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LETTER

Reduction in reversal of global stilling arising from correction to encoding of calm periods*

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Abstract

We describe an undocumented change in how calm periods in near-surface wind speed (and direction) observations have been encoded in a subset of global datasets of sub-daily data after 2013. This has resulted in the under-estimation of the number of calm periods for meteorological stations across much of Asia and Europe. Hence average wind speeds after 2013 have been over-estimated, affecting the assessment of changes in global stilling and reversal phenomena after this date. By addressing this encoding change we show that globally, since 2010, wind speeds have recovered by around 30% less than previously thought.

1. Introduction

Terrestrial near-surface wind speed (i.e., ~10-m above the ground as recommended by the World Meteorological Organisation, WMO 2018) is a key meteorological and climate variable (e.g. Pryor *et al* 2006). Wind transports not only moisture around the globe, but also plant pollen, insects and birds (e.g. Nathan & Muller-Landau 2000, Rayner 2007, McMahon *et al* 2013, Donohue *et al* 2010, McVicar *et al* 2012a), as well as pathogens, pollutants and scents. Furthermore, electrical power from wind resources is an increasingly important part of the global renewable energy mix (Veers *et al* 2019). Extreme winds associated with tropical and extratropical storms cause damage to lives, infrastructure and the natural world (e.g. Schwierz *et al* 2010, Cui & Caracoglia 2016).

Monitoring of global near surface winds has shown a decline in the average speeds from the early 1970s to around the mid-2010s, which was termed 'stilling' (Roderick *et al* 2007, McVicar *et al* 2012b). Several causes have been proposed for this decline (see Wu *et al* 2018 for an overview), including an increase in surface roughness induced by the greening of the planet (Vautard *et al* 2010; Zhu *et al* 2016) or urbanisation (Chen *et al* 2020; Zhang *et al* 2022), natural variability induced by internal decadal ocean-atmosphere oscillations (Zeng *et al* 2018, 2019), or errors induced by instrumentation issues (Azorin-Molina *et al* 2018a).

More recently, a slowing, cessation or even reversal of this stilling has been noted (globally e.g. Azorin-Molina *et al* 2020, 2021, Zeng *et al* 2019; and regionally e.g. Kim & Paik 2015, Azorin-Molina *et al* 2018b, Chen *et al* 2019, Zhang *et al* 2021, Wu & Shi 2021, Utrabo-Carazo *et al* 2022), with suggested causes being uneven

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surface heating or reversal of long-timescale (decades) ocean-atmosphere oscillations (see also IPCC AR6 WGI [Gulev *et al* 2021]).

Many of these studies of the change in wind speeds use datasets that are based on the Integrated Surface Dataset (ISD, Smith *et al* 2011, Lott 2004), a large global holding of sub-daily, multi-variate climate observations. It was produced and is regularly updated by the National Oceanographic and Atmospheric Administration's (NOAA) National Centre for Environmental Information (NCEI). It contains over 35,000 stations that report on a sub-daily basis and for multiple variables, though many of these have short records. The ISD itself comprises over 100 sources, ranging from some with a handful of stations to others with 1,000s of sites. The largest collection arises from archival versions of real-time GTS (Global Telecommunications System, WMO 2015) transmissions. Many years of work have been involved with the creation and curation of this valuable resource. Other products have been built upon the ISD, including the Global Summary of the Day (GSOD) by NOAA-NCEI, and the HadISD (Dunn *et al* 2012, 2016, Dunn 2019) by the Met Office Hadley Centre.

The GSOD is an automated derivative of the ISD, and daily summaries are available a few days after the time of the observations. The records start in 1929, and there are over 9,000 stations available with data stored in Comma Separated Value (CSV) files (US-imperial units). To derive the daily summary, a minimum of four observations must be present in the day.

