AMS 100th Annual Meeting, 15 January 2020
Poster 1125

Deriving Complete Upper Air Station Histories Using Sensitive Data Variables – An Essential Step in Homogenizing the Atmospheric Climate Record

Steven Schroeder[1]

[1]Department of Atmospheric Sciences, Texas A&M University, College Station, TX

ATMOSPHERIC SCIENCES
TEXAS A&M UNIVERSITY

Summary

PROBLEM STATEMENT

To compute long-term atmospheric temperature and moisture trends from archived radiosonde soundings, data must be adjusted to compensate for changing biases as newer instruments are introduced. The two main radiosonde error causes are as follows:

1. **Sensor lags:** Response lags average values over a distance below the radiosonde, causing usually warm and moist biases, and
2. **Radiation:** A sensor is cooled by radiation to space and is heated in sunlight.

Modern radiosondes usually have smaller errors, so the multi-decade global trend contains artificial cooling and drying. Most stations apply manufacturer adjustments before transmission, but adjusted soundings can still be biased because the adjustments consider only limited factors.

To properly identify discontinuities (breakpoints) for developing rigorous corrections, historical metadata is needed, listing upper air stations, locations, elevations, instruments, and change dates, and other factors that affect reported values. However, metadata compilations are quite incomplete and outdated, so researchers often make data adjustments that do not coincide with instrument changes.

Some homogenization projects attempt to identify breakpoints automatically, mostly using temperature discontinuities relative to a long-term average, other stations, or satellite data. There are many missed and false detections because large natural variations mask many instrument discontinuities, many stations frequently alternate between radiosonde models so discontinuities are blurred, many projects do not use available specific instrument information, and most comparisons are based only on monthly averages instead of individual soundings.

An additional error source is erroneous or outdated station locations and elevations. A radiosonde station location should be the actual launch location (and elevation). WMO does not have a definition of “station location” applicable to radiosondes, and catalogs often report the surface station location, but the radiosonde station may be many km away. Ship (and oil platform) radiosonde elevations are usually stated as 0 meters, but many such marine launch locations now have elevations over 40 meters. Complete station and instrument histories are needed.

PROJECT GOALS AND METHODS

This project focuses on developing serially complete station and radiosonde histories by consolidating many previously-unused current and historical metadata sources, then using monthly averages and individual archived soundings to check all metadata and to fill in missing information. So far, >3000 upper air instrument types and >6000 stations (including name changes) are documented. The metadata format is suitable for other upper air profiling instrument types such as dropsondes and wind profilers, but information is currently most complete for radiosondes.

An appropriate discontinuity in a station time series usually identifies the actual change date between different instruments reported in successive catalogs. Instrument discontinuities are best detected and attributed to specific instrument models using “sensitive” variables focusing on extremes of sensor reporting (especially humidity near 0 or 100%). All stations using the same instrument usually have certain common data characteristics, and differing distinct characteristics among soundings at a station can sometimes identify use of up to 3 instrument types.

Station location metadata is partly verified by determining a complete elevation history. Computing the surface elevation hydrostatically from reported heights has identified the exact time of thousands of station moves, and >1000 launch locations have been verified to 10-100 m accuracy using site photos or descriptions, along with online satellite photos.

Validating and inferring metadata is a mostly manual process. Metadata is often found in “informal” internet sources. After metadata and archived soundings are suitably compiled, “sensitive” variables that appear to distinguish instrument types need to be identified. Sounding data can be processed with computer programs to compute and display appropriate statistics, but it is a mostly manual process to identify consistent characteristics and time periods across stations, signals of discontinuities, and evidence of use of multiple radiosonde types at a station.

This poster does not report on developing instrument corrections themselves. That is a separate project with its own challenges.

DATA AND METADATA SOURCES

Archived sounding data is available in several sources, mostly derived from operational Global Telecommunications System (GTS) data. Historical GTS datasets simply archive current incoming reports. Several historical sources reprocess GTS data into a consistent format. The largest historical upper air dataset is the Integrated Global Radiosonde Archive (IGRA, versions 1 and 2). This project mainly used NCAR Dataset DS353.4, containing soundings accepted by NCEP from 1973 to February 2007, and DS351.0, soundings accepted by NCEP (stored in BUFR files) since October 1999. Many other smaller historical datasets are available containing soundings that were not transmitted on the GTS or its predecessors, including data rescue to digitize paper records of soundings from individual countries, stations, or field programs. Many archives, including IGRA2 and the University of Wyoming, ignore instrument types and other metadata usually reported in GTS soundings.

