A methodology for study of in-service drift of meteorological humidity sensors

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Abstract
Meteorological measurements of air humidity in ground-based weather stations worldwide are increasingly being used in studies of climate change. However, electronic humidity sensors often suffer gradual drift in sensor readings, particularly at the high end of the relative humidity range. This phenomenon is well known, but there is currently limited quantitative information available about the drift characteristics, and hence about the consequent measurement bias or uncertainty that should be attributed to historical humidity data sets.

In order to quantify weather-station hygrometer drift, a dataset has been studied from UK weather-station hygrometer records supplied by the UK Met Office calibration laboratory. As well as documenting the calibrations and adjustments, the records include ‘as-found’ checks of the hygrometers on return from field use. This allows average in-service error and drift to be evaluated for the population of instruments.

The approach of the study is presented, together with illustrative initial results quantifying mean sensor drift of up to 5%rh. The implications of this for estimating bias in observations are discussed, along with discussion of associated uncertainty. This includes consideration of the distribution of the data, including the end-limited range where readings are capped at 100%rh. The study results justify the Met Office practice of adjusting hygrometers to minimise the errors in use. Preliminary conclusions and recommendations are made, and further steps are identified for developing the methodology.

Keywords: hygrometer, drift, sensor, weather station, climate, humidity, metrology for meteorology

(Some figures may appear in colour only in the online journal)
Analyses of surface humidity in order to inform understanding of climate change have been made by Dai [4], Willett et al [5, 6], and Simmons et al [7], among others. Validated humidity datasets with global coverage over extended time periods are becoming available, for example HadISDH [8]. These global datasets are commonly summarised at the level of 5° by 5° gridded areas of the surface of the Earth, and in some cases at finer resolution [7]. One 5° by 5° grid box is of order half the area of the UK, and hence considerable averaging is involved. For such datasets, steps are being taken to provide estimates of uncertainty associated with the averaged data, such as in the work of Willett et al [6, 9]. To do so requires an understanding not only of the statistical aggregation of data and the related assumptions, but also of the uncertainties in the original measurements. The state of the art in such analyses is evolving, and will in future ideally take into account both the characteristics of the measuring instruments and any changes in the technology as instruments are updated. However, relevant metadata, detailing techniques in use at particular weather stations at given times, are rarely available. This would be highly desirable, and meteorology researchers (for example Ingleby et al [10]) have encouraged national weather services to make these metadata available in future.

Weather station observations of humidity are in fact conventionally reported in terms of dew-point depression. From this and temperature, other humidity quantities are derived—such as relative humidity, dew point, and mixing ratio—which each convey different information for climate as illustrated for example by Willett et al [9]. The study reported here looks at relative humidity, because that is the humidity quantity actually measured by the electronic hygrometers in weather stations, and in terms of which the calibrations are provided.

In what follows, section 2 further explains the background and need for this work. Section 3 outlines the approach to the study methodology, and section 4 gives some results of this initial stage of the study, including mean drift observed. Section 5 gives a summary of the main findings so far, and section 6 outlines the approach to utilising this information to make estimates of bias in weather station humidity data, and looks at and distributions of data. The results are discussed in section 7, followed by section 8 conclusions, recommendations, and comments on possible further work.

Throughout this report, the quantity relative humidity is as defined in Annex 4A of the CIMO Guide [1] and is expressed using the symbol %rh, in line with widespread usage, and as given by Lovell-Smith et al [3]. The measurement terms ‘error’ and ‘uncertainty’ are used as defined in the International Vocabulary of Metrology [11]. Measurement error is effectively ‘instrument reading minus reference value’, such that an instrument over-reading represents a positive error. ‘Measurement uncertainty’ is effectively the ‘quantified doubt about a measurement result’ [12]. This is expressed in terms of an interval (usually denoted ±), together with a coverage probability of the ‘true value’ lying within that interval, and a coverage factor k. The coverage factor is the multiple applied to a standard uncertainty to obtain the chosen coverage probability for an assumed form of the probability distribution [12, 13].