The HadISD takes a subset of the longest and most complete stations in the ISD, performs further compositing and detailed quality control to produce a global synoptic database of sub-daily observations for over 9,000 stations at the last release (v3.3.0.202202p, 7 March 2022). The data are stored in Network Common Data Format (netCDF) files, starting in 1931 using SI units. Updates that append to the current calendar year are performed monthly, with major updates that also refresh the station list occurring annually. The HadISD has formed the basis of the annual monitoring of winds in the Bulletin of the American Meteorological Society - State of the Climate reports in recent years (e.g. Azorin-Molina *et al* 2021).

2. Missing calm periods in the Datasets

To demonstrate an issue with calm periods in recent years in these datasets, we use the HadISD 3.2.0.2021f to calculate the daily average wind speed between 00 and 23UTC for those days which have at least one observation in each 6-h quadrant of the day, following the methodology presented in e.g. Azorin-Molina at al., 2021, 2020. To ensure even coverage across each calendar year, we further restrict to stations that have sufficient daily data in each month (75%), at least two months within each 3-month season (JFM, AMJ, JAS, OND) and at least three seasons for each year. Finally, to ensure good temporal coverage across years, we only use stations where annual values could be calculated for at least 26 out of the 30 years over 1981–2010 (>85% complete). This reduces the station count from over 9,000 to around 2,500.

We extract the 'calm fraction' directly from the sub-daily observations for these selected stations, by calculating the 'non-calm' fraction (wind speed > 0 m s^{-1}) and subtracting from 1. We show two example years in figure 1 (2012 & 2014). We note that the definition from the WMO is that 'Calm should be reported when the average wind speed is less than 1 kt (0.5 m s^{-1}) (WMO 2018). Older anemometers were less sensitive than modern instruments, and so the starting speed and occurrence of calm periods could be higher in earlier decades than in more recent times, when more sensitive anemometers (including sonic wind sensors) were included in automatic weather stations (AWSs). However, as the ISD uses reported weather data, we can use the value of 0 m s^{-1} for calm periods.

As shown in figure 1, the fraction of calm periods for large numbers of stations in Asia and parts of Europe in 2014 are (very close to) 0%, which is strikingly different to the values in 2012. To show this another way, we look at the sub-daily wind measurements from a single, example station in this region in figure 2. We show time series for a single example station from both the sub-daily HadISD (figure 2(a)) and the daily GSOD (figure 2(b)). The absence of any calm periods after around 2013 is very clear in the bottom right of both these time series plots. As figure 1 strongly suggests that this is a concern for a large part of the globe including most of Asia and parts of Europe, we show in figure 3 the calm fractions globally and regionally.

It is unlikely that this abrupt breakpoint in the frequency of calm periods in 2013 in figure 3 is the result of changes to instrumentation across a wide network. First, the magnitude of the change in individual stations resulting in no calm periods at all is too large as even in windy parts of the world some rare calm periods would be expected in the sub-daily HadISD data. Second, the geographically broad nature of the change over a comparatively short time-period, affecting most of Asia and Europe, rules out a planned change to more sensitive instrumentation as network-wide changes to this many stations cannot be done instantaneously. And third, as outlined in section 3.1, an undocumented change in the encoding of calm periods in a database of global sub-daily wind speed observations has been confirmed in a data source of the ISD.

