San Sebastian-Igueldo Weather Station in the Bay of Biscay (Atlantic shore, northern Spain); (b) Transition case study with the old SEAC and new THIES placed at the top of the meteorological tower; the new sensor is ~0.50 m above the old sensor.

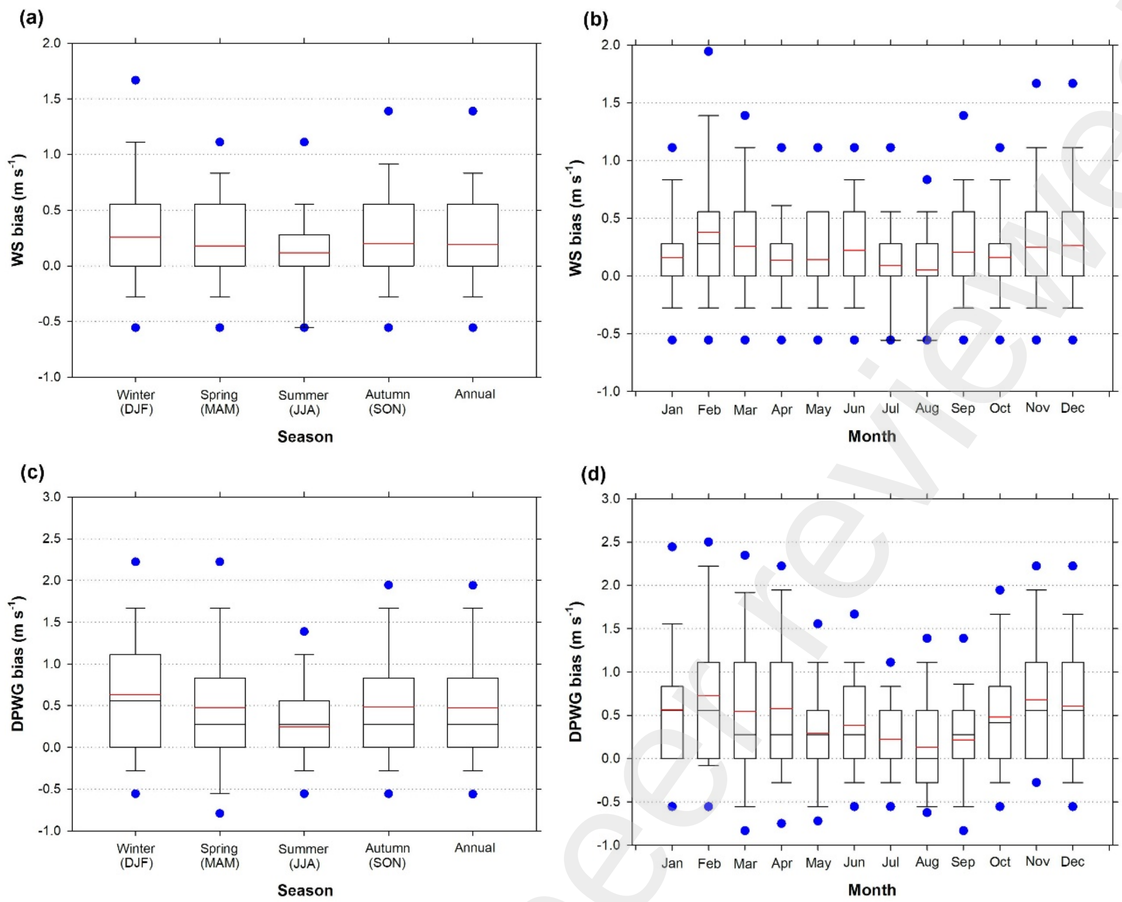

Figure 2. Annual and seasonal (a and c) and monthly (b and d) box-and-whisker plots of the anemometer biases in WS (upper plots) and DPWG (bottom plots). The mean (red line), the median (black line), the 25th and 75th percentile range (boxes), the 10th and 90th percentiles (whiskers) and the 5th and 95th percentiles (blue dots) are shown. Differences calculated as [THIES - SEAC]