2. The background to this work

It is well known, qualitatively, that electronic relative humidity sensors are found to drift in service, due mainly to the effects of condensation and contamination. These influences can lead to permanent changes in the sensor dielectric medium, giving false indication of detected water vapour; increasingly so over time. The extent of this depends greatly on the usage of an instrument, but in weather observations it can commonly lead to significant over-readings of hygrometers, particularly at high relative humidities. Some reports estimate drift at more than 5%rh per year for some sensor types [14]. This is important for the attribution of uncertainty to aggregated hygrometer data as used in the study of climate. In such datasets, averaging can reduce the impact of random effects, but systematic errors, if they are present, need to be recognised and, ideally, corrected [9]. In addition, where humidity observations lead to reported values of more than 100%rh, climate analyses tend to reject these data, while accepting results at 100%rh [6]. It is unclear whether this is the best approach to dealing with these data.

Although the phenomenon of hygrometer drift is well recognised, there is limited information quantifying the effect. Some past studies have examined the drift behaviour of individual humidity sensors and have observed a tendency for upward drift in readings, for example by Skaar et al in 1989 [15], and by Visscher and Kornet in 1994 [16]. In contrast, Lacombe et al in 2011 [17] found little or no drift; this is possibly because their trial provided few cases of condensing conditions. However, because developments in humidity sensors are relatively fast-moving, studies more than a few years old do not necessarily reflect the performance of present-day instruments that are commercially available.

Some workers have demonstrated methods for studying hygrometer bias or drift. A study by Miloshevich et al in 2001 [18] demonstrated an approach to quantifying bias in humidity sensors for radiosondes, arriving at estimates of bias, for uncalibrated single-use sensors. More recently, in 2013, Ingleby et al reported study of progressive drift in a variety of hygrometers in a single weather station [10], as well as reviewing the related literature. Their work provides a valuable case study, covering a small set of individual instruments of different types. However the work reported here goes further, by looking at data for a large set of hygrometers of one widely used type. This allows us to draw some conclusions about a population of instruments, and to demonstrate a methodology for studies of this kind.

3. The study method

3.1. Overview of study approach

This study, using historical calibration laboratory data provided from the UK Met Office, is designed to demonstrate the estimation of typical drift of weather station hygrometers, and the resulting bias in using weather station data. Met Office calibration records have been made available for a large number of electronic hygrometers used in UK weather
stations, covering the period 2010–2014. Initially a subset of the records has been analysed.

The records contain information about hygrometer measurement error at a range of relative humidities when checked ‘as found’ following their return from weather stations. The records also detail any adjustment performed before the calibration and return of the hygrometer to field use, once acceptance criteria are met. Calibration is performed as defined in the International Vocabulary of Metrology [11], and is effectively the process of comparing an instrument against a reference to evaluate the instrument error. Calibration is distinct from adjustment of an instrument to correct error, which is a separate step.

The change in measurement error between calibration (before entering service) and the ‘as-found’ measurements (on return from service) is a measure of the in-service drift of the hygrometer. The availability of records of the ‘as-found’ measurement error of the hygrometers in these records is therefore critical to this study methodology. The sizeable dataset available enables a detailed study of the in-service drift of the type of electronic hygrometer used by the Met Office during this time period. Using this approach, an estimate can be made of the bias of weather station observations of relative humidity. Potential correction for this bias can be proposed, together with the associated uncertainty with or without applying such a correction.

### 3.2. Met Office hygrometers and calibration procedure

At the time of writing, the UK is served by some 432 weather stations (such as the ones shown in figures 1 and 2). Of the total, some 269 are automated, and 263 provide humidity measurements using electronic relative humidity sensors. In addition, some station relative humidity observations continue to be derived from wet-bulb readings. The weather station electronic hygrometers for land sites are routinely calibrated annually by the calibration laboratory (QA Lab) of the Met Office at Exeter. In general, individual hygrometers are deployed for a period of a year, unless an instrument failure requires action sooner. The deployments are handled via field servicing centres whose personnel install freshly calibrated hygrometers in weather stations, and return the used ones, on a rolling programme throughout the year. Thus the ongoing record of observations is not based on continuity of any particular instrument at a given location over time.

During the period covered by the study, the electronic hygrometers in use were Rotronic HygroClip models S3/TF and HC2-S3/TF using capacitive humidity sensors with a polymer sorptive layer, similar to the example shown in figure 3. The nominal operating range of the instruments is specified as 0%rh to 100%rh. The UK exposure conditions are mainly between about 50%rh and 100%rh, with the maximum (saturation) value occurring most commonly overnight.