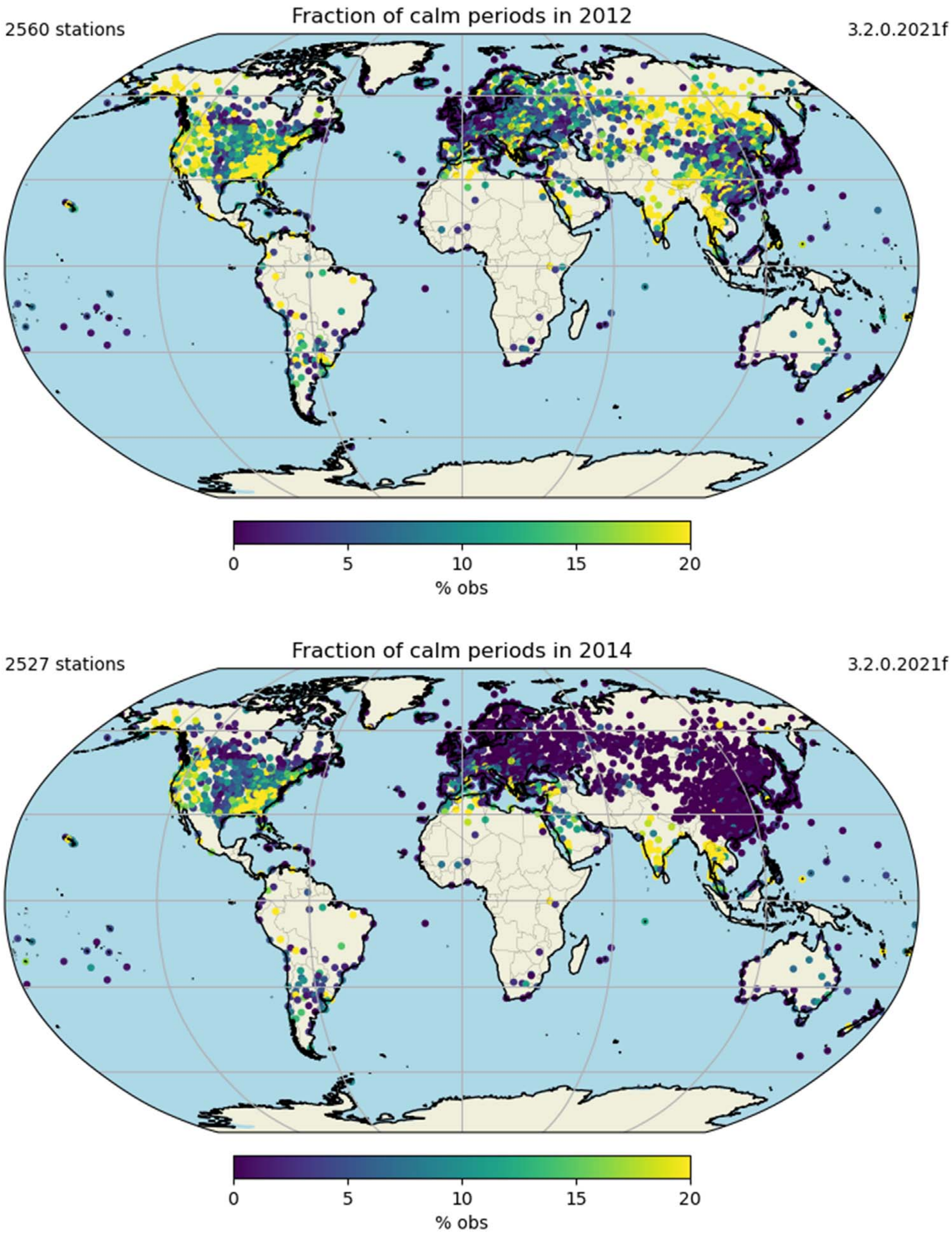

Figure 1. Maps of the percentage of calm periods (0 m s^{-1}) per station in 2012 and 2014.

Studies based on ISD derived datasets (including HadISD and GSOD) may not have adjusted for this erroneous feature, and so under-represent calm periods in their analyses. In the case of calculating average wind values, these will be over-estimated by the absence of calm periods in the individual station time series. In particular, Zeng *et al* (2019) show a reversal of global stilling around 2010, which has also been noted regionally in the BAMS State of the Climate monitoring reports (e.g. Azorin-Molina *et al* 2020, 2021) and other studies (see Introduction). We show in section 4 how part of this reversal may be due to the absence of calm periods from these global analyses. In addition, we should expect a higher frequency of calm periods for the first decades of the series compared to the last years, as old 3-cup anemometer sensors were less sensitive to measure weak wind speeds.

