Completeness of radiosonde humidity observations based on the IGRA

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Abstract. Radiosonde measurements from the 1930s to present give unique information on the distribution and variability of
10 water vapor in the troposphere. The sounding data compiled in the Integrated Global Radiosonde Archive (IGRA) Version 2
(released by the NOAA's National Centers for Environmental Information) are examined here until the end of 2016, aiming to
describe the completeness of humidity observations from radiosondes in different times and locations. The IGRA stations
reporting radiosonde data in at least 5 % of the annual soundings for at least one year are evaluated according to specified
completeness parameters for every year in their period of record. The selection of source data essentially removes pilot-balloon
15 sites, retaining a set of 1723 stations (designated 'IGRA-RS'), including 1300 WMO upper-air stations, of which 178 belong
to the current GUAN network. Completeness of humidity observations (either relative humidity or dewpoint-depression) for
a radiosonde station and a full year is defined by: the number of humidity soundings; the fraction of days having humidity
data; the mean vertical resolution of humidity data; the mean atmospheric pressure and altitude at the highest measuring level;
and the maximum number of consecutive days without humidity data. The completeness of the observations qualified for
20 calculating precipitable water vapor – i.e., having adequate vertical sampling between the surface and 500 hPa – is particularly
studied. Individual soundings are described by the (vertically averaged) vertical resolution and the pressure level and altitude
of the top of humidity measurements. For illustration, the study presents a global picture of the completeness of radiosonde
humidity observations over the years, including their latitudinal coverage. This overview shows that the number of radiosonde
stations having a long enough record length for studies on the climatic variability and trends of humidity-related quantities
25 depends critically on the temporal continuity, regularity and vertical sampling of the humidity time-series. It is hoped that the
derived metadata will help climate and environmental scientists to find the most appropriate radiosonde data for humidity
studies by selecting upper-air stations, observing years or individual soundings according to various completeness criteria –
even if differences in instrumentation and observing practices require extra attention. A dataset is presented for that purpose,
consisting of two main sub-sets: 1) humidity metadata for each of the IGRA-RS stations and year within the period of record
30 (yearly metadata); and 2) humidity metadata for individual observations from the same stations (ascent metadata). These are
complemented by 3) a list of the stations represented in the dataset, along with the observing periods for humidity and the
corresponding counts of observations. The dataset is to be updated on a two-year basis, starting in 2019, and is available at
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1 Introduction

For more than three-quarters of a century, the global radiosonde network designed and developed for weather forecasting has provided in situ observations of humidity from the surface up the middle troposphere, eventually reaching the stratosphere. Satellite-based remote sensing of atmospheric water vapor is part of modern weather forecasting and climate monitoring (Kley
5   et al., 2000; Andersson et al., 2007). In the present state-of-the-art, some satellite retrievals of moisture-related quantities are used as a reference to compare humidity measurements from different radiosonde types, aiming to monitor radiosonde stations and improve satellite calibration (Kuo et al., 2005; John and Buehler, 2005; Sun et al., 2010; Moradi et al. 2013). However, limb-sounding satellite techniques with high vertical resolution (albeit very course in the horizontal), using GPS radio-occultation, are a recent acquisition, of main interest to access water vapor in the upper troposphere and lower stratosphere so
10   far (Kishore et al., 2010; Shangguan et al., 2016; Rieckh et al., 2018; Vergados et al., 2018). Reanalysis outputs based on past radiosonde data, assimilating also satellite data when available, offer multiple-level, global gridded, synoptic-scale moisture fields up to 4 times daily from 1948 (as in NCEP/NCAR products) to present time – even though radiosonde observations are scarce over the ocean, unevenly spaced over land, and taken normally twice a day, not to mention differences in vertical coverage. Naturally, since air moisture is highly variable in time and space, humidity data from different reanalysis models
15   show discrepancies and can differ significantly from the collocated radiosonde data (e.g., Noh et al., 2016). Therefore, the radiosonde archives represent the primary source of information on the short-term and long-term distribution of moisture in the troposphere, despite sampling differences among stations and over time, minor uncertainties related to observation time and balloon drift (Kitchen, 1989), and differences in data accuracy – which depends on humidity sensors and varies with measured conditions (e.g., Nash, 2002).

20   The growth interest in climate change motivated a renewed attention to radiosonde data since the 1990s. Soon it was realized that the usefulness of radiosonde data archives to investigate climate trends relies on homogenization procedures to overcome biases and sudden shifts arising from instrument changes and sampling differences (Elliott and Gaffen, 1991; Schwartz and Doswell, 1991; Parker and Cox, 1995, Luers and Eskridge, 1998). Subsequent climate studies based on radiosondes have mostly focused on the detection of climate change in temperature trends (Free and Seidel, 2005; Thorne et
25   al., 2005; Haimberger et al. 2008). Concerning humidity, radiosonde-based climatic studies are for now confined to the lower and middle troposphere, because of the large errors and insufficient data in the upper troposphere and lower stratosphere. Radiosonde data have been used for studying the long-term trends and the annual cycle of several humidity parameters (precipitable water vapor, specific humidity and relative humidity), at least in well-sampled regions of the globe and if data inhomogeneities are removed (Elliot et al., 1991; Gaffen et al., 1992; Ross and Elliott, 1996; Ross and Elliot, 2001; McCarthy
30   el al., 2009; Durre et al., 2009). On a rather different scale, radiosonde measurements with high vertical resolution near the ground are suitable for studying water evaporation over land and the structure of the planetary boundary layer, provided that the lag of humidity sensors as they move through a rapidly changing environment is accounted for (Sugita and Brutsaert, 1991; Connell and Miller, 1995; Seidel et al., 2010.

Since its creation in 2004, the Integrated Global Radiosonde Archive (IGRA) was meant to be the largest data set of up-to-date weather-balloon observations freely available, by collecting quality-controlled data from upper-air stations across all continents. The first version contained practically data after 1945 (Durre et al., 2006). The IGRA Version 2 used in this paper (Durre et al., 2016) extends back in time as early as 1905, although humidity data begin in 1930 with a sole location in

5   Europe. The extension to observations prior to 1946 resulted mainly from the addition of data from the Comprehensive Historical Upper-Air Network (CHUAN), which is the most important collection of upper-air observations taken before 1958 (Stickler et al., 2009). In view of the huge amount of data collected in IGRA (which is also a combination of radiosonde and pilot-balloon observations) and the differences in the observing period, temporal regularity, continuity, vertical resolution and vertical extension of humidity data among different stations, finding the most suitable humidity-reporting stations (or humidity

10   soundings from different stations) for a specific purpose can be difficult to put into practice.

The purpose of this paper is to study the completeness of humidity observations collected in IGRA according to various needs – number and latitudinal distribution of observing stations, fraction of observing days in a year, resolution and range of vertical levels, length and continuity of the time-series, minimal sampling between the surface and the 500-hPa level – aiming to facilitate the use of radiosonde humidity data by atmospheric and environmental scientists. The task is two-fold:

15   first, to elucidate the completeness of the humidity observations from IGRA for each year in global terms, including the latitudinal coverage of stations and the length of regular time-series; second, to provide metadata describing the completeness of humidity observations from each station. The observing periods without missing years in humidity data must be clarified. Latitudinal and regional differences should be easily derived from the geographic coordinates of stations.

The remain of this section is intended to clarify the term "completeness of observations" concerning the use of

20   radiosonde data and to present an historical account of the main factors that limit the completeness of humidity observations from radiosondes: vertical levels in radiosonde reports; missing observations associated with humidity sensor limitations. The next sections are organized as follows. Section 2 indicates the IGRA data set used in the study and explains the data analysis. Section 3 presents a global picture of the completeness of humidity observations over the years, as derived from the IGRA stations reporting a minimum of radiosonde data, i.e., discharging stations with practically wind-only data in their period of

25   record. Section 4 provides the definition of the metadata parameters describing the completeness of humidity observations from each IGRA station relevant to the study – both in terms of annual statistics and in individual soundings – and the format description of the corresponding data sets. The availability of the resulting dataset supplied by the study (Ferreira et al., 2018) is indicated in Sect. 5. A summary of results and some suggestions for future application are given in Sect. 6.

1.1 Completeness of observations for radiosonde humidity studies

30   Data completeness in a data set refers to the extent to which the data set collects the expected elements: quality-assured data are not left-out; missing or invalid values are properly indicated. This is a basic requirement for data quality, and it is assured in IGRA. In a different way, and uncommon, data completeness may refer to *whether the required data for a specific purpose are available or not.* That meaning is not new in the field of meteorology. For instance, the WMO recommendations on "data

completeness" (sic) required for calculating monthly means and climate normals from meteorological surface data refer to the temporal continuity and regularity of observations for different climate elements (WMO, 1989). Broadly, Bellamy (1970) discussed the acceptability of meteorological observations in terms of their degree of completeness, considering that the goal of meteorological observations is to "depict the space-time distributions of everything-atmospheric everywhere always, ever

5   more completely in ever-increasing detail"; appropriately, he used the expression *completeness of observations*. This is the terminology used in the present paper.

Concerning the completeness of radiosonde humidity observations, the vertical coverage and vertical resolution of sounding data is of first concern, chiefly between the surface and the middle troposphere (~500 hPa) regarding the precipitable water vapor content; in addition, the temporal regularity and continuity of humidity profiles are important to trend analysis

10   and to detail annual cycles. Although the vertical and temporal completeness of station-based humidity time-series can be treated separately from the issues of spatial coverage and record length of stations, it seems to us that studying the completeness of observations in a global, historical data set of radiosonde observations should address these issues too.

Several factors contribute to differences in the completeness of humidity observations among radiosonde stations and individual soundings: i) The geographical coverage of radiosonde stations evolved over time, and so, the period of usage varies

15   among stations; ii) A lack of equipment maintenance may result in interruptions of observations; iii) The number of vertical levels and vertical extent in radiosonde reports depend on the standard pressure levels in use, as well as on the reported significant levels (assuming that the balloon bursts at the proper altitude); iv) Missing humidity observations arise from difficulties associated with the performance of humidity sensors and the observing practices related to their working range. While (i) and (ii) are of a random nature, points (iii) and (iv) deserve an explanation because of historical changes with

20   implications in the vertical coverage and resolution of radiosonde humidity profiles.

1.2 Vertical levels in radiosonde observations

In radiosonde soundings, temperature, relative humidity (eventually dewpoint depression too) and wind speed and direction are measured together with atmospheric pressure; geopotential height is indirectly measured from hypsometric calculations but may be missing in radiosonde reports. As a common practice, only standard pressure levels and significant levels are stored

25   and reported. Currently, the *standard levels* are 1000, 925, 850, 700, 500, 400, 300, 250, 200, 150, 100, 70, 50, 30, 20, and 10 hPa (WMO, 1996). But historical changes deserve due attention. An inspection of the earliest soundings collected in IGRA – made in 1905 at Lindenberg, Germany, a quarter of a century before radiosondes were available – reveals temperature data reaching sometimes 100 hPa, with the reported levels being 1000, 925, 850, 700, 600, 500, 400, 300, 250, 200, 150 and 100 hPa (although most of the soundings did not reach beyond 700 hPa). Radiosonde humidity measurements at the same station,

30   as collected in IGRA, began in 1950. Nevertheless, the 150- and 100-hPa levels were first recommended by the WMO in 1953, while the levels 70, 50, 30, 20, and 10 hPa were proposed in 1957, the International Geophysical Year. Even so, the levels above 200 hPa were still referred as non-standard by the WMO in 1958, until the 100-hPa level was finally adopted that year (WMO, 1957; WMO 1958). In the years that followed, the pressure levels ≤ 150 hPa (representing roughly the stratosphere)

became common worldwide. As to the lower levels ≥ 200 hPa (representing roughly the troposphere), they were in general use since the early 1940s, with two exceptions: first, the 250-hPa level was only adopted in 1970, to satisfy aviation demands (WMO, 1970); second, the 925-hPa (within the planetary-boundary layer above low-altitude stations), although planned since 1977, was first required in WMO Antarctic stations in 1987, until it was adopted worldwide by the end of 1991 (WMO, 1977,

5   p. 15; WMO, 1987, pp. 57-58; Oakley, 1993, p. 23). Note, however, that these two levels were in use to in some stations before international agreement, and for a long time as exemplified by the Lindenberg station. Besides the standard levels, some intermediate fixed levels within the troposphere (e.g., 800, 750, 650, 600 hPa) are regularly used in some stations (Shea et al., 1994). The Lindenberg station also indicates the early use of 600 hPa. The additional (high-stratospheric) levels 7, 5, 3, 2 and 1 hPa have been used in agreement with WMO recommendations (WMO, 1970), depending on regional and national practices.