The protocol followed by the Met Office at their calibration laboratory had three main stages: an initial check of ‘as-found’ measurement error upon the return of the hygrometer from field use, adjustment of the hygrometer to read closer to reference values, and a final calibration of the adjusted hygrometer before return to the field.

Checking of hygrometers on return from the field was routinely carried out, as follows. Initial ‘as-found’ checks of up to 5 hygrometers simultaneously were performed at 23 °C in the chamber of a Rotronic HygroGen bench-top humidity generator. At least 4 values of relative humidity in the range from 20%rh to 95%rh were generated in a rising series. The measurement errors of the hygrometers were recorded relative to a reference hygrometer (itself a Rotronic electronic
hygrometer, with calibration traceable to national standards for humidity). Check points at high and low extremes of relative humidity (20%rh and 95%rh) were always included at this stage. Results of this step are detailed in section 4 below, and further elaborated in later sections.

After initial checking, hygrometers were then routinely adjusted in order to approximately correct (remove) past drift due to recent field use. To do this, a series of humidity values ranging from 10%rh to 95%rh at 23 °C were applied using the same bench-top humidity generator. At each value, electronic adjustments of the hygrometer readings were made using the manufacturer’s software. The adjustments were made to reduce individual hygrometer measurement error, bringing readings close to the value of the calibrated reference hygrometer. However, as routine practice, small biases were deliberately applied to the hygrometer readings in anticipation of drift likely to occur while in the field. This adjustment is intended to ensure that the hygrometers read close to correctly for as much of their service life as possible. At high relative humidities the hygrometers were adjusted to under-read by of order 1%rh as partial compensation for expected upward drift. At low relative humidities, the hygrometers were adjusted to slightly over-read, to anticipate slight downward drift in use in this range. Following this, the adjusted hygrometers were checked again at 20%rh and 95%rh and, if acceptance criteria were met, the hygrometers then progressed to the calibration stage of the procedure.

The Met Office humidity calibration facility allows calibration of up to 6 hygrometers simultaneously in a manifold held inside a temperature-controlled chamber, and supplied with air of well-defined dew-point temperature using a separate Michell Instruments flow-mixing generator. Measurements of air temperature and dew-point temperature in the manifold are used to derive the reference relative humidity values for the calibration, with traceability to the SI (International System of Units). The evaluation of reference relative humidity uses the WMO definition of relative humidity [1], together with formulae for saturation vapour pressure and water vapour enhancement factor given by Sonntag [19]. During the period of this work, the reference hygrometers were Michell model S4000 and MBW model 473 chilled-mirror hygrometers. The temperature reference was a Fluke 1590 Super-Thermometer and MBW model 473 chilled-mirror hygrometers. The information obtained from the paper records included: hygrometer serial number, distribution centre, ‘as-found’ measurement error during check stage, measurement error after adjustment, and measurement error at the calibration stage.

At a given relative humidity value:

\[
\text{Drift of a single sensor} = \psi_F - \psi_I, \quad (1)
\]

where \(\psi_I\) is initial post-calibration residual measurement error and \(\psi_F\) is final as-found measurement error after service in the field.

Considering use of aggregated data from a large number of hygrometers, as is the case in climate study,

\[
\text{Mean drift for a pool of sensors} = \frac{1}{n} \sum (\psi_F - \psi_I), \quad (2)
\]

where \(n\) is the number of instruments.

This can be alternatively expressed as

\[
\text{Mean sensor drift for a pool of sensors} = \frac{1}{n_2} \sum \psi_F - \frac{1}{n_1} \sum \psi_I, \quad (3)
\]

where \(n_1\) and \(n_2\) are numbers of instruments, initially and finally. Naturally we might expect \(n_1 = n_2\), but this is not necessarily true, as there are sensors that fail in service, so that \(n_2\) is typically less than \(n_1\).