3. Encoding of calm periods

To explain what has happened to the encoding of calm periods in these datasets from a user perspective, we turn to the ISD. The ISD station data files are fixed-format ASCII files, where the column number(s) of (a set of) characters determine their meaning (see the ISD format document at https://www1.ncdc.noaa.gov/pub/data/noaa/isd-format-document.pdf; last accessed 18 March 2022, see also figure 4). Wind speed and direction (columns 61–70) are documented to be encoded as follows:

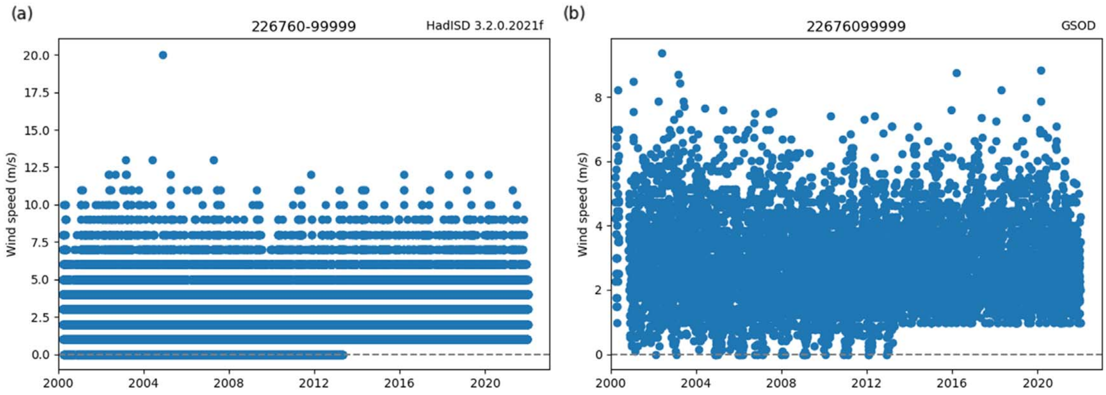

Figure 2. (a) Time series of *sub-daily* wind speed values for station Id. 226760–99999 (Sura, Russia, 63.58 N, 45.63E, 62.0m a.s.l.) from HadISD v3.2.0.2021f over 1-Jan-2000 to 1-Jan-2022. (b) Time series of *daily* wind speed values for 22676099999 (same station) from GSOD over 1-Jan-2000 to 1-Jan-2022 and converted to m s^{-1} [downloaded 25 January 2022]. The absence of calm (0 m s^{-1}) periods after 2013 is clear in both panels.

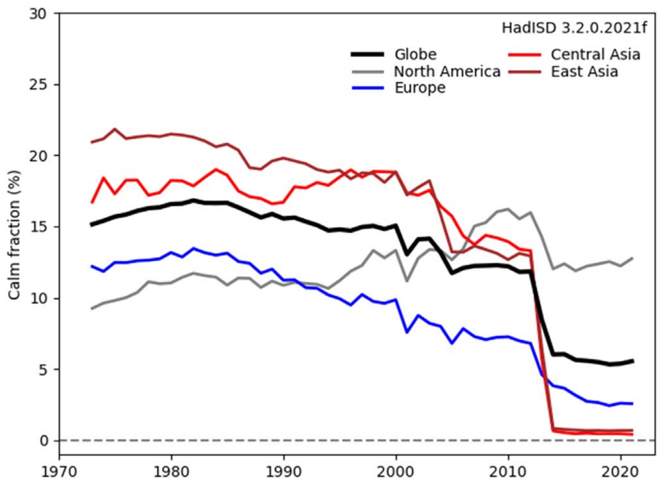

Figure 3. Calm fractions globally and regionally, using the regions as presented in the BAMS State of the Climate (Azorin-Molina *et al* 2021) from HadISD v3.2.0.2021f.