10   E.g., they form part of 'upper-level' observations in the U.S. National Weather Service (OFCM, 1997).

The number of *significant levels* – non-standard levels needed to reproduce the vertical temperature and dew-point temperature profiles, capturing turning points or abrupt changes (such as thermal inversions and the tropopause) – depend on atmospheric conditions, manual rules and, before automation, on the observers' skills. By the late 1950s, the rules for choosing significative levels were still under discussion (WMO, 1957), being established over time by WMO regulations (WMO, 1988).

15   Interestingly, the almost linear increase in the average number of non-standard levels in weather-balloon sounding reports (radiosondes + pilot balloons) from about zero by 1945 to about 30 by 2000 – as revealed from the first IGRA data set, inferring from Fig. 7 in Durre et al. (2006) –, can hardly be attributed to an increased attention to significant levels alone. It suggests that a significant number of stations have reported additional levels apart from the standard and significant levels (both "mandatory" in WMO's nomenclature).

20   The *surface level*, which is treated separately in upper-air sounding reports, was reported in most of the radiosonde stations since the mid-1940s. However, it has been reported systematically only since around 2000 (as shown later in Sect. 2.3.3).

1.3 Missing humidity observations

Combining adequate spatial and temporal resolution with enough accuracy for synoptic use, radiosonde measurements reach

25   the upper troposphere, much beyond the layers where most of the atmospheric water vapor resides. While the vertical sampling of temperature soundings is limited by the burst altitude and the mandatory levels (standard and significant), the maximum height and the vertical resolution of humidity soundings are further restricted by sensor limitations. Upper-air humidity measurements began in the 1930s but became substantial only in the 1940s. Despite radiosonde hygrometers (measuring relative humidity (RH)) have improved over time, humidity has been always difficult to measure in very cold or dry air. As it

30   was once pointed out, "humidity measurements in the free atmosphere are probably the least satisfactory of the regular aerological observations" (Hawson, 1970). Balloon-based chilled mirror hygrometers, designed to measure water-vapor mixing ratios in the stratosphere (an extremely cold and dry environment), has been used for more than half a century but are exclusive to scientific research or comparison with humidity measurements from operational radiosondes (Mastenbrook and

Daniels, 1980; Vömel et al. 2007; Hurst et al., 2011; Hall et al., 2016). Since a long time ago, meteorological radiosondes are expandable balloons carrying relatively low-cost and light instrument packages (Brettle and Galvin, 2003). Here is a brief review of the main humidity sensor types and their limitations, since the time when balloonsondes were abandoned by national weather services and electric hygrometers began to be incorporated in radiosondes (circa 1940; DuBois (2002)). The lithium

5 chloride humidity sensors, which were widely used in radiosondes between the mid-1940s and the mid1960s, did not respond to temperatures below around −40º C. From the early 1960s on, the new carbon hygristor allowed measurements at lower temperatures – down to −65°C in the early 1990s, however with a time lag in the sensor´s response as large as 10 minutes (Garand et al., 1992). In practice, humidity measurements at temperatures below −40°C where discontinued in many countries before the 1990s, limiting the vertical extent of routine humidity observations to about 400 hPa (≈ 7 km altitude) (Gutnick,

10 1962; Gaffen, 1993). Besides, the radiosondes using lithium chloride hygrometers suffered from a low-frequency limitation in the transmission of RH less than 15–20 %, known as motorboating (Wade, 1994). The radiosondes using the carbon hygristor enabled, in principle, measurements in that region – however, the accuracy and reproducibility of low-RH values was little known and suspected to be poor for many years, giving the wrong impression that relative humidity lower than about 20 % did not occur in the lower troposphere (Wade, 1994; Nash, 2015). Therefore, values of RH below 20 % were usually cut off

15 in humidity reports; in the radiosonde network of the U.S.A. this happened between 1973 and 1992 (Elliott and Gaffen, 1991). Note that changes in instrument and reporting practices in different countries took place at different times. E.g.: hair hygrometers were only abandoned in the mid-1950s; rolled hair hygrometers were used in a few places until about 1980; the threshold value of RH varied in the range 10–20 %; the lowest temperature of −40ºC for reporting humidity, and the shift to lower temperatures, was also applied in different periods; humidity could be reported up to a specified pressure level (Gaffen,

20 1993). The newly capacitive thin-film sensors introduced in 1981, with different versions emerging in the 2000s to avoid contamination from rain and thick clouds (using a protective cap, or rather using two sensors alternately heated and used for measurement), have improved the response time at low temperatures and the capability of measuring very low humidity. However, RH reports at temperatures lower than −40 °C did not develop significantly until about 2000; in recent years, for temperatures of −50 °C to −70 ° C only the newest humidity sensors respond quickly enough to make useful measurements;

25 moreover, the best ones had an uncertainty of around 16 % RH at temperatures as low −70 ºC (occurring over Antarctica and around the tropical tropopause), which is barely acceptable for numerical weather prevision but not suitable for climatic studies (Nash, 2015). Improvements over time were not restricted to sensor type but also to data reduction and calibration. E.g.: measurements from the carbon hygristor in VIZ radiosondes were improved in the 1990s by correcting the low-humidity algorithm; some modern radiosonde systems apply corrections for slow time constant of response and for daytime heating of

30 the humidity sensor; calibration at low temperatures was perfected. While radiosonde humidity measurements are now generally reliable in the troposphere, uncertainties remain concerning the upper-stratosphere, with temperatures below −50ºC, in addition to dry conditions found above the lower troposphere and wet conditions that occur in thick clouds (Miloshevich et al., 2006). Although the capacitive thin-film sensors have been widespread (with Vaisala radiosondes), two older sensor types

are still in use: the carbon hygristor (in VIZ radiosondes) and the goldbeater's skin sensor, introduced in 1950s and still used in radiosondes made in Russia and China; this peculiar sensor responds too slowly to be useful at temperatures lower than – 20 °C and suffers from hysteresis following exposure to low humidity (Nash, 2015; Moradi et al., 2013).

The trouble in measuring upper-air humidity affects the completeness of observations in several ways: the vertical
5 extent of humidity soundings varies much among radiosonde stations and over time owing to sensor limitations in very cold air; likewise, vertical gaps in low humidity regions are expected, due to cut-off of RH below sensors' measuring capability; lastly, missing days in radiosonde humidity records may originate from adverse conditions (dry days, wet days, cold days) at individual stations (Garand et al., 1992; Ross and Elliott, 1996; McCarthy et al., 2009). As explained above, the actual extent of missing data depends on the observing practices intricated with sensor limitations. In addition, failures in some part of the
10 radiosonde system can compromise soundings. Faulty ground-equipment used for control checks (sensors' calibration before balloon release), data reduction and data recording or telecommunication of coded reports may cause long inoperative periods; poor signal reception from the radiosonde make sometimes data processing impossible. In sum, the vertical extent, vertical resolution, temporal regularity and continuity of humidity reports are anything but uniform.

2 Input data and methods

We have examined the IGRA 2 dataset until the end of 2016, comprising over 45 million soundings. Section 2.1 presents briefly that dataset, including the quality assurance of humidity data. Section 2.2 provides a first look on the data, to find out how many and which of the IGRA stations have a non-negligible amount of radiosonde observations (RAOB), and at the same time to give a hint of the amount of humidity data. Section 2.3 describes the data analysis, aiming to explore the completeness
20 of humidity observations in the sense introduced in Sect. 1.

2.1 IGRA 2 – sounding data

The IGRA 2 consists primarily of radiosonde[1] and pilot-balloon[2] soundings taken at 2761 globally and temporally distributed stations (2662 fixed and 99 mobile), even though the coverage over oceans is limited to ships, buoys and remote islands. IGRA 2 has also derived data for a selection of WMO stations, but this paper concerns with the sounding data (Durre et al. 2016).
25 The main difference between IGRA 2 and the former version is the amount of sounding data: 33 data sources instead of the initial 11, implying about 80 % more stations; new data from hundreds of stations before 1946 and the addition of

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[1] In modern usage, the term radiosonde refers not only to the early radiosondes but also to the rawindsondes (in use since the 1950s), which, besides measuring thermodynamic parameters, provide wind information with the aid of a radio-theodolite, a radar device, a radio navigation system or, more recently, GPS (Dabberdt et al. 2002). Observations from either radiosonde type are often abbreviated as 'raob' in meteorological jargon.

[2] Free balloon tracked by optical theodolites or radar to measure upper-air winds (Wenstrom, 1937, Hickman, 2015). Often abbreviated as 'pibal'. In visual tracking, rarely used today but still important where radar tracking or wind measurements from a rawindsonde are not possible, a flashlight is used during night or twilight hours.

floating stations (fixed weather ships and buoys, mobile ships, and Russian ice islands); furthermore, humidity data priory to 1969 were added. The latter change is related to how humidity values were stored in radiosonde reports. Until 1969, humidity observations were given only as RH; from then on, RH measurements have normally been converted to dewpoint depression (DPD) and reported too in that form. Different assumptions in the conversion code can lead to inconsistencies of data (Garand

5   el al., 1992). The former IGRA contained only DPD, while IGRA 2 contains humidity data in either form, as available in original reports, provided they pass the following conditions:

   i) Data completeness: valid temperature accompanies humidity data;

   ii) Valid range: 0-100 % for RH; 0 to 70 ℃ for DPD;

   iii) Internal consistency: DPD-derived RH differs from reported RH by 10 % at most;

10   iv) Plausibility: (derived water-vapor pressure) $\leq 0.1 \times$ (atmospheric pressure).

Quality checks (i)–(ii), save for the RH range, are integral to IGRA from its creation (Durre et al., 2006); (i) for RH (with the later introduction of this variable in the archive) and (iii)–(iv) were added in IGRA 2 (Imke Durre, personal communication, April 12, 2018). In radiosonde data, consistence between pressure and geopotential height (whenever the latter is reported in source data) is assured in IGRA since its first version. In wind data from pilot-balloons, the vertical coordinate is geopotential

15   height (presumably adjusted from geometrical height measurements and the gravitational field). Note that RH measurements from radiosondes have a typical absolute accuracy of ∼ 5 % on average tropospheric conditions. However, accuracy varies substantially as a function of RH and temperature, degrading in dry or cold conditions to a greater or lesser extent depending on the radiosonde type (Nash, 2002; Miloshevich et al., 2006; Nash, 2015). The information about instrument changes (stations' history), whenever available, is provided in a separate metadata file in IGRA 2 [update of the metadata given in the

20   first version of IGRA, which were mostly taken from Gaffen (1996)].