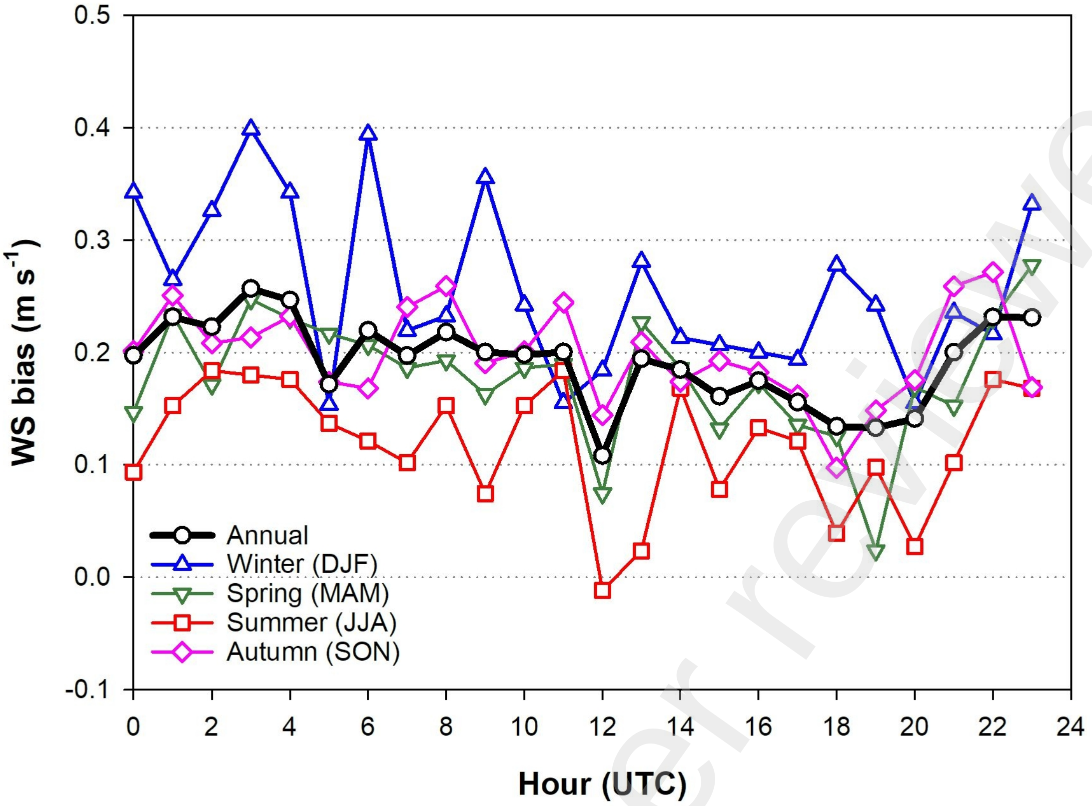

Figure 3. Hourly mean biases WS measurements between the SEAC and THIES anemometers at annual and seasonal scales. Differences calculated as [THIES - SEAC]