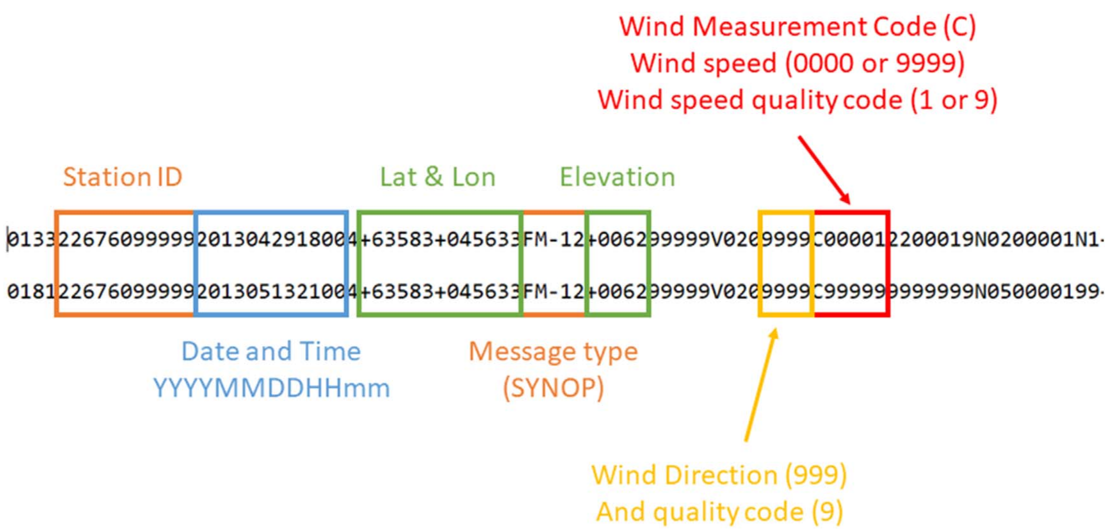

Figure 4. Example of ISD data for 226760–99999 (Sura) showing how 'calm' conditions were encoded before (April 2013) and after (May 2013) the encoding change.

61–63	Wind direction angle (000–360)
64	Wind direction quality code (0–9)
65	Wind measurement code (e.g. N-normal, C-calm, V-variable)
66–69	Wind speed (in 1/10ths m s)$^{-1}$
70	Wind speed quality code (0–9)

Missing values in the wind direction and speed are given by '999' and '9999', respectively, though the ISD guidance notes that with a 'V' measurement code, a missing wind direction denotes a variable direction, and a '9' measurement code with '0000' for the speed, indicates that conditions were calm. Hence, prior to 2013 and as the documentation suggests, calm periods were stored as '0000' with a measurement code of 'C' or '9'. However, during 2013, coding practice changed so that for some stations calm periods are given as '9999' and are only indicated by the calm measurement code ('C'), see section 3.1. The undocumented use of the missing data indicator has meant that downstream datasets of the ISD have not captured the times when calm winds were occurring, affecting both HadISD and GSOD and hence also studies using these datasets.

The results shown in figures 1–3 indicate that both HadISD and GSOD have used the missing data indicator without the extra information present in the data measurement flag 'C', and hence calm periods are replaced by missing data.

During calm periods, the wind direction is clearly not measurable. A standard set of conventions used for wind speed and direction are presented in De Gaetano (1997) and formed part of the quality control checks applied in HadISD (Dunn *et al* 2016). These indicate that for calm periods a direction of 0°N is used, whereas northerly winds are given a direction of 360°N. The HadISD QC replaces missing directions with 0°N in calm periods to follow this convention.