   The most frequent nominal observation times are 0300 and 1500 UT until 1957 and 0000 and 1200 UT afterwards, which reflects the shift in observing time that occurred in 1957 in major WMO radiosonde networks. In the beginning of 1958 the primary standard hours of WMO upper-air observations were already 0000 and 1200 GMT (WMO, 1958). However, in some countries, different synoptic hours were practiced over the years; sometimes stations have performed up to four soundings

25   per day for certain demands (see Gaffen, 1993).

   NB – In the remaining of this paper, IGRA 2 is simply referred to as IGRA, unless stated otherwise.

2.2 Identification of radiosonde stations

The examination of the IGRA reveals that 958 stations have wind-only observations in their full period of record, i.e., 34.7 % of the stations represented in the entire archive. These stations form part of the global pilot-balloon (PIBAL) station network,

30   which evolved over time. As to the rest of the stations, some of them changed from a PIBAL launching site to a radiosonde launching site at some point in their period of record, – meaning that they are not, strictly, PIBAL stations nor radiosonde stations. Obviously, the number of PIBAL stations or radiosonde stations at a certain time depends on the stations opened and

closed before that time, of either type. In the following, terms like "observations", "soundings" or "reports" refer to the upper-air stations and balloon data of IGRA, which retains most of the source data.

Figure 1a shows the yearly number of the *RAOB stations* – i.e., the stations with RAOB observations at any time of the year, at least of temperature, regardless of humidity/wind – and of the *PIBAL stations* – i.e., the stations measuring only wind throughout the year (assuming data are not lost). For comparison, the number of stations reporting any humidity data – indicating that radiosondes are equipped with a hygrometer – and with humidity observations in more than 95 % of the radio soundings, is also shown. Constituting the bulk of the IGRA stations until the early 1940s, the PIBAL stations represent nowadays only 13 % of the total. The reason for the apparent discontinuity in the PIBAL stations between 1972 and 1973 is this: beginning in 1973, IGRA data largely come from the GTS (Global Telecommunication System) and include many more PIBAL data than prior data sources (Imke Durre, personal communication, April 12, 2018). The number of RAOB stations increased rapidly from the mid-1940s, staying in the range 850–900 from around 1970 to virtually present (2016). Note that, before the advent of the radiosonde, upper-air measurements of temperature and relative humidity were made using kites, registering balloons and aircrafts; these platforms were gradually abandoned until the radiosonde era was established in the mid-1940s (DuBois, 2002; Stickler et al., 2010). Since the first radiosonde prototypes were developed between 1929 and 1930, the early observations of temperature collected in IGRA, beginning with one station in 1905 (Lindenberg, Germany), were made by meteographs without radio-telemetry. The first upper-air humidity observations are from 1930, coming from a single station: Kjeller, Norway. According to IGRA, until 1942 there were less than 10 stations reporting humidity, with that number growing rapidly in the following years together with the total number of radiosonde stations, reflecting the widespread use of radiosondes (see 'Higrom.' and 'RAOB' in Fig. 1a). The major relative change occurred between 1945 and 1946, coincident with the end of the second world war, when the global count of radiosonde stations triplicated. Note that the replacement of hair hygrometers by the lithium chloride humidity element began in some radiosonde networks shortly before; in the U.S.A., apparently that change took place between 1940 and 1943 (Elliott and Gaffen, 1991; DuBois, 2002), although IGRA does not contain data prior to 1946. After a major development until around 1970, the number of reporting radiosonde stations has been in the range 850–900. Fig 1a shows also that the fraction of radiosonde stations measuring humidity in more than 95 % of the soundings increased over the years, getting very close to 100% in the last decade (see relative difference between the curves 'RAOB' and 'Higrom. > 95 %').

Figure 1b shows the evolution of the global, annual mean number of soundings performed per day, for the different atmospheric parameters apart from pressure: temperature, humidity and wind. Recall that pressure is always measured in RAOB soundings, while in PIBAL soundings wind is measured as a function of altitude[3]. For clarity, the PIBAL wind soundings are depicted separately from all wind measurements, which also comes from RAOB soundings since the mid-1940s. Although, as a rule, radiosonde launches are carried out twice a day, in fact there is a significant number of missing days in

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[3] Pressure levels are present in the wind-only data coming from 28 IGRA stations (standard levels with missing height), indicating that an on-board pressure sensor with a radio transmitter was used along with the wind-finding system.

temperature and humidity data, i.e. days without any RAOB data: roughly 1 in 5 days during the year, on average, as it can be concluded by comparing Fig. 1a (RAOB) with Fig. 1b (TEMP, HUM).

Aiming to study humidity completeness, the IGRA stations having a negligible amount of temperature data in every year of their period of record were excluded, because temperature is required to measure RH. Specifically, we have selected the *stations with RAOB soundings in 5 % or more of the annual soundings in at least one calendar year within their full period of record* until the end of 2016. These will be hereafter referred to as *IGRA-RS stations* (RS stands for radiosonde), even if some of them contribute with relatively few RAOB data. The above selection reduces the number of IGRA stations by 38 %, whereas the number of soundings is only reduced by 13 %, amounting to 39.5 million, out of which there are 30.2 million radio soundings including 29.8 million humidity soundings (see Table 1). Wind-only soundings are still present in 23.6 % of the soundings from the selected stations. Note, however, that 92.2 % of the removed stations are strictly PIBAL stations and the remaining 7.8 % have RAOB data in less than 0.6 % of the corresponding soundings, apart from two cases with a period of record shorter than one year. In sum, the IGRA-RS subset retains practically all the RAOB soundings, particularly the humidity soundings, as shown in Table 1.

The IGRA-RS stations and their locations are listed in supplementary Table S1, along with the full periods of record (Full POR), the periods of record for humidity (Hum POR) and the corresponding numbers of humidity observations (Hum Obs), i.e., the number of individual soundings reporting either DPD or RH data. Since missing years are considered, the full period of record of one station may be segmented into two or more periods for humidity. Table S1 comprises 1723 stations, of which 1300 are WMO stations (denoted by the letter 'M' following the 2-character country code of IGRA identifier codes).

Focusing on the usefulness for climatic studies, the subset of WMO upper-air stations integrating the Global Climate Observing System (GCOS), i.e., the GCOS Upper-Air Network (GUAN), deserves attention. Formally established in the 1990s, together with the surface stations of the GCOS Surface Network, the GUAN is aimed to provide long-term, consistent, homogeneous and reliable observations needed to monitor the atmospheric component of the global climate system (WMO, 2002; McCarthy, 2008). At present the GUAN comprises 178 stations, all of which are represented in IGRA-RS. The IGRA-derived statistics of humidity observations from the GUAN stations for the period 2001/10/01 to 2016/12/31 is shown in supplementary Table S2, as explained next. 'Hum POR' indicates the years with any humidity data in the year, as found in IGRA, beginning at the time when each station was included in GUAN, or, at least, at the earliest time for which performance indicators for the GUAN stations are available through the NOAA/National Centers for Environmental Information website; this is the first day of the month of 'Begin Date' indicated in Table S2. '# Days' is the number of days in Hum POR, excluding the months before Begin Date. The last three columns give the corresponding count of humidity observations around the principal nominal hours, 0000 UT and 1200 UT (± 1 h), and at any other times (0200 UT through 1000 UT and 1400 UT through 2200 UT). Stations are identified by the WMO region and WMO number, followed by the station name and country. (To find out the corresponding IGRA ID codes in Table S1 it suffices to observe that the last nine characters must be 'M000' followed by the WMO number.) Note that most of the GUAN stations have humidity data at or around 0000 UT and 1200 UT almost every day; however, the exceptions to the rule, and even gap years, are not negligible.

Moreover, the IGRA-RS contains 16 stations that form part of the GCOS Reference Upper-Air Network (GRUAN), (half certified and half to be certified according to current GRUAN status), of which eight (half certified too) are also GUAN stations. All GRUAN sites report default data (from radiosonde manufacturers) to the GTS; at present, most of them already send BUFR messages with high resolution (Michael Sommer[4], personal communication, September 18, 2018). Despite the differences in data processing between GRUAN internal data and real-time data, the quality of routine observations carried out at GRUAN sites in recent years should be above average (WMO, 2011; Dirksen et al., 2014). For reference, the IGRA ID codes of the GRUAN sites appearing in the IGRA-RS station list are underlined on Table S1; of course, other GRUAN sites performing only research measurements are not part of IGRA. Likewise, the WMO numbers of the GUAN stations coincident with GRUAN sites are underlined on Table S2.

2.3 Analysis of humidity data

Overall, the analysis of data from IGRA-RS stations, selected as described in the previous section, aimed to answer the following questions:

1. What is the amount of humidity observations in different years and latitude regions?
2. What is the typical vertical resolution and vertical extent of humidity observations?
3. How many stations have enough data to allow the estimation of precipitable water?
4. How long are the humidity time-series and how many consecutive missing days there is on average?

Each question was explored as detailed below in Sects. 2.3.1–2.3.4, with the results presented later in Sect. 3. The description of the related metadata parameters regarding (*a*) RS station and year in record or (*b*) RS station, date and nominal hour, is deferred to Sect. 4.

2.3.1 Amount, frequency and latitudinal coverage

The amount and frequency of humidity observations over time was studied in terms of *annual number of stations with any humidity observations* and *fraction of humidity-observing days in a year averaged across stations*. In both cases, the data were divided into subsets according to climatic zones, considering only the fixed stations.

The latitudinal distribution of humidity-reporting stations in different years was further studied by means of an index that accounts for the area of a latitude band between latitudes θ_1 and θ_2:

$$zonal-coverage\ index \overset{\text{def}}{=} \left(\frac{N_{band}}{A_{band}}\right) \div \left(\frac{N_{globe}}{A_{globe}}\right)$$

$$= 2\left(\frac{N_{band}}{N_{globe}}\right)|\sin\theta_1 - \sin\theta_2| \tag{1}$$

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[4] GRUAN Lead Centre, Lindenberg Meteorological Observatory - Richard Aßmann Observatory, Germany.

where N denotes number of stations and A denotes surface area, the last expression using the spherical-Earth approximation. Of course, the mean station density over a latitude band, or the whole globe, may differ a lot from the local density because radiosonde stations are concentrated in continental, near urban areas of developed countries. The above-defined index is simply the mean stations density within a latitude band, such as a climate zone, divided by the global mean density. So, a value greater

5   (/smaller) than 1 indicates that the mean stations' density for the latitude band is above (/below) global average, which is to say that the corresponding latitudes are overrepresented (/underrepresented).

2.3.2 Vertical resolution and vertical extent

Since the vertical resolution varies with height – according to the height of the reported pressure levels (standard and significant) and depending on the number of levels with non-missing data for humidity –, the vertical resolution of an individual

10   sounding must be defined by a vertical average. Since the vertical distance between consecutive levels, say dz_k, generally increases with height, with the lower levels being more populated than the upper layers, a geometric mean is more suitable than an arithmetic mean. So, the *mean vertical resolution of a single humidity sounding* was defined by the geometric mean of $\{dz_k\}$ for all levels with humidity data in the sounding profile:

$$mean\ vertical\ resolution \overset{\underset{\mathrm{def}}{}}{=} \frac{R_d T_0}{g_0}\left\{\prod_{k=1}^{M}\left(\frac{\bar{T}_k}{T_0}\ln\frac{p_{k-1}}{p_k}\right)\right\}^{1/M} \tag{2}$$

where p_k is the atmospheric pressure at level k ($k = 0$ denoting the lowest level with humidity data), M is the number of levels with humidity data above the lowest level, $\bar{T}_k$ is the estimated mean temperature between level k and its immediate, relevant lower level $k-1$, T_0 is a constant temperature in the range of the values found in the troposphere (used in the calculation to

20   avoid overflow in case M is too large), R_d is the specific gas constant for dry air and g_0 is the standard gravity. (Note: IGRA's data-quality checks assures that vertical levels with valid humidity data have also valid temperature and pressure data.)