The two terms in equation (3) can be treated as independent quantities applying to the same population (same sensor type, same usage, etc), provided that they relate to consistent instrumentation and methods over the dataset studied, especially the consistent procedure of adjusting the instrument. Separating the terms has several advantages. One benefit is that looking at pooled initial and final data is considerably easier than sequentially tracking the progress of individual sensors. Since pooled data is the basis of climate studies this satisfies the study requirement. With this proviso, then the reasoning extends to any pooled data.

3.3. NPL study procedure

The paper records of checks, adjustments and calibrations were scanned by NPL to retain copies electronically, and the originals were returned to the Met Office. Pertinent data for this study were identified from these records. The records contain handwritten data (such as shown in figure 4), and these were transcribed into Microsoft Excel for detailed analysis. The information obtained from the paper records included: hygrometer serial number, distribution centre, ‘as-found’ measurement error during check stage, measurement error after adjustment, and measurement error at the calibration stage.

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It can be noted that that initial reading \(\psi_I\) is relatively constant (with some scatter) because of consistent instrument adjustment of hygrometers to a calibrated reference value. However, final reading \(\psi_F\) varies, due to varying drift in field use. It is then of interest to consider summary statistics (mean, standard deviation and others) and distribution of the data for \(\psi_I\) and \(\psi_F\).
4. Results of study

Records of 152 weather-station hygrometers from 2013 have been analysed initially. The typical period of service for a hygrometer is one year (but sometimes less). The results give an indication of the magnitude of in-service drift, which varies with the relative humidity measured.

Figure 5 shows the results in terms of residual error, for a large set of hygrometers after calibration at several values of relative humidity, with data grouped at the nominal calibration values. This illustrates the small offsets applied at the adjustment stage, in anticipation of drift in the field. A straight-line fit,

\[ y = -0.0341x + 1.671, \]

is shown, which approximates the data. The downwards slope reflects the offsets applied to the hygrometers as a function of relative humidity.

Figure 6 shows the hygrometer errors as found after return from service in the field, with results grouped at the nominal humidities at which the check measurements were made. A curve fit approximating the data is

\[ y = 0.0016x^2 - 0.1259x + 1.2947. \]

A quadratic polynomial is used here, for illustration, but another more optimal fit may be possible. The results show that, on return from the field, the hygrometers typically under-read slightly at relative humidities below 60%rh. From 80%rh upwards, they over-read, more so at the highest humidities.

The data shown in figures 5 and 6 can be used to estimate net drift of the sensors at different relative humidities. But first it is instructive to consider the distributions of the datasets.
Table 1. Summary details of the distributions of error as found after return from field use, for the set of hygrometers studied. Some entries for median and range are shown to more decimal places according to the resolution available for those individual data.

| Applied relative humidity/%rh | Mean/%rh | Standard deviation/%rh | Median/%rh | Range minimum/%rh | Range maximum/%rh | Number of data |
|------------------------------|----------|------------------------|------------|-------------------|------------------|---------------|
| 20                           | −0.62    | 0.75                   | −0.67      | −2.7              | +1.7             | 152           |
| 40                           | −0.97    | 1.06                   | −0.95      | −5.7              | +2.6             | 100           |
| 55                           | −0.39    | 1.14                   | −0.66      | −1.77             | +4.61            | 52            |
| 60                           | −1.29    | 1.17                   | −1.3       | −4.8              | +1.9             | 100           |
| 80                           | +1.48    | 3.58                   | +0.4       | −4.0              | +14.9            | 100           |
| 85                           | +1.31    | 3.54                   | −0.12      | −2.24             | +12.2            | 51            |
| 90                           | +4.14    | 4.01                   | +3.75      | −2.4              | +10.0            | 100           |
| 95                           | +2.98    | 2.46                   | +5.0       | −2.16             | +5.0             | 146           |

Figure 7. ‘As-found’ hygrometer measurement error distribution of 100 hygrometers at 60%rh.

would in many cases have indicated above 100%rh, were the output not limited at this value. This has some implications which are discussed further below in sections 7 and 8.

5. Initial summary of results

The main results for hygrometer error and drift are shown in figure 11. After field use, at relative humidity values below 60%rh the hygrometers were mainly found to drift downwards. Mean error in this range is up to −1.2%rh but with significant scatter, having standard deviations of order 1%rh, with a minority of individual sensors drifting upwards, not downwards.