3.1. Cause and correction

To look into this in more detail, we traced the issue through the datasets which comprise the ISD to one provided by the Federal Climate Complex (FCC) of the United States Air Force (USAF) 14th Weather Squadron. They have confirmed that the encoding issue started on 1 May 2013 with the implementation of the JM (Joint METOC) Decoder (METOC = METeorology and OCeanography) at Offutt Air Force Base (Nebraska), home of the 557th Weather Wing. The issue affects report types of FM-12 (SYNOP, report of surface observation from a fixed land station), FM-13 (SHIP, report of surface observations from a sea station), and FM-14 (SYNOP MOBIL, report of surface observation from a mobile land station). Full details of the encoding issue are given in the appendix. Other messages decoded as part of the USAF's role or messages incorporated into the ISD through other routes are not affected by this issue. These message types are received from meteorological stations across the globe, and so the issue is worldwide, though NCEI uses a NOAA data source in ISD for stations in the USA. The NOAA data take precedence over the USAF surface observations database in ISD so stations in the USA are unaffected by this issue.

The USAF have addressed this issue going forward for observations after 1600 UTC 15 March 2022, and will rectify the decoding done on earlier BUFR (Binary universal Form for the Representation of meteorological data) and TAC (Traditional Alphanumeric Codes) messages in the near future. In due course, this will ensure a correct record that will be available in the archives and datasets of climate data.

4. Correction and impacts

As the correction to past data will take some time to filter through, starting in HadISD 3.3.0.202201p, the ISD ingestion routines have been amended to account for the measurement code 'C' and in those instances overwrite the missing data indicator with 0 m s^{-1}. We show in figure 5(a) that this recovers the calm periods for the example station from figure 2, and reduces the inhomogeneity in the global and regional calm fractions in figure 5(b) compared to figure 3.

The simple correction applied to the HadISD data presumes the measurement code ('C') correctly identifies calm periods. One action of the decoder was to set the measurement code to calm even when TAC messages contained missing wind values. In this case the simple correction to HadISD will over-correct by overwriting true missing values with 0 m s^{-1}. However, this is unlikely to be a substantial fraction of the affected observations, as figure 5(b) shows no indication of a meaningful increase in calm wind fraction after 2013 in comparison to values before that time. In the longer term, the efforts to correctly decode calm periods will be brought through into the HadISD, and the simple correction will no longer be needed.

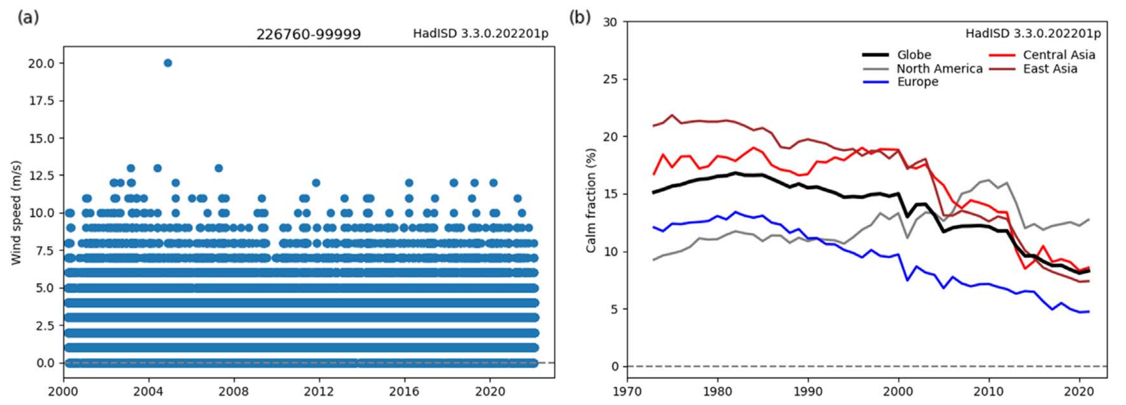

Figure 5. (a) Wind speeds from 226760–99999 as for figure 2, and (b) the global and regional calm fractions as for figure 3, but using the revised HadISD dataset (v3.3.0.202201p).