 Since geopotential altitude is only given in part of the RAOB reports, the *vertical extent of an individual humidity sounding*, i.e. its *maximum height above mean sea level reached by the humidity measurements,* was estimated by adding the station's elevation to the height from the surface calculated upon pressure and temperature data from the surface level up to

25   the top of the humidity sounding (highest level with a non-missing value for DPD or RH), whenever values of temperature and pressure at the surface are given; otherwise the height from the surface cannot be calculated. For moving stations, the elevation of station is taken equal to the geopotential height at the surface level, if given (otherwise, the vertical extent was not calculated). For the purpose, it suffices to neglect moisture in the hypsometric equation; given that the virtual temperature is typically within 4 K above the actual temperature, the error amounts to less than 1 %.

30   Following the above definitions, the statistical distributions of the vertical extent and the vertical resolution in humidity soundings were studied over time by grouping individual values of both parameters in annual bins. To assess the shortness of humidity observations in RAOB, we have also calculated the vertical extent of temperature observations and their vertical resolution up to the top of the humidity soundings.

2.3.3 Soundings qualified to estimate precipitable water vapor

Usually, the precipitable water vapor (column integrated water vapor mass per unit surface area) is estimated from the profile of water vapor mixing ratio between the surface to the 500-hPa level – i.e. the layer where ~ 95 % of the columnar mass of water vapor is and where humidity data from radiosondes are more often available and generally more accurate (Elliot et al.,

5   1991; Gaffen et al., 1992; Ross and Elliott, 1996; Durre et al., 2009). In this paper, a humidity profile is considered eligible to estimate precipitable water vapor under the following conditions:

    i. *Humidity data are given at the station's surface and at all standard levels laying between the surface and the 500-hPa level, except for the 925-hPa level.*

    ii. *If humidity data is missing at a standard level apart from 925-hPa, a nearby significant level is acceptable if its height*

10   *from the surface differs from the height of the missing standard level by less than 5 %.*

    iii. *The distance between any consecutive levels with humidity data between the surface and the lowest level located more than 1 km away from the surface should not exceed 1 km, unless the station elevation is larger than 500 m.*

The 925-hPa level is not required here because this level was not standard until 1991. However, condition (iii) assures a minimal resolution in the planetary boundary layer, by including near-surface significant levels as well as the 925-hPa level

15   when it is given; this is required because water vapor is highly variable and abundant in this region; the exception for very elevated stations contemplates the case when the first upper-air humidity record is at 850-hPa, i.e. ≈ 1.5 km above the mean sea level, but the height from the surface is less than 1 km. The IGRA-RS soundings fulfilling the above conditions will be hereafter referred to as *Sfc-to-500hPa humidity soundings*.

    Typically, the first standard level higher than 1 km from the ground is 850-hPa. Thus, by including enough data at

20   significant levels below the 850-hPa level, instead of requiring data at standard levels in the same layer – sorted out of 925-hPa and 1000-hPa, depending on the surface pressure – the definition given above accommodates much more soundings, particularly before 1992 when the 925-hPa level was not mandatory. To be sure, the relative amount of humidity data at near-surface levels is now examined, excluding 1000-hPa (around 0.1 km altitude) since this is frequently placed below the stations' elevation (339 m on average for the IGRA-RS fixed stations).

25   Figure 2 shows the evolution of the global percentage of humidity observations at the 925-hPa level and at any significant level between the surface and 850-hPa, out of the IGRA-RS soundings having humidity data at the surface on condition that the surface level pressure is higher than 925 hPa and 850 hPa, respectively (referred in the following as surface-upper-air soundings). The percentage of surface observations in all humidity soundings is also show. First, note that the surface observations began in 1943 (in fact, not only of humidity but also of temperature), rising rapidly in the next 5 years to ≈ 95 %

30   of the humidity soundings, decreasing then to a minimum of 60% in 1965 and broadly increasing again until 2000, staying above 95 % since then. In short, the humidity measurements at the surface level are mostly available since 1945 and have been in widespread use since 2000. Secondly, the percentage of the surface-upper-air soundings having humidity data at the 925-Pa is almost step-wised, with a discontinuity around 1992. It increases from only 2 % in 1991 to 60, 86 and 98 % in the

following three years. This change is coincident with the introduction of the 925-hPa level as an additional standard level in radiosonde messages in November 1991, and consistent with the fraction of stations already reporting that level in mid-1993 (Oakley, 1993, p. 24). Lastly, the percentage of the surface-upper-air soundings that have humidity data at any significant level below the 850-hPa level, beginning in 1948, generally increased with time, mainly in the 1960s, with a value larger than 80 %

5   in recent years.

Using the definition given at the beginning of this section, we have studied the number and the percentage of stations whose Sfc-to-500hPa humidity soundings exceed a given percentage out of the humidity soundings made in each year. The distance between missing standard levels and nearby significant levels was calculated from pressure and temperature data, neglecting moisture. A stricter definition of Sfc-to-500hPa humidity soundings, specifically, having humidity data at the

10   surface and all upper-air, current standard levels up to 500-hPa was also studied for comparison.

2.3.4 Size of missing days and current record length of time-series

Although the fraction of days with humidity observations during a year gives a sense of the regularity of observations, it says little about the continuity of data over the year. In this respect, it is of interest to know the size of the *maximum interval of consecutive days without humidity data in a year* – denoted hereafter as *'size of missing days'*.

15   The '*current record length*' of a humidity time-series in a given station and year, is herein defined as the *number of elapsed years in the time-series with no gap years in the interim*. For readiness, a calendar year with any amount of humidity data is counted as one. For past years, the current record length generally differs from the span of the entire time-series, which may continue after the year under consideration. Also, note that one station can have more than one time-series for humidity, as the humidity observations can be interrupted by one or more gap years. So, the full 'period of record' of a RS station may

20   be divided into several sub-periods of record for humidity. Recall that the years with humidity observations at each RS station are indicated in Table S1.

. The above defined measures of temporal completeness are critical to study climatic trends (long-term changes in the annual mean or in the seasonal cycle of humidity-related quantities) on specific locations or areas of the globe, which otherwise requires merging procedures using radiosonde data from nearby locations to circumvent large data gaps. Using the above

25   definitions, first we have computed the size of missing days averaged across all fixed stations reporting humidity within each major latitude region, year by year. Then, we have studied the evolution of the average current record length the humidity time-series, from all stations, year by year. The same was done for the time-series with humidity soundings 90 % of the days in the year, at least, and particularly consisting of Sfc-to-500hPa soundings, with their own record lengths. The calculation of the distribution of the current record length of the time-series with Sfc-to-500hPa soundings 90 % of the days in the year or

30   more was repeated, by restricting the corresponding size of missing days to less than 10 days.

3 Overview on the completeness of radiosonde humidity observations

This section gives a general picture of the completeness of humidity observations over the years, using the data from the IGRA-RS stations defined in Sect. 2.2 and following the data analysis described in Sect. 2.3. The results of Sect. 3.1 refer to fixed stations, including ocean stations with fixed location. In the remaining Sects. 3.2–3.4 mobile stations are equally included, apart from one case at the beginning of Sect. 3.4.

3.1 Amount and frequency of humidity observations by climate zones

Figure 3 shows the count of fixed IGRA-RS stations with humidity observations in each year, by climatic zones on Earth. Although most of the few early humidity-reporting stations were placed in the northern polar zone (Arctic), from 1945 on they were located predominantly in the northern temperate zone, even though they raised in all regions, at the fastest rate in the subsequent two decades. In the climatic zones to the south of the Southern Tropic the number of stations is much smaller than in other zones, except for the southern subtropical zone which, from the 1970s on, compares with the Arctic in absolute number. Noticeably, the number of arctic stations decreased considerably between 1970 and 2000. The absence of mobile stations affects very little the curves of Fig. 3, since mobile stations are short numbered and have a short period of record (a few years). E.g., considering the polar regions, according to IGRA, in 2016 there were only two ships reporting radiosonde observations in waters around the Arctic Circle – although the cumulative number of observations over the years, gathered from different arctic missions, may be relevant.

The latitudinal distribution of humidity-reporting stations is better expressed in terms of percentages for the same latitude bands, out of the total number of radiosonde stations over the globe, as shown in Fig. 4a; percentages are calculated at different times separated by an interval of 15 years. Clearly, the northern temperate zone accounts for about half of the world stations, although its relative weight has been decreasing since 1955. The decrease of the percent of stations situated in mid- and high latitudes north of parallel 35º N is counterbalanced by a general increase in other regions, notably in the Tropics. A similar histogram, but for the relative density of stations, i.e. the zonal-coverage index defined by Eq. (1), gives a different picture of the station coverage across latitude zones, as in Fig. 4b. The differences between the North and South Hemispheres are enlightened in the following way. From at least 1970 to 2015 the northern subtropical and temperate zones are equally overrepresented. In contrast, the southern temperate latitudes are always the most poorly represented, which is not surprising since this is a region with significantly more ocean and less land. Lastly, the Arctic has been much better covered than Antarctica. Although it has decreased since the 1950s, the present-day mean artic stations density represents half of the global mean density.

Figure 5 represents the fraction of days in a year having humidity observations, averaged across all humidity-reporting fixed stations in each of the three major latitude regions of both hemispheres, along with the standard deviation. The plot begins in 1945, about when upper-air humidity measurements became routine. In all regions, the average fraction of the days in a year with humidity observations increased rapidly until around 1960, stabilizing since 1965 to values in the range 70–80

% in low latitudes and 80–95 % in mid- and high latitudes. Besides, the corresponding standard deviations indicate that a non-negligible percentage of the stations have observations on every day in the year since the 1950s.

The fraction of days with humidity observations, detailed by station and year, is part of the first metadata set presented in this paper (see Sect. 4.1). Similar information is given for the Sfc-to-500hPa humidity soundings alone.

5 **3.2 Global vertical extent and resolution of humidity observations**

Figure 6a shows the distribution of the vertical-mean resolution in the annual humidity soundings since 1945, along with the homologous distribution in the simultaneous temperature soundings, limited to the highest level with humidity measurements for comparison. The vertical-mean resolution of each soundings was calculated by Eq. (2), rounded to the nearest decameter. For clarity, the curves displaying the mean and the quartiles are smoothed by a 5-year running mean. The differences between
10 the distributions for temperature and humidity indicate missing humidity data in a few percent of the vertical levels with temperature data; although statistically irrelevant, such vertical gaps may be quite significant in individual soundings. The vertical resolution was relatively poor on average and highly variable in the early decades: until around 1965 the mean and median were coincident and varied in the range 1.1–1.4 km, with a midspread (interquartile range) of almost 1 km. Both the average resolution and the midspread improved consistently from 1965 to between 2000 and 2005. Since 2005, ¾ of the
15 soundings have a vertical-mean resolution better than 0.5 km, with half of the values ranging from 0.3 to 0.5 km.

Figure 6b shows how the maximum height above the mean sea level reached by either temperature or humidity measurements is distributed among the corresponding soundings on each year. The distribution is restricted to temperature and humidity soundings with surface data, these representing, respectively, 86.7 % and 86.0 % of the total RAOB soundings in the period 1945–2016. Also, the soundings from mobile stations with missing geopotential height at the surface level had to be
20 excluded. Curves are smoothed by a 5-years running mean, as in Fig. 6a. Note that the vertical extent of temperature measurements in RAOB soundings is normally much larger than the vertical extent of balloon-born observations of any kind: e.g., ¾ of all soundings reach 100 hPa (≈ 10 km) in 2003, from the data of the first version of IGRA, as reported in Durre et al. (2006); whereas ¾ of the temperature soundings with surface data reach 22 km in the same year, according to the present analyses of IGRA-RS data selected from IGRA v2. This difference is essentially due to the removal of PIBAL stations in our
25 analysis.