Above approximately 60%rh, the hygrometers were mainly found to have drifted to over-read, more so at higher values in the range, with increasing standard deviation. At 80%rh, mean over-reading was approximately +1.5%rh and standard deviation approximately 3.6%rh (again with a minority of hygrometers under-reading).

At 90%rh and 95%rh, the hygrometers were seen to typically over-read, on average by 3%rh to 3.5%rh, with many reading the maximum output value of 100%rh.

Because of the adjustments applied to hygrometers, the mean errors seen after return from field use are less than the total drift. This justifies the Met Office practice of adjusting hygrometers to anticipate drift, to reduce the typical error in readings.
6. Principle of estimation of bias and uncertainty

In principle, a pooled estimate of the in-service drift of the population of hygrometers can be made by subtracting the mean ‘post-calibration’ measurement error from the mean ‘as found’ measurement error. This is valid for the majority of the range, where the data values are not capped at 100%rh.

Based on such a pooled estimate of drift in service, it would be possible in principle for the bias due to drift to be corrected in climate analysis of historic data, for measurement records known to be for this type of hygrometer.

To apply such a correction, some assumption has to be made for the rate of drift over time. In the absence of full information, a correction of half of the full in-service drift might be applied. This corresponds to assuming that the drift of a given sensor takes place uniformly over the usage period of a sensor, or alternatively that for a set of sensors in use, at various stages of drift, the average among them will have undergone the equivalent of half the total typical drift.
The mean sensor drift is found by evaluating equation (3) and can be fitted approximately by a polynomial

\[ y = -0.0016x^2 - 0.0918x + 0.376, \]

where \( y \) is the mean drift, in percent relative humidity, as a function of relative humidity, \( x \). Based on this, an estimate of bias in observations due to drift could potentially be made corresponding to half the total drift.

However since the Met Office hygrometers are adjusted before being put in service, drift is partially compensated. Hence the observation bias is better represented as being the mean of the initial error (after adjustment) and the final error after field use. The graph in figure 12 shows both estimates of hygrometer observation bias, derived from the mean error after field use and also from the estimated mean drift. Here, estimates of bias use the data at 90%rh and 95%rh, but it is recognised that in this range it may not be valid to infer bias from values of drift, because of the censored form of the data.

For unadjusted hygrometers, the estimated mean bias would range from \(-0.8\%\) rh at 20%rh, up to \(+2.7\%\) rh at 95%rh, passing through zero near 60%rh. For hygrometers adjusted according to the Met Office approach, the estimated mean bias would be within \(\pm0.5\%\) rh between 20%rh and 85%rh, and \(+1.1\%\) rh at 95%rh. Overall, such an estimate of bias in principle allows a correction to be made, to give a best estimate of mean humidity condition, for the data for a given sensor type and calibration regime.

Suitable uncertainty needs to be attributed to such an estimate of bias, or its correction. Although this remains as further work to be completed, some initial comments can be made. For the example presented here, the overall uncertainty should take into account the uncertainty in mean values due to scatter of data for both ‘as-found’ values and values at

\[ \text{Figure 11. Graph showing estimates of mean residual error of adjusted calibrated hygrometers (hollow dashed line), mean error after field use (dash-dot line), and total hygrometer drift (solid line).} \]

\[ \text{Figure 12. Graph showing estimates of mean bias, with adjustment of hygrometers (dashed line) and without adjustment (dotted line). For comparison, the mean errors before and after field use, and estimated total drift are also shown.} \]
calibration. It should include the uncertainty of calibration, and of determining the as-found error by comparison with a reference value. It should take into account the possible difference in hygrometer measurement response at +10 °C and +23 °C when comparing as-found and post-adjustment results. Uncertainty in applying the findings to wider temperature ranges would also need to be considered. Additional uncertainty is incurred in approximating the data using a smooth fitted function. Most importantly, if the bias is not corrected, then this itself is a source of uncertainty in using the data.

The censored form of the datasets at 90% rh and 95% rh means that uncertainty in this range will be more difficult to evaluate. Some considerations for this are discussed in the following section.

7. Discussion

This work addresses the interpretation of aggregated humidity data, for the production of global climate datasets. In this context, the key question is; for a given mean reported humidity (for a group of readings from many sensors, or at many times, or both), what is the best estimate of the actual mean humidity condition during those measurements.