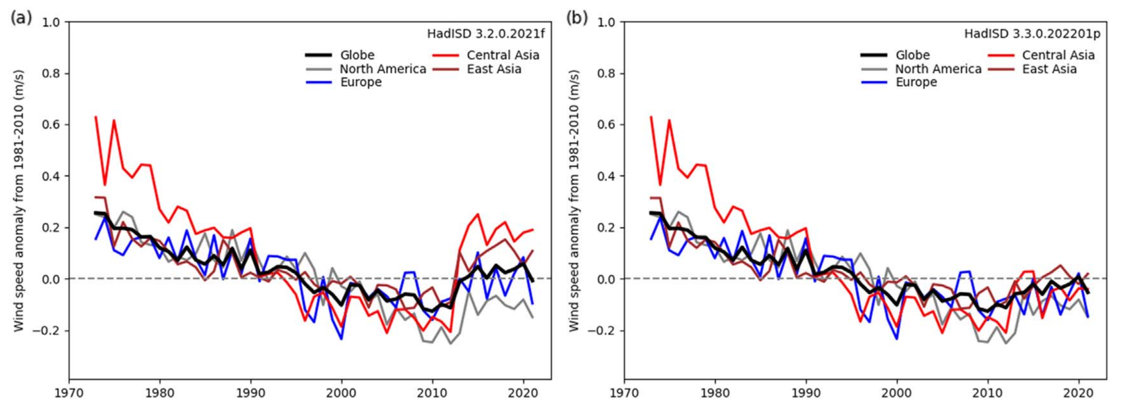

Figure 6. Average wind speed anomalies (m s^{-1}, relative to 1981–2010) for the globe and regions from the HadISD dataset; (a) version 3.2.0.2021f with calm periods missing from 1st May 2013 onwards and, (b) version 3.3.0.202201p with calm periods restored. Following the approach in Azorin-Molina *et al* 2020, 2021.

We use this updated version to replicate the analyses presented in the BAMS State of the Climate report (Azorin-Molina *et al* 2021), and show the impact on the global average wind speed in figure 6. This approach selects stations for record length and completeness to obtain wind speed anomalies from 1981 to 2010. Averages are then taken globally and for northern hemisphere regions. Low station densities in the southern hemisphere mean that the global value is dominated by changes in the northern hemisphere as each station is given the same weight when calculating the average anomaly values.

Using the uncorrected GSOD, Zeng *et al* (2019) show that by 2017 wind speeds had returned back to levels last seen in the late-1980s. And similarly, using the uncorrected versions of HadISD, Azorin-Molina *et al* (2021, 2020) show a rapid reversal in the early 2010s, followed by stable wind speed anomalies at values last seen in the early-1990s. Compared to both Zeng *et al* (2019) and Azorin-Molina *et al* (2021), this simple correction to restore calm periods in HadISD reduces the apparent reversal in global wind speeds since around 2010 (figure 6). Using the global values in figure 6, and starting from a lowest global anomaly of -0.133 m s^{-1} in 2010, global wind speeds were seen to recover to a 5-year average (2017–21) of 0.025 m s^{-1} without the correction. After correction, they recovered only to -0.030 m s^{-1}. Hence, the correction of the treatment of calm periods results in around a 30% reduction in the magnitude of the global wind speed reversal. By restoring the calm periods in HadISD, the reversal of global windspeeds is reduced, reaching values last seen around 2000. And regionally in figure 6, the effect of correctly including the calm periods is apparent in Central and Eastern Asia when compared to Azorin-Molina *et al* (2021, 2020).

In contrast, the regional assessment by Yang *et al* (2021) shows that no reversal in winds is seen in over China using an independent dataset from the Chinese Meteorological Agency, whereas by comparison they show HadISD and GSOD, both of which show a reversal (both versions of which contain the issue described above). More detailed investigations into the reversal are needed, globally and also regionally, where independent data sources can help to identify problems in the underlying data holdings.