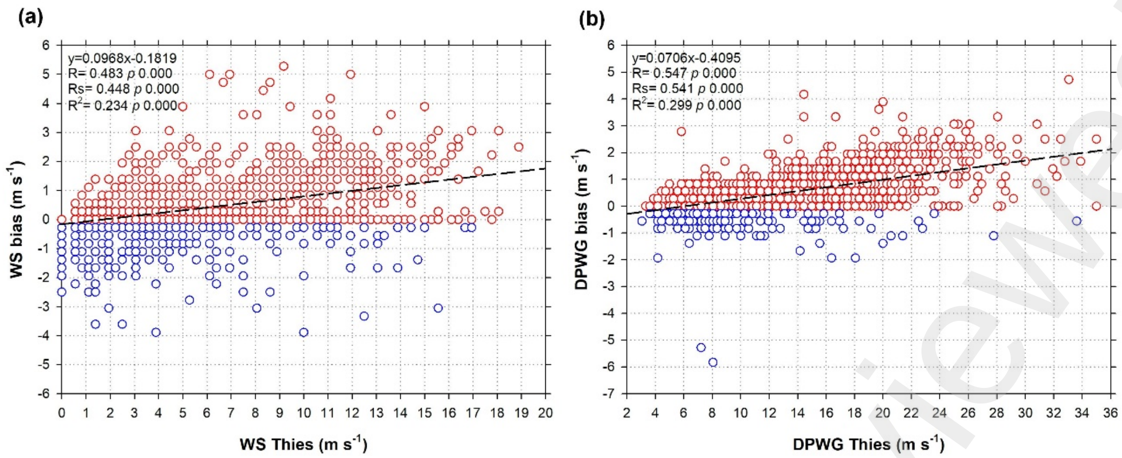

Figure 4. Scatterplots of the biases in (a) WS and (b) DPWG when measurements from the SEAC and THIES anemometers were compared, plotted against the THIES measurements (X-axis). Positive and negative biases are coloured in red and blue, respectively. The inset numbers indicate the linear regression equation, the Pearson correlation (R), Spearman rank correlation (Rs), and determination (R^2) coefficients. Differences calculated as [THIES - SEAC]

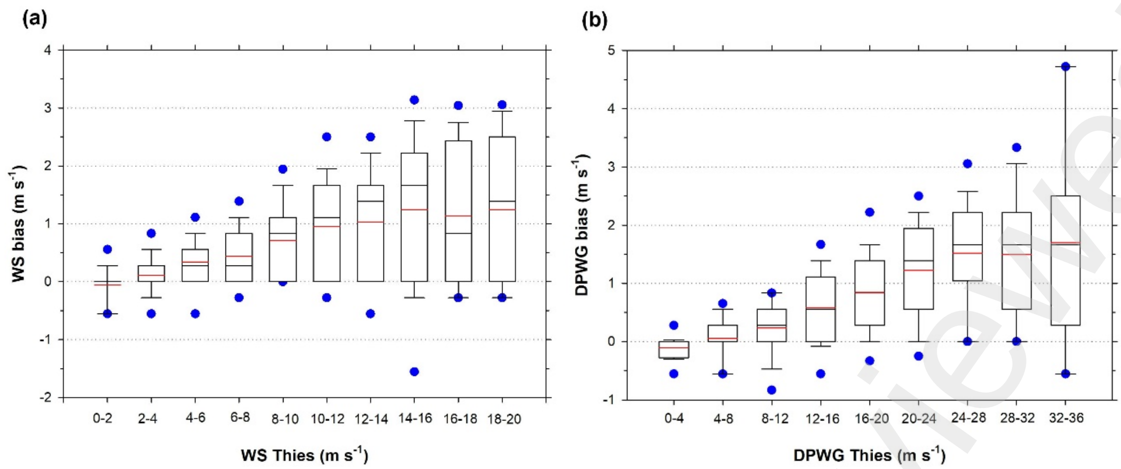

Figure 5. Box-and-whisker plots of the biases in (a) WS and (b) DPWG, when measurements from the SEAC and THIES anemometers were compared, plotted as a function of different WS and DPWG ranges, as measured by the THIES (X-axis). The mean (red line), the median (black line), the 25th and 75th percentile range (boxes), the 10th and 90th percentiles (whiskers) and the 5th and 95th percentiles (blue dots) are shown. Differences calculated as [THIES - SEAC]