The initial results of this study quantify, for a large pool of sensors, estimates of drift in service, at selected values of relative humidity. With suitable care, this information can potentially be analysed to provide estimates of the bias and uncertainty when pooled data from such sensors is used.

The datasets of order 50–150 here are large enough for mean and standard deviation of the data to be calculated with reasonable accuracy. However, it is instructive here to look not only at summary statistics but also at the information available about the distribution, in order to identify how to evaluate standard uncertainty and probabilistic coverage intervals. Datasets of this size are less than satisfactory for establishing the exact form of the distributions. Nevertheless, some points can usefully be understood.

The data distributions fall into three broad cases: data distributed approximately normally; data with a significantly skewed distribution; and censored-form data including values artificially capped at 100% rh, leading to a sharp peak at this value.

For the approximately normally distributed datasets, mean and standard deviation can meaningfully be evaluated. The estimation of intervals corresponding to coverage probabilities does not pose any special challenge. For data in skewed distributions, such as at 80% rh and 85% rh, mean and standard deviation of the data can still be evaluated. However, the asymmetry of the distributions needs to be taken into account in evaluating uncertainty; it will not be satisfactory to use a symmetrical coverage interval to provide a chosen coverage probability of (say) 95%. Instead, approximate coverage intervals might be estimated directly from the data, by constructing a corresponding cumulative distribution function (CDF), and basing intervals on the area under the CDF curve.

For the censored-form distributions (90% rh and 95% rh), although mean and standard deviation can be calculated, these do not usefully characterise the distribution in a way that can clearly link to the corresponding real conditions at the time of measurement. They cannot correctly be used for a realistic estimate of bias; it will be underestimated. Therefore the treatment reported here is only approximate for this range.

For the results from 80% rh upwards, the median is useful measure of centrality of the data. In general the difference between the mean and the median is a measure of skewness of a distribution. For the data at 90% rh, the median is a useful indicator, because the mean is strongly affected by the capped data. For the data at 95% rh, the median is within the proportion of the data artificially capped at 100% rh, and the difference between mean and median appears low, as does the standard deviation. These can be evaluated, but taken in isolation they would fail to characterise how anomalous the data are.

The artificial limiting of hygrometer readings to a maximum value of 100% rh has interesting practical implications. In nature, conditions of supersaturation are rarely seen, if ever. Because of this, there is an apparent logic to limiting the range of a hygrometer to prevent it reading 101% rh, or higher. But where the reading is in error, corrections can be applied arithmetically so long the readings are not artificially constrained in range. As it stands, however, when an instrument in this study reads 100% rh, information is lost because it could not read higher. When using the data distribution, or summary statistics, to infer information about the measured condition, this cannot be done well for censored-form data. Unfortunately, this consequence of the censored distribution may not be apparent to users of weather station humidity data for climate purposes. It is therefore recommended that hygrometers for meteorology should not be limited in reading at 100% rh. Secondly it is recommended that workers interpreting data of measurements at high relative humidity, especially using summary statistics, should be aware how censored-form distributions resulting from artificially range-limited hygrometers can distort the possible interpretation of the data.

In reporting this preliminary study, there are a number of points that have not yet been fully addressed, or which need to be qualified. The work reported here is intended to demonstrate both the potential magnitude of hygrometer drift, and a potential approach to quantifying this. The study involved only one type of sensor; conclusions are shown for this example only. In addition is it recognised that relative humidity observations derived from dew point, or from psychrometer wet-bulb readings, require different treatment. The approach of the study is applicable for instruments and methods that are used consistently over a period of time. In fact, since the period covered by this study, both the hygrometers and the Met Office practices have been gradually refined, so that what is presented here is a ‘snapshot’ of that period. Finally further work is needed to develop uncertainty evaluation as detailed above in section 6.

8. Conclusion and plan for future work

The work presented here proposes a methodology for analysing calibration records of weather station hygrometers in order to derive a generalised estimate of bias for measurements made using these hygrometers. The analysis here provides estimates...
of bias as a function of uncertainty in this bias estimate. The demonstration here used data for a particular instrument type, and showed that the estimated mean drift ranges from about $-1.7\%$rh at $20\%$rh to $+5.5\%$rh at $95\%$rh, with significant scatter around these mean values. The drift observed justifies the Met Office practice of adjusting hygrometers to anticipate drift, in order to minimise the typical error in readings.