Contrary to wind and humidity, temperature is usually measured up to the height achieved by the sounding balloon (or close to it), i.e., the burst altitude. In Fig 6b we can observe that the top of the humidity observations is at present situated almost 5 km below the burst altitude on global average (either mean or median). But the difference in vertical extent between temperature and humidity observations has changed greatly over the years, with a maximum mean value of 12.5 km by 1980.
30 Until the late 1960s the burst altitude increased at a much faster rate that the top of humidity observations, except for a few years after 1965 where the reverse happened. This last feature and is coincident with the introduction of the carbon hygristor. Likewise, the isolated peak of the global mean maximum height of humidity observations around 1970, as seen in Fig. 6b ('HUM'), seems to indicate an exploratory period with the new instrument. Noteworthy, in 1970 the WMO stated that "no

routine observations of humidity are made in the stratosphere and no practical use is envisaged for such current observations"
(Hawson, 1970). Figure 6b undoubtedly shows that humidity was mostly measured in the troposphere until the mid-1960s. In
contrast, from the mid-1980s on, the vertical extent of humidity observations has increased consistently and faster than the
burst altitude – roughly by 4 km per decade on global average –, denoting improvements of humidity sensors (see Sect. 1.3).

5   In 2015, ¾ of the humidity-top values extend to over 13 km, and half to over 26 km, indicating that many humidity reports
extend into the lower stratosphere. The accuracy of radiosonde humidity measurements in the stratosphere is beyond the scope
of this paper; however, the accuracy of fairly recent measurements in the upper-troposphere, and certainly more above too,
was considered inadequate for climate studies and a challenge for future operational radiosondes (Durre et al., 2005). It is
interesting to note that the interquartile range of the top height of humidity soundings has increased much in the period 1985–

10   2000, i.e., individual values became widely dispersed around the median. This is likely related to the proliferation of humidity
sensors of different kinds, thus increasing the instrument variations among stations as new instruments coexist with older ones.
For instance, by 1989 the WMO had identified 20 major radiosonde types in use worldwide (Kitchen, 1989a). While this
number has fallen to 13 by 2002 (Elms, 2003), Fig. 6b shows that the dispersion in the vertical range of different humidity
sensors has increased in the meantime; changes in instrument-dependent observing practices may have a role.

15   The average vertical resolution of the humidity observations, by year and station, as well as the individual values by
station, date and time, are given in the metadata sets provided in this paper (see Sect. 4). Similar metadata is provided for the
Sfc-to-500hPa humidity soundings, as defined in Sect. 2.3.3, in which case the vertical resolution is calculated for the levels
between the surface and the 500-hPa level and is normally finer than depicted in Fig. 6a.

          Since IGRA-RS observations do not have surface humidity data prior to 1945, and surface data is not always given

20   after that year, to account for all soundings the vertical extent of humidity observations must be alternatively represented by
the lowest pressure corresponding to humidity data. The same applies to soundings from mobile stations, since the station's
elevation is variable, and the geopotential height of the surface level is missing in 30 % of the corresponding RAOB. Therefore,
the average pressure of the top of humidity soundings, by station and year, are given in the first metadata set presented in this
paper; average values are represented by a geometric mean (see Sect. 4.1). As to the second set for individual observations –

25   metadata by station, date and time – both the top pressure and the corresponding altitude, whenever this can be calculated, are
provided (see Sect. 4.2).

3.3 Global relative amount of Sfc-to-500hPa humidity soundings

Recall that our definition of Sfc-to-500hPa humidity soundings (see Sect. 2.3.3) is intended to represent the sounding with a
minimal amount of data, and almost evenly distributed near the surface, such that the water vapor profiles can be properly

30   described and the precipitable water can be estimated. In this respect, the completeness of such humidity observations based
on current standard pressure levels alone is unsatisfactory for two reasons: first, the level 925-hPa was barely used before 1992
(see Fig. 2); second, the sounding data at significant levels, often related to features of temperature rather than RH, or at other
additional levels, are equally good provided that the vertical resolution (habitually increasing towards the surface) is not too

different. Next, we will compare the distribution of Sfc-to-500hPa soundings among IGRA-RS stations in each year using alternative definitions:

A) Humidity data at the surface and all current standard levels above the surface up to 500 hPa, i.e. at pressure levels $\{p: p \in \{1000, 925, 850, 700, 500 \text{ hPa}\} \cup \{p_{SFC}\}, \ p \leq p_{SFC}\}$;

5   B) Definition given in Sect. 2.3.3.

The soundings meeting either of the above two definitions are coined as *Hum-A* or *Hum-B* in the following analysis. Note, however, that only definition B was used to prepare the metadata sets supplied in this paper.

Figure 7a shows the evolution of the number of stations with the percentage of Hum-A soundings exceeding given values, out of all soundings with humidity in each year – since nearly the time radiosonde humidity data at the surface level

10 are first available. Comparing Fig. 1a with Fig. 7a, we can see that between 1945 and 1991 only a small fraction of the RS stations carried out Hum-A observations in most of the soundings, say, within a percentage range P > 95 %. Things changed drastically between 1992 and 1994, when the number of stations with a significant percentage of Hum-A soundings, e.g. 20 % < P < 80 %, increased by an order of magnitude. This change reflects the change in the observing practice shortly after 925-hPa was internationally adopted as a standard pressure level (see Fig. 2). In recent years there are over 400 stations with P >

15 95 % and almost 800 with P > 80 %. Figure 8a shows how the probability of finding a RS station with a percentage of Hum-A soundings exceeding a given value has reversed over about fifty years ago: only 12 % of the stations had at least 20 % of Hum-A soundings, whereas at present ≈ 91 % of the stations have at least 80 % of Hum-A soundings.

Figure 7b is the counterpart of Fig. 7a, when using the less stringent definition of Sect. 2.3.3 for "Sfc-to-500hPa humidity soundings" (Hum-B). Recall that 925-hPa is now treated in the same way as any near-surface non-standard level,

20 and, for the rest, significant levels close to standard levels are allowed. (Note: the filling of missing data according to condition (ii) of Sect. 3.2.3 affected 22 % of the total Hum-B soundings.) One can observe that, before 1992, the number of stations having moderate to high percentages P of Hum-B observations is much larger than the number of stations having the same percentages of Hum-A observations; from 1992 on, that difference is moderate and only significant when P is very high. Besides the sudden increase of the stations with many Hum-B observations in 1992, there other two noteworthy change points:

25 a sudden increase around 1970 and 2000. These changes are related to the increase of the global percentage of humidity soundings with surface data happening at about the same time (cf. Fig. 2). For example, the number of stations providing Hum-B vertical profiles in more than 80 % of the soundings doubled from ≈ 40 to 80 between 1969 and 1971, it doubled from 250 to 500 between 1990 and 1993, it increased from 520 to 700 between 1999 and 2001; a much more constant value of around 800 is observed in the period 2005–2015. The inverse cumulative distribution function in Fig 8b shows the probability of

30 finding a RS station with a percentage of Hum-B soundings exceeding a given value in different trienniums. About fifty years ago, the fraction of stations having at least 20 % of Hum-B soundings was as large as 40 %, increasing gradually to nearly 100% at present. Furthermore, 97 % of the presently active stations have at least 80 % of Hum-A soundings.

The number of Hum-B Sfc-to-500hPa humidity soundings in each station and year, as well as the fraction of days in a year having such soundings, are both given in the first metadata set presented in this paper (see Sect. 4.1). Information on

other parameters describing humidity completeness but focusing on these soundings is also provided. The metadata set regarding individual observations identifies the Sfc-to-500hPa humidity soundings and provides information on their vertical resolution between the surface and 500 hPa (see Sect. 4.2).

3.4 Average size of missing days and amount of long-term time-series

Figure 9 represents the typical 'size of missing days' in humidity observations in each year, as averaged across the fixed stations located within each major latitude zone. Recall that we only care with sub-year missing days, since gaps of one or more years are exceptions related to interruptions of station's operation or maybe to the lack of a functioning hygrometer. So, Fig. 9 gives a glint of the typical continuity of humidity time-series having any observations in the year. As a general picture, the average size of missing days decreased from 4–6 months to about 1 month between 1945 and 1960. From 1960 to 2015, the stations at low latitudes present a trend in the size of missing days, from $\approx$ 30 days to 40 days on average; while stations at mid- to high latitudes present typical values of $\approx$ 20 days, except during the mid-1990s ($\approx$ 30 days). Nonetheless, the dispersion of values away from the mean (not shown) indicates that some stations have time-series much more continuous than others, e.g. with daily data throughout the whole year.

Figure 10a (black lines) illustrate the number of humidity time-series, one per station, fixed or mobile, with a 'current record length' (elapsed years until the year in abscissa) exceeding a given number of decades: 1, 3 and 5. In this case the time-series refer to periods of consecutive years with any observations in the year. For comparison (color lines) the same is shown for the time-series with data 90 % of the days in the year or more. It should be noted that the concurrent series with more than 10 years of back data begin in 1948, even though the first upper-air humidity measurements began in 1930 and by 1949 there were already around 300 stations measuring humidity (cf. Fig. 1a). The initial slope of the curves in Fig. 10a denotes the rapid growth of the global radiosonde network after the second world war, with many stations measuring humidity regularly. Nevertheless, the curves are not monotonous, due to the closing of stations in the past and to the existence of gap years in many stations. E.g., if we want to collect the largest amount of parallel humidity time-series extending back in time to over 10 years, Fig. 10a tells us that we should pick IGRA data until 1987–90, corresponding to about 750 radiosonde stations. However, as of 1976, the number of parallel time-series with humidity observations 90 % of the time or more and extending back in time to over 30 years has been increasing over the years, representing 200 stations in 2016. by restricting the series to those having sufficient vertical sampling between the surface and 500 hPa to estimate precipitable water vapor, the number drops to about 15 between 1978 and 2000, only then increasing steadily to about 50 by 2015; if we consider a much shorter duration, e.g. 10 years as a minimum, the time-series until the same year becomes several times more numerous and start much earlier.

Fig. 10b represents the distribution of the current record length under more restrictive conditions. First, it considers only the time-series consisting of Sfc-to-500hPa soundings (definition of Sect. 2.3.3) covering 90 % of the days in the year or more; secondly, it further limits the time-series to those with less than 10 consecutive missing days in every year, meaning that all months are evenly represented. We can see that the number of parallel time-series with regular (fraction of days in a year $\geq$ 90 %) Sfc-to-500hPa soundings and extending back in time to more than 10 (30) years has increased rapidly since 2000, after

four (two) decades with a value of less than 100 (20), only then increasing steadily to about 330 (50) by 2016. However, the Sfc-to-500hPa time-series with the same length but being almost continuous (fraction of days in a year ≥ 90 %; size of missing days < 10 days) are much less numerous.

Evidently, Figs. 9 and 10 are only illustrative. There is no simple answer to the question of since when we have enough data to (in theory) perform climate studies from radiosonde humidity data: it depends on the strictness of completeness criteria. The size of missing days of humidity data at each station and year is given in the first metadata set provided in this paper; the same information is given for the sub-data consisting of Sfc-to-500hPa humidity soundings (see Sect. 4.1). Note that the length of the time-series under user-specified conditions for any of the metadata parameters defined in the next section, either backward or forward in time, can be derived from the information contained in the same metadata set. In addition, the years with humidity observations can be found in Table S1 (as well as in a file accompanying the two main metadata sets): one or more periods per station, depending on whether there are gap years present in the station's full period of record.