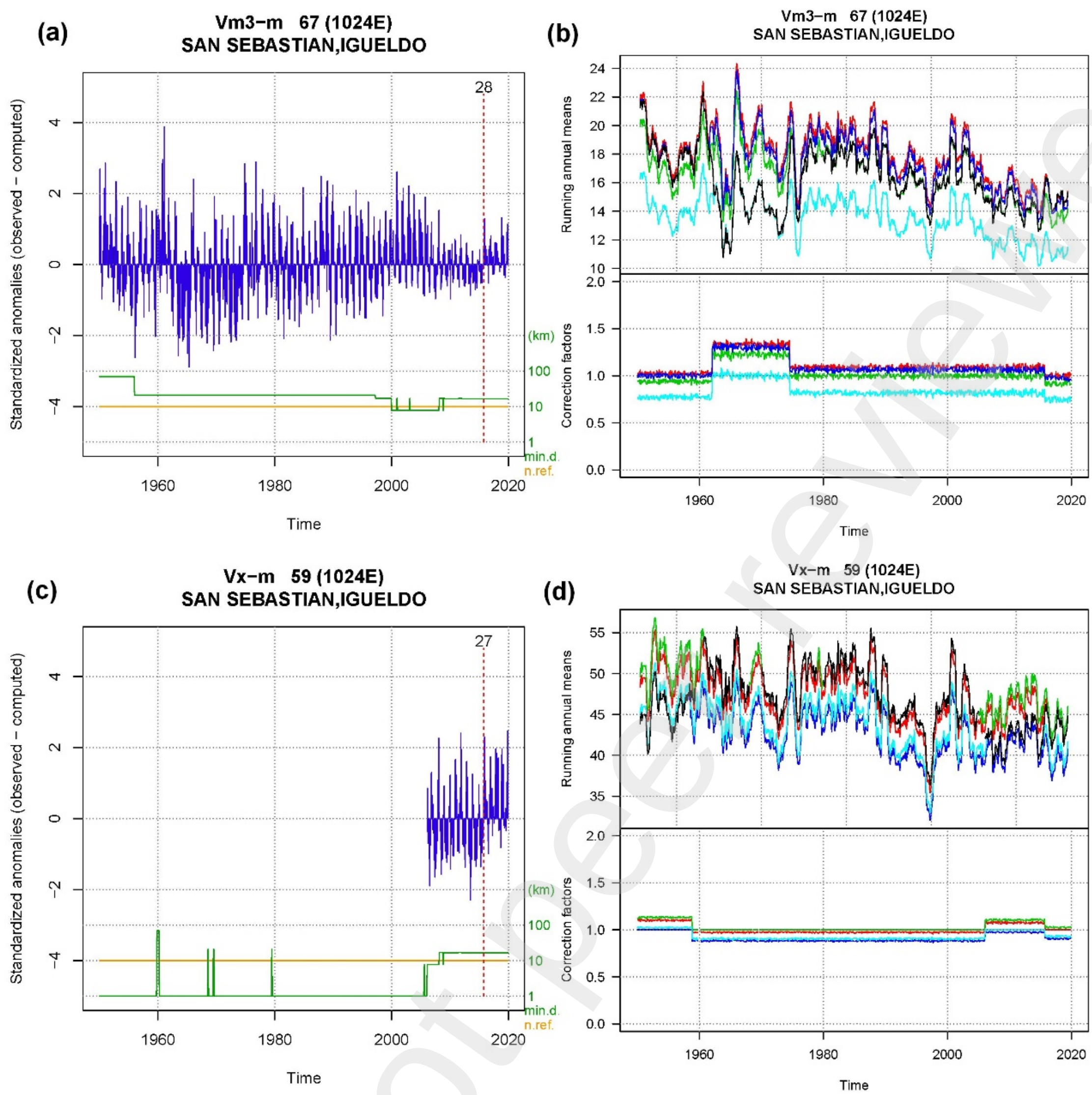

Figure 6. Break-point detection and correction for data from station #1024E-San Sebastian Igueldo. (a) and (c) show the standardized spatial anomalies in blue bars, and the dashed red line marks the highest Standard Normal Homogeneity Test (SNHT) value in October 2015 (28 for WS in (a) and 27 for DPWG in (c), labelled in black). The green line shows the distance to the nearest available WS and DPWG data point in the series, and the orange line shows the number of reference data points used (on the same logarithmic scale located at the bottom right). (b) and (d) show the series reconstruction (top) and correction factors (bottom), applied to the homogeneous subperiods. Series are plotted as running annual means (in the original km/hr units) to

avoid overly noisy graphs. The original data are shown in black and the reconstructed series are shown in different colours.