As noted in Menne *et al* (in prep) , the ISD is being replaced during late 2022, with a new Global Historical Climate Network Hourly (GHCNH) dataset taking its place in the NOAA/NCEI dataset offerings. GHCNH has been co-developed with a Copernicus Climate Change Service (C3S) providing access to *in situ* observations (Thorne *et al* 2017, Noone *et al* 2021). These efforts are also including the parent datasets of the ISD, and this issue is present in these products too, until such time as the USAF has corrected the decoding of past messages. However, the documentation will be updated and clarified to ensure that users can make informed decisions on how to manage calm periods in these datasets while the issue persists.

5. Summary and outlook

We have presented a previously undocumented change in how calm periods (0 m s^{-1}) in wind speed (and direction) have been encoded in global datasets of sub-daily data between May 2013 and March 2022, affecting the ISD and its downstream products (including HadISD and GSOD). This manifests clearly when plotting the fraction of calm observations in each calendar year for each station, with a notable change after 2013. We show details of the encoding change so that users of the ISD can be aware of this, and also confirm that data affected by this will be reprocessed.

By implementing a simple correction to the HadISD dataset, we show that calm periods are successfully recovered from version 3.3.0.202201p onwards We use this corrected HadISD version to calculate the global and regional wind anomalies over time to show the effect on monitoring studies of global and regional stilling and the reversal phenomena. For instance, the reversal of global wind anomalies after around 2010 is reduced by around 30% when taking these previously missing calm periods into account.

Forthcoming datasets from NOAA and C3S will replace the ISD with improved workflows and increased sub-daily station counts. We look forward to their release and investigations into the long-term behaviour of surface winds with an increased set of surface stations.

Herein we have presented the discovery, details and correction of one artefact in global climate data archives. As is the nature with these human endeavours, it is very likely that this will not be the last. Therefore, we encourage data users to report issues found in datasets back to the data providers to enable them to be investigated, and by so doing improve the global climate record for all.

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Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://www.ncei.noaa.gov/products/land-based-station/integrated-surface-database.

Data Statement

The ISD is affected by the issue described in this manuscript for data between 1 May 2013 and 15 March 2022. The GSOD is an automatic product build on the ISD, and so is similarly affected. HadISD also is affected by this issue, but the adjustment described herein has recovered calms where possible over the period affected. The C3S data are also affected over the time span, and a timescale for the next public release is not yet set.

ISD - https://www.ncei.noaa.gov/metadata/geoportal/rest/metadata/item/gov.noaa.ncdc%3AC00532/html# [Not accessed directly during this analysis]

HadISD - https://www.metoffice.gov.uk/hadobs/hadisd/ [v3.2.0.2021f accessed 2022–01–25, v3.3.0.202201p accessed 2022–02–07]

GSOD - https://www.ncei.noaa.gov/access/metadata/landing-page/bin/iso?id=gov.noaa.ncdc:C00516 [Downloaded 2022–01–25]

C3S In situ observations - https://cds.climate.copernicus.eu/cdsapp#!/dataset/insitu-observations-surface-land?tab=overview [Not accessed directly during this analysis]

Appendix

The details of the three separate decoding/encoding errors are given below

1. BUFR. The decoder incorrectly set the wind measurement code to N (normal) and usually had a direction. We fixed this to set the code to C and remove the direction.
2. TAC where calm was encoded. The decoder set the wind condition code to C (calm), but some wind speeds were 0 m s^{-1} and some were null/missing (9999). The fix was to identify the observations encoded as calm and set the wind speed to 0 m s^{-1}.
3. TAC where missing wind was encoded. Decoder set the wind condition code to C (calm), but some wind speeds were 0 m s^{-1} and some were null/missing (9999). The fix was to identify the observations encoded as missing and set the wind speed and wind condition code to null.

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