4 Metadata sets of completeness of radiosonde humidity observations based on the IGRA

The metadata sets describing the completeness of radiosonde humidity records collected in the IGRA are outlined next. They are constructed upon the metadata parameters introduced in Sect. 2.3 and examined in Sect. 3, except for minor adaptions described in the subsections below. The combination of selection criteria, by simply specifying value ranges for the metadata parameters, offers a plethora of choices to the user. Both sets refer to sounding data from the IGRA-RS sub-set of IGRA 2 stations, as defined in section 2.1 and listed in Table S1, which essentially excludes pilot-balloon stations.

4.1 Metadata by station and year

The metadata parameters regarding each IGRA-RS station and year (annual statistics) are defined in Table 2. Since pressure is the vertical coordinate that is always present in humidity radiosonde data, and the calculation of height above mean sea level is impossible when the surface level is missing, the average vertical extent of humidity data at a given station and year is represented by the geometric mean value of the lowest pressure with humidity data. (Given the huge number of values involved, the arithmetic mean of the logarithm of pressure was calculated first and then exponentiated.) Note that the geometric mean pressure of the highest level with humidity data provides a natural measure of the corresponding arithmetic mean altitude: insomuch as pressure decrease almost exponentially with height, the arithmetic mean height above sea level is roughly proportional to the logarithm of the geometric mean pressure. The statistics for the vertical resolution of humidity data consists in the annual mean of the 'mean vertical resolution' of individual soundings at each station, calculated by Eq. (2). The IGRA data meeting the definition of Sfc-to-500hPa humidity soundings (stated in Sect. 2.3.3) have their own metadata number of observations, average vertical resolution, size of missing days, and fraction of days in a year having humidity data.

The metadata set is as a plain-text file, each data record containing the metadata values, station-by-station and year-by-year. For each station, the yearly variables defined in Table 2 are presented chronologically. However, to put humidity metadata into context, the yearly number of soundings and of RAOB soundings are also given besides HUMa. The years within a station's period of record with observations of any meteorological variable (wind, temperature, humidity) are kept, using

5   appropriate missing values when humidity data is missing throughout a whole year. While humidity data begin 1930, the pre-radiosonde is included to preserve the stations history.

NB – The metadata set is complemented by a list of the IGRA-RS stations with information on geographic coordinates (if fixed), name, and country, along with original metadata describing the periods of record for humidity and the corresponding amounts of observations. This is an ASCII version of Table S1, for computing purposes.

10   **4.2 Metadata by station, date and time**

The metadata parameters regarding individual soundings at each IGRA-RS station are defined in Table 3. The utility of the corresponding metadata set is to allow a fine selection of humidity data, as a complement to a first selection based on the statistical parameters of Table 2. This metadata set is organized into one plain-text file per station, and one data record per sounding. Below the headline, each record contains: the date, nominal hour, latitude and longitude of the balloon launch,

15   followed by the related humidity metadata.

5 Availability of metadata sets

A dataset combining the two metadata sets presented in Sect. 4 is available on Zenodo, DOI: 10.5281/zenodo.1332686. The accompanying 'Readme' file gives the necessary information about the data format and file contents. The update is planned to

20   take place each time two full years have been completed in IGRA, starting on January 2019 for the period 2017–2018.

6 Summary and recommendations

The completeness of radiosonde humidity observations from IGRA (Version 2) was studied, upon selecting the stations with a minimal amount of radiosonde observations in their period of record until the end of 2006, denoted herein as 'IGRA-RS'.

25   The selected set comprises 1723 stations, including 1300 WMO stations, of which 178 and 16 are, respectively, current GUAN and GRUAN sites. The early humidity reports are from the 1930s, when the radiosonde era had begun, but the data amount is only significant after around 1945. Several parameters describing the completeness of humidity observations were defined and then examined in statistical terms based upon IGRA-RS sounding data, providing a global picture of humidity completeness in radiosonde observations over time. The main conclusions, regarding the data later than 1945, are as follows.

- The relative coverage of radiosonde stations measuring humidity in different climatic zones can be accessed in terms of the ratio between the stations' mean density across the corresponding surface area and the mean density across the globe ('zonal-coverage index'). The northern subtropical and temperate regions are clearly overrepresented (although not as much as in the past, regarding the extratropics). The zonal-coverage index of the tropical region has increased constantly since the mid-1950s, being presently above average. The worst coverage is found in the southern temperate region (largely oceanic), followed by Antarctica. The zonal-coverage index in the Artic is several times better than in Antarctica; however, it has decreased significantly over the years.

- The fraction of days in a year with humidity observations has greatly increased until 1960, on average calculated for each year across the stations on each of the main latitude regions. Since 1965, the mean values are in the range 70–80 % in low latitudes and 80–95 % in mid- and high latitudes annually, although individual values vary widely among stations.

- The vertical-mean resolution of humidity observations (geometric mean of the distance between consecutive levels with data), has a median in the range of 1.3–1.4 km until 1965, among all humidity soundings in each year, with an interquartile range of ≈ 1 km. Thereafter, the median and midspread have improved constantly before stabilizing in the early 2000s; since then, half of the annual soundings present a vertical-mean resolution between 0.3 and 0.5 km.

- Humidity was measured mostly in the lower to middle troposphere until the mid-1960s. Since the mid-1980s, the mean height achieved by humidity measurements has increased by ≈ 4 km per decade on global average; the gap distance to the burst altitude (denoted by the maximum height of the temperature measurements) more than halved. At present, that gap is ≈ 5km and ¾ of the humidity soundings reach to at least 13 km altitude. However, the dispersion of the maximum height of humidity data around the mean has increased too, likely due to the coexistence of older humidity sensors with new sensors.

- The number of stations providing Sfc-to-500hPa profiles with adequate resolution for calculating precipitable water vapor in more than 80 % of the reported humidity soundings in a year has changed from a few dozen in the period 1945–1970 to around 800 in recent years (97 % of the active radiosonde stations by 2014/16). In general, the amount of stations having a significant percentage of Sfc-to-500hPa observations shows a sudden increase around the years 1970, 1991/92 and 2000. These change points are associated with the availability of data at the surface level and at non-standard near-surface levels; the latter provide important information in the planetary boundary layer before 1992, when the 925-hPa level was not standard and it was rarely used.

- Between 1945 and 1955, the 'size of missing days' in humidity observations (largest gap in days) in each year having any humidity data decreased from about five months to one month on global average. After 1960, the size of missing days exhibit averages around 20 days in middle and high latitudes; in low latitudes it has increased over time from around 30 to 40 days.

- The amount of long-term humidity time-series with consecutive years of data until a given year depends on the year, the current record length and other completeness criteria. E.g.: the station-based time-series extending back in time for at least 30 years and being 90 % complete (in terms of fraction of days in a year) begin with a few units in 1977 and represent around 200 stations in recent years; by further requiring Sfc-to-500hPa completeness, the other criteria being the same, the number of time-series drops to 50 by 2016. Evidently, the equivalent time-series until the same year but with a much shorter duration, e.g. 10 years as a minimum, are several times more numerous and start much earlier. In short, the amount of humidity data that are available to perform climate studies, discounting discontinuities in accuracy, depends strongly on the strictness of the completeness criteria.

Finally, the paper presented a dataset detailing the completeness of humidity observations based on the data from the IGRA-RS stations. The dataset (Ferreira et al., 2018) consists of: 1) statistical metadata for each station and year, in a single file for the 1723 stations and their full period of record until 2016; 2) metadata specific to individual soundings, organized in one file per station and covering 39.5 million soundings for the same stations; and (3) list of stations along with the observing periods for humidity and the corresponding number of observations. The metadata parameters were designed to facilitate the selection of upper-air humidity data from IGRA according to a plethora of choices, therefore being able to meet specific research needs in the areas of atmospheric and environmental sciences.

It is widely known that the usefulness of historical radiosonde data depends crucially on metadata information about instrumentation and observing practices (Schwartz and Doswell, 1991; Elliot and Gaffen, 1991; Gaffen et al., 1996; Parker and Cox, 1995). However, sampling differences among stations associated with geographical coverage, observing periods and missing data, are no less important than differences in data precision and accuracy. Reporting practices related to limitations of humidity sensors affect particularly the humidity records (Garand et al., 1992; McCarthy et al. 2009). In this respect, the metadata presented in this paper, if used as a tool to find out the more complete humidity time series – relatively long, regular and continuous; vertically extensive and well resolved –, should be crossed with the coordinates of stations and the station history metadata available in IGRA. On the other hand, the present metadata might accelerate progress in the current research on the homogenization of radiosonde humidity data (McCarthy et al., 2009; Dai et al., 2011), by sampling stations with coincident observing periods and satisfying reasonable completeness criteria.

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LIST OF FIGURES 1–10

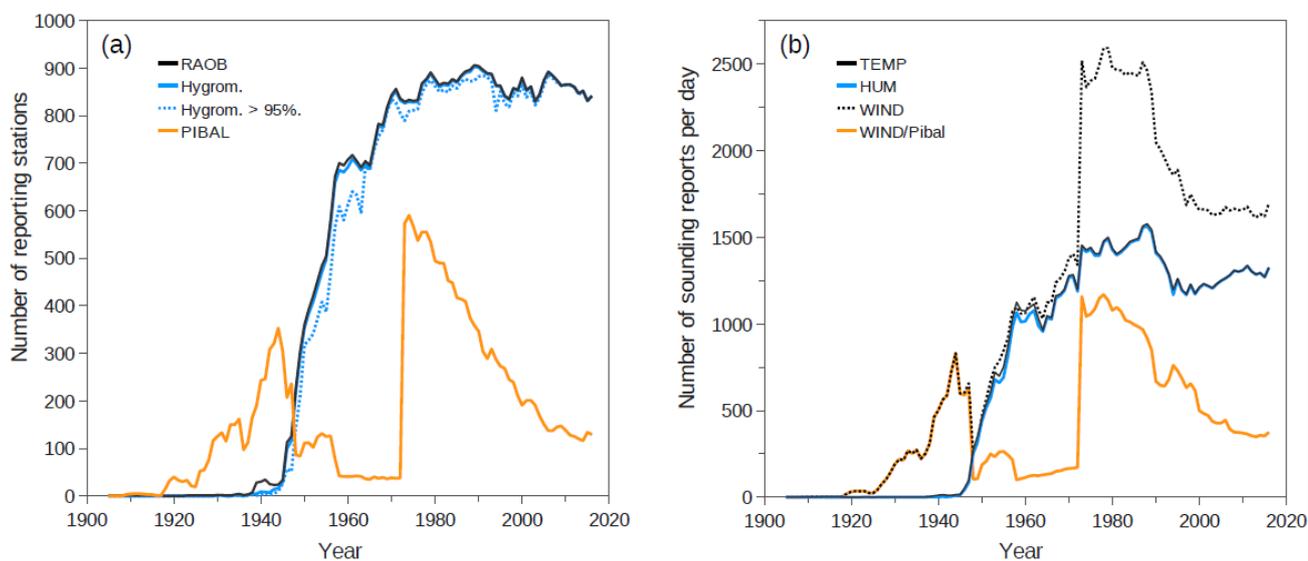
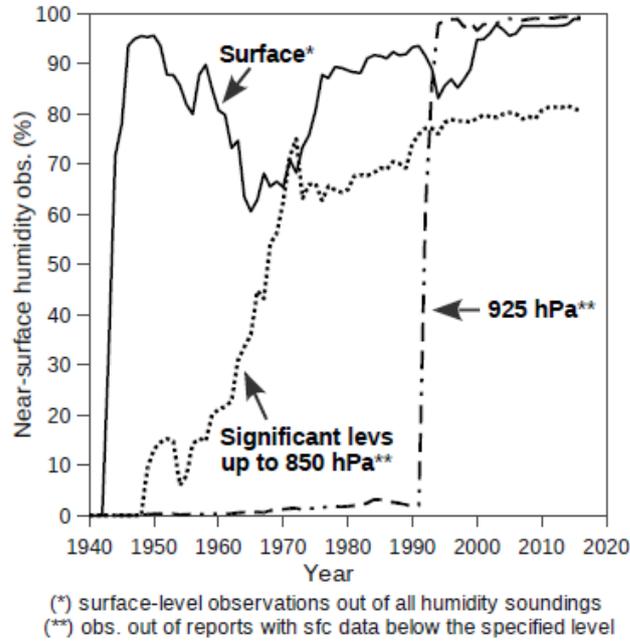



Figure 1

(a) Number of IGRA stations, for each year until 2016, reporting: any amount of radiosonde observations (RAOB); only wind observations (PIBAL); any humidity observations (Hygrom.); humidity data in at least 95 % of the RAOB soundings (Hygrom. > 95 %). (b) Number of IGRA sounding reports per day by atmospheric parameter: temperature (TEMP); humidity (HUM); wind

10 **from radiosonde or pilot-balloon measurements (WIND); wind-only data (WIND/Pibal)**

15   **Figure 2**

Percentage of humidity observations: at the surface level out of all humidity soundings in each year; at 925-hPa, out of the soundings with surface data below that level; and at any non-standard level – excluding the 925-hPa, irrespective of the year – between the surface and the 850-hPa level, whenever this is above the surface.