This information is of potential use in attributing uncertainty or bias to observations, but particularly in analysis of observations in a climate context where aggregated data are used. Mean bias can be estimated based on estimates of mean drift for the hygrometers studied. From the total drift, resulting estimates of mean bias in observations are approximated to be half the drift, and therefore ranging from about $-0.8\%$rh at $20\%$rh up to $+2.7\%$rh at $90\%$rh. For the Met Office hygrometers, which have been adjusted to anticipate sensor drift, estimates of observation bias are smaller, being within $\pm 0.5\%$rh between $20\%$rh and $85\%$rh, and rising to $+1.1\%$rh at $95\%$rh.

It is interesting to note that for these sensors, the mid-range values of humidity were the least affected by instrumental drift. This suggests that, for this instrument type, data in the middle part of the range near $60\%$rh may be the most reliable. Drift is found to be worst in the range approaching $100\%$rh. Observations near $100\%$rh are of key importance, this being the threshold for formation of dew, rain, fog and cloud. In the context of climate, air at the highest relative humidity corresponds to the maximum water content and hence the maximum stored energy, at any given temperature. However, this range of special interest is also the most challenging for characterising hygrometer bias and the uncertainty in this.

The demonstration here used data for hygrometers of a particular type, but the approach is more widely applicable. It could be of use for any instrument type where significant drift occurs in use, where there is continuity of the sensing component (not completely replaced) and where calibration records contain ‘as found’ calibration results for the instrument as well as calibration results after adjustment.

There are many further steps desirable to continue and extend this work. Further study based on the data distributions could enable expression of the uncertainty in mean values (and therefore of estimates of bias), in terms of coverage interval, coverage factor and coverage probability. In addition, it would be of interest to analyse subsets of the data which might reveal correlation of drift with sensor age, time spent in service, season of use, or types of location of deployment, such as coastal or polluted areas. It would be desirable to make studies of when drift takes place (on early exposure to condensation, or linearly over time) to inform the best estimate of bias. It is known that not all makes or types of electronic humidity sensor drift in the same way, or to the same extent. Similar studies of other humidity sensor types used in weather stations would also be desirable, particularly for those in climate reference networks. Future studies are more likely to take advantage of data that are already in electronic form.

From the study so far, some initial recommendations can be made. Firstly, users of weather-station data for analyses of climate and other studies should take note of the nature of humidity sensor characteristics. This opens up the possibility of applying some correction or uncertainty for bias in humidity observations due to drift from electronic hygrometers, bearing in mind that sensor types will differ. Users of such data should be informed about how the censored-form distribution of weather-station humidity data near $100\%$rh adversely affects the validity of using summary statistics such as mean and standard deviation.

Secondly, the authors suggest that in weather stations, where high and condensing humidities are of key interest, there is little benefit in the artificial capping of readings of relative humidity instruments at $100\%$rh. While users of the data would be free to reject readings above $100\%$rh, availability of such readings would be a resource usable to characterise bias and uncertainty of aggregated humidity data. Capping readings at $100\%$rh impedes this, and also compromises the interpretation of any genuine readings of $100\%$rh. In addition, the availability of readings above $100\%$rh would provide a useful alert to service personnel of sensor drift. It is recognised, however, that any change in this convention would have significant implications for reporting practices.

There are other potential changes to practices that could improve outcomes. As already mentioned in section 1, better recording and reporting of metadata such as hygrometer type would ideally support the interpretation of weather station hygrometer data, especially to distinguish between electronic hygrometers and wet- and dry-bulb instruments. In addition, the ability to apply calibration corrections (not just adjustments) arithmetically to individual sensors would be desirable, although this is currently not feasible. Another obvious improvement would be to use sensors with improved drift characteristics as these become available. There are frequent developments in humidity sensors, and in related technologies such as sensor heating. As such alternatives are considered, or are introduced in weather stations, they too need to be studied to assess the impact on humidity observations and on the uncertainty in reported humidity values.

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