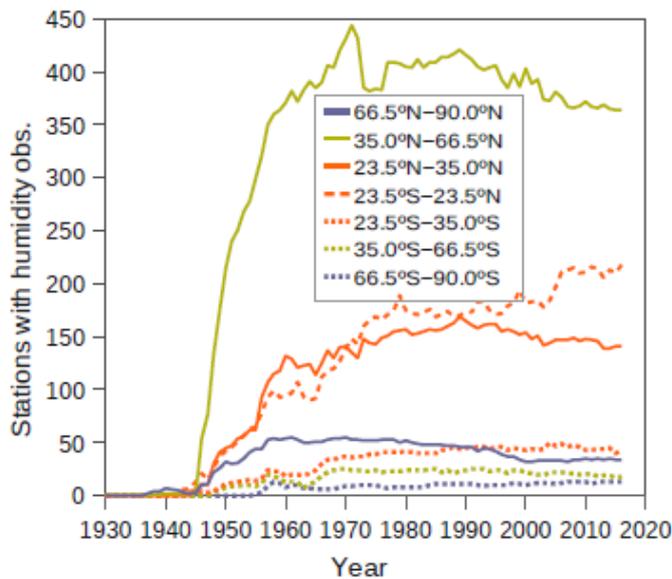



Figure 3

Yearly number of fixed stations reporting humidity observations in each climatic zone, since the time of the earliest humidity data

35   in IGRA.

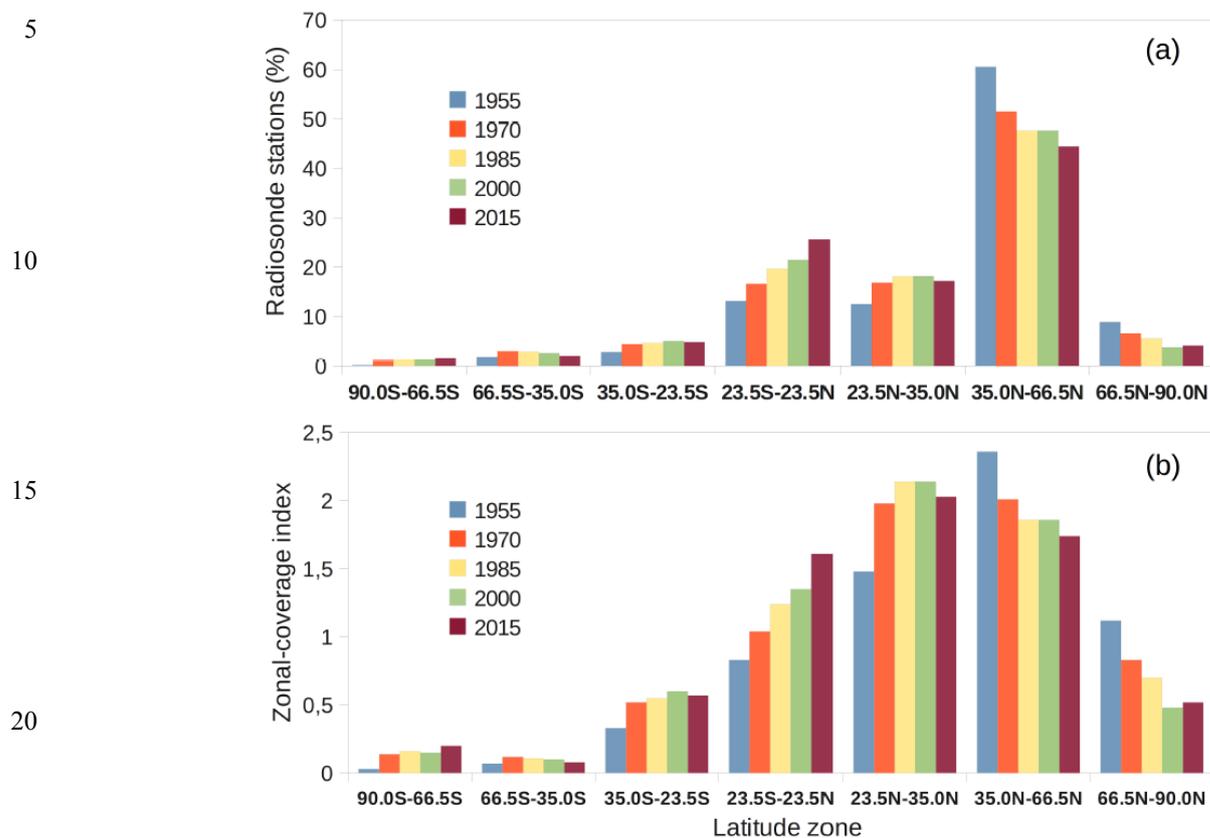



Figure 4

(a) Percentage of radiosonde stations measuring humidity, by climate zone, from 1955 to 2015 with 15 years interval. (b) Zonal-coverage index corresponding to (a), calculated by Eq. (1).

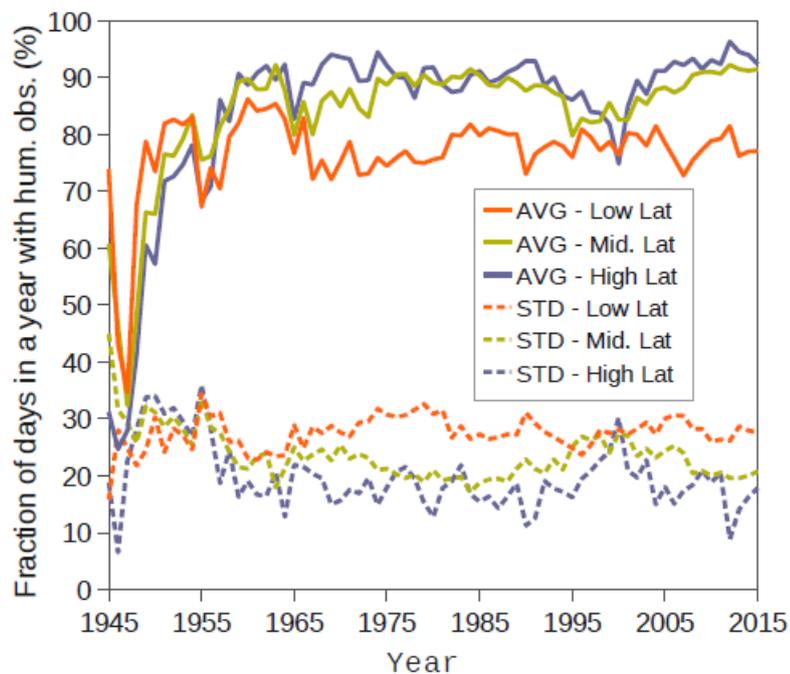



Figure 5

Statistics measures of the fraction of days in a year with humidity observations from 1945 to 2015, representing the fixed radiosonde

stations over the major latitude regions for both hemispheres: average among stations with humidity data, and standard deviation.

Low Lat – abs. latitudes < 30°; Mid. Lat – abs. latitudes between 30° and 60°; High Lat – abs. latitudes > 60°.

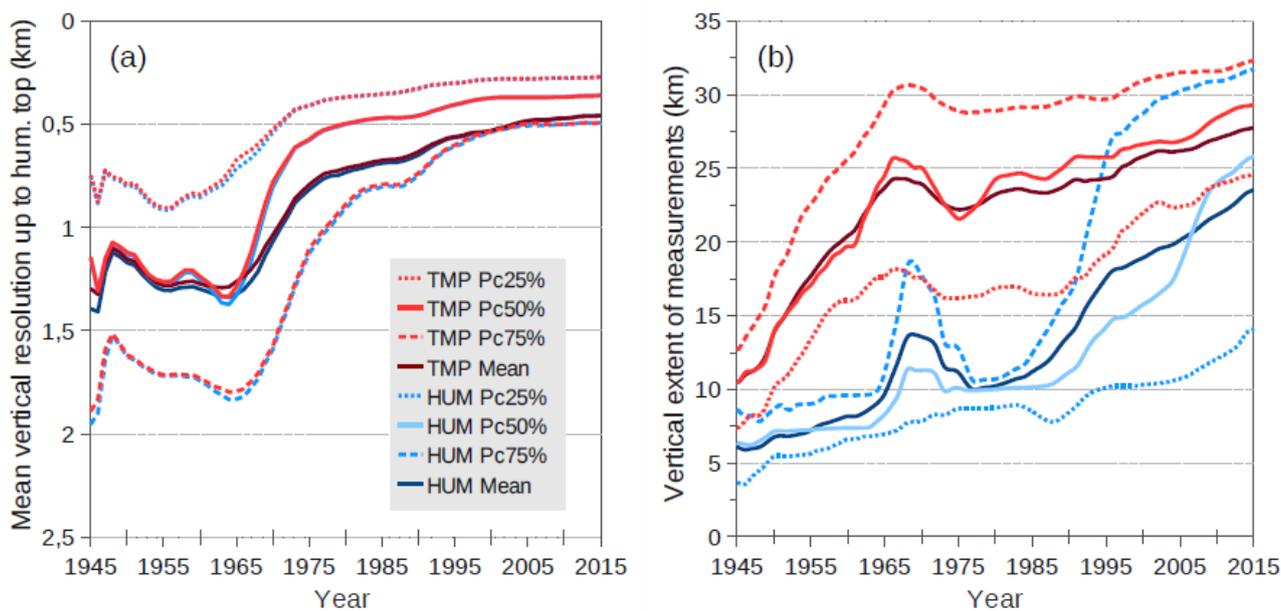



Figure 6

(a) Distribution of the 'mean vertical resolution' (definition of Eq. (2)) in the annual soundings of temperature (TMP) and humidity
5 (HUM) across the globe: mean and quartiles. (b) As in (a), but for the vertical extent of soundings. All the curves are smoothed by a
5-years running mean.

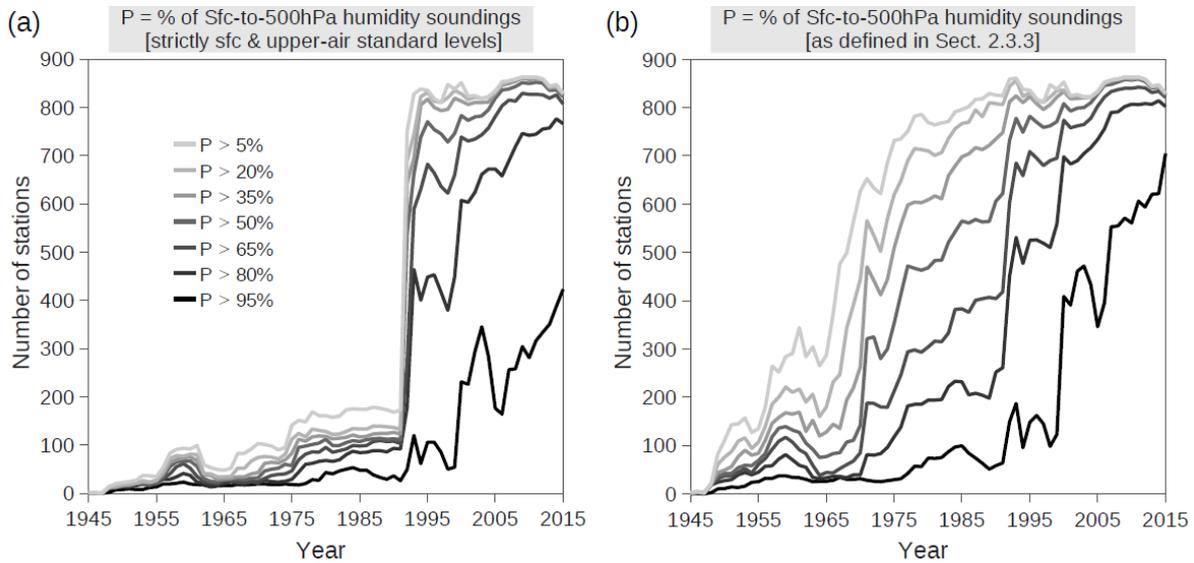



Figure 7

Number of stations for which the percentage of Sfc-to-500hPa humidity soundings, out of all soundings with humidity in each year, exceeds a given value (see inset of panel a): (a) Requiring humidity data at the surface level and all current standard levels above the surface up to 500 hPa; (b) Using the definition of 'Sfc-to-500hPa humidity soundings' given in Sect. 2.3.3.

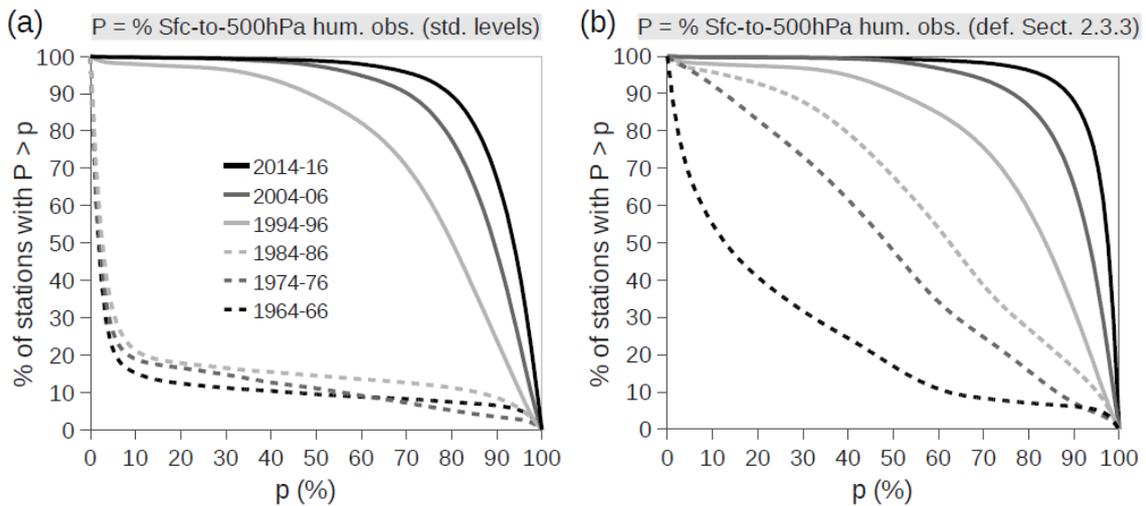
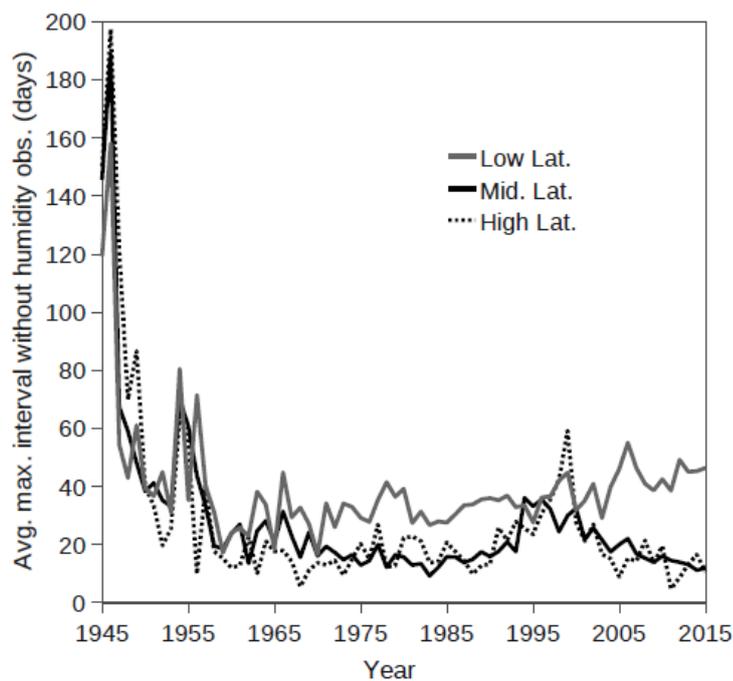



Figure 8

Percentage of stations, out of all IGRA-RS stations, with a percentage of Sfc-to-500hPa humidity soundings exceeding a given value (shown in abscissa), out of the humidity soundings in several trienniums with 10 years interval (see inset of panel a): (a) Requiring humidity data at the surface level and all current standard levels above the surface up to 500 hPa; (b) Using the definition of 'Sfc-to-500hPa humidity soundings' given in Sect. 2.3.3.

20 **Figure 9**

Maximum number of consecutive days without humidity data in each year with some humidity observations ('size of missing days'), averaged among the fixed stations within each of the major latitude regions defined as in Fig. 5.

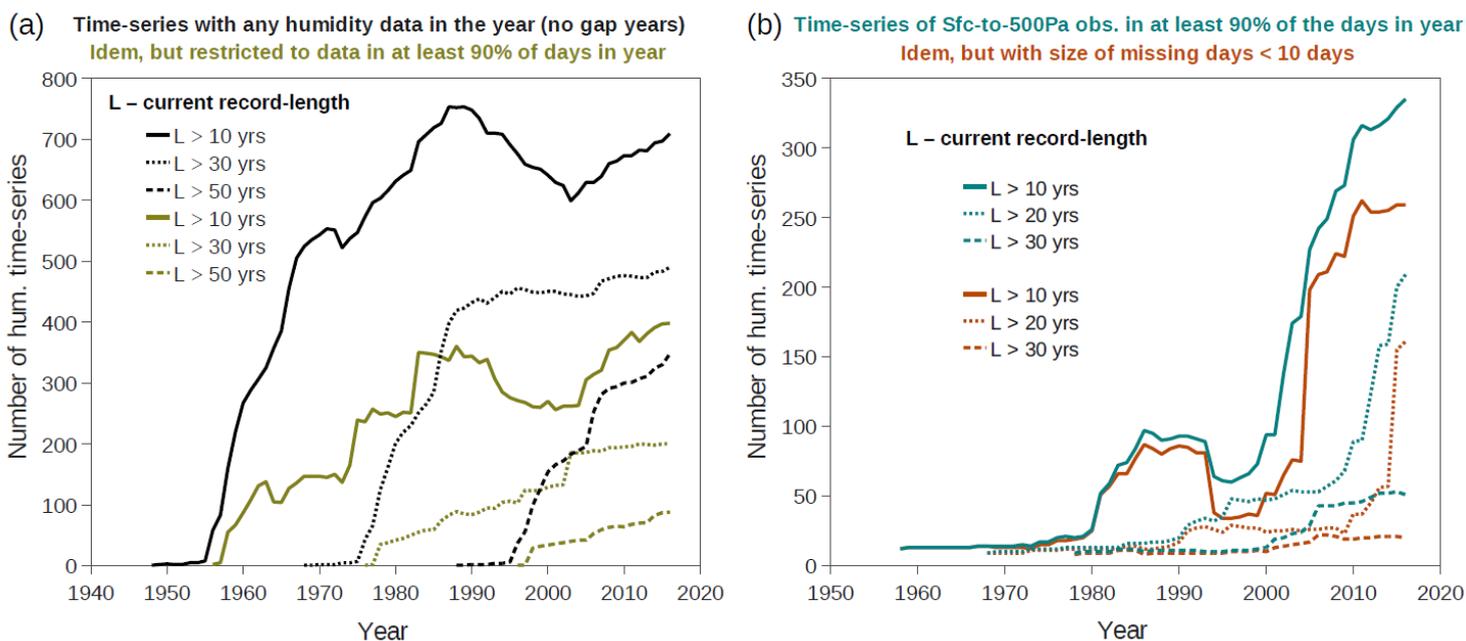



Figure 10

5 **Number of humidity time-series with a record length exceeding a given number of years until the year in abscissa (see insets), under different completeness criteria (indicated on top of the graphs).**

LIST OF TABLES 1–3

Table 1. Number of soundings in IGRA and IGRA-RS subset until the end of 2016

	IGRA (2761 stations)	IGRA-RS (1723 stations)
Total (PIBAL + RAOB)	45,677,409	39,526,638
PIBAL (*wind-only data*)	15,463,235	9,312,891
RAOB	30,214,174	30,213,747
RAOB with humidity data	29,801,708	29,801,324

Table 2 Parameters of humidity completeness for each IGRA-RS station and year

Parameter	Description (*Statistics refer to a year within the period of record of the station*)
HUMa	# of soundings with humidity observations
HUMb	# of soundings with Sfc-to-500hPa humidity observations[1]
RESa	Annual mean vertical resolution of humidity observations[2]
RESb	Annual mean vertical resolution of Sfc-to500hPa humidity observations[3]
TOPP	Annual geometric mean pressure of the highest level with humidity data
GAPa	Largest interval of days in the year for which humidity observations are missing
GAPb	Largest interval of days in the year for which Sfc-to-500hPa hum. obs. are missing
FDYa	Fraction of days in a year with humidity observations
FDYb	Fraction of days in a year with Sfc-to-500hPa humidity observations

([1]) As defined in Sect. 2.3.3. ([2]) Arithmetic mean of the 'mean vertical resolution' given by Eq. (2).
([3]) Calculated as RESa, but between the surface and 500 hPa.

Table 3 Parameters of humidity completeness for each sounding

Parameter	Description
RAOB	Classifies the RAOB according to the thermodynamic data reported: 0 = none (only wind data); 1 = TEMP data, but missing HUM; 2 = TEMP and HUM data; 3 = TEMP and Sfc-to-500hPa HUM[1]
RESa	Mean vertical resolution of humidity data[2]
RESb	Mean vertical resolution of Sfc-to-500hPa humidity data[3]
TOPP	Atmospheric pressure of the highest level with humidity data
TOPZ	Altitude above mean sea level of the highest level with humidity data

([1]) As defined in Sect. 2.3.3. ([2]) Calculated by Eq. (2).

([3]) Calculated as RESa, but between the surface and 500 hPa.