Some datasets contain adjustments applied by forecast centers for homogeneity, on top of station corrections in GTS soundings. Since these adjustments were applied in real time, usually without updated notification of station instrument changes, the wrong adjustments were applied for a considerable period after most instrument changes, so such datasets do not accurately identify real instrument changes.

Station and instrument metadata is also available from many sources, but still needs to be compiled into a consistent global history. The most widely used sources are station catalogs, usually focusing on surface stations, and are available at variable intervals back to 1912. Such catalogs depend on notifications from countries, so many entries are outdated, occasionally for decades, or simply erroneous. When a change appears in a catalog, the actual change date is rarely stated. Locations are usually stated to the nearest minute, but some locations are in error by up to hundreds of km. Before about 1995, geodesy was still being refined, so even accurately surveyed locations differ as much as several hundred m from the latest GPS-based WGS-84 global standard. Most data archives have a station list, but it is usually simply copied from the agency’s own sources without checking, so further errors are frequent, and most catalogs list only the latest known station location.

Global WMO upper air station catalogs have been located back to 1957, just before the International Geophysical Year. However, information about instrument types is often quite generic, such as “United States” or “Canadian” or “US military AN/AMT-4” (a military specification used for many radiosondes with several manufacturers and substantial changes in sensors from about 1948 to 1980).

The most extensive **worldwide historical station and radiosonde metadata effort** is documented in Gaffen (1996), based on a project to request such historical information from all WMO countries in 1990 (Gaffen 1993). They received replies from 49 countries, and Gaffen (1996) adds WMO catalogs (some unpublished) from 1965, 1977, 1982, 1986, and 1993, and several reports from individual countries obtained by personal contacts. Most sources are “snapshots” or “static events” of station location and instrument types as of the latest update received, so only 20% of the events are “dynamic events”, or changes with dates. The information is presented in a consistent format, but no attempt was made to resolve inconsistencies. IGRA and IGRA2 metadata files are built on Gaffen (1996) metadata, but the number of added entries after 1995 is still quite small. Note also that these efforts were mostly performed before the internet was available.

This project has located a very large number of **internet references** to radiosonde or station information, including unexpected information found because, for example, a web search for a station name and “radiosonde” often provides results for a different station, since the requested key words merely need to be somewhere in the web page. Also, systematic searches were made of dozens of journals, and *Meteorological and Geoastrophysical Abstracts* from 1950 to about 2004. All such results need to be checked. It was found that peer-reviewed papers often contain vague or even inaccurate station or instrument information because most researchers are unaware of the errors of different instrument types, and it is not the purpose of a typical paper to discuss instrument information in detail.

SOME ONGOING ISSUES

The main reason this project is needed is that transmitted soundings have always reported minimal metadata (usually only station ID and observation time) because of severely limited communication capacity. Transmitted observations use rigid formats, mostly 5-digit groups, because Morse Code was most rapidly transmitted manually in 5-character (or 5-digit) groups, and some remote stations used Morse Code even in the 1980s or later. The human-readable (letters and numbers) format approach is referred to as Traditional Alphanumeric Code (TAC).

Metadata reported in soundings. With gradual transmission capacity increases, WMO provides for some instrument metadata reporting.

Starting in 1968, the a_4 variable, “wind tracking method”, was to be reported in the wind portion of soundings.

The 31313 section was introduced in 1992 to include a 5-digit “instrument and system code”, but some major countries did not report this group until 2012 or later. This contains a 2-digit “instrument and ground system” code, which is actively managed as WMO Common Code Table C-2. In principle, reporting this code in every sounding gives a complete radiosonde history, but with a limited number of code values, the same code may represent multiple instrument varieties (such as 27 = Russia MRZ, used since 1987) with differing biases, especially if a code is used for ~10 years or more. So, all soundings still need to be checked for homogeneity, whether the instrument code is reported or not.

BUFR format. WMO is gradually changing from TAC to a binary code format (not human-readable) called Binary Universal Form for the Representation of meteorological data (BUFR). It was defined starting in 1984 as a generic encoder/decoder and a collection of tables (so the binary format approach is called Table Driven Code Forms (TDCF). The original reason to develop BUFR was the concern that communication capacity was not growing fast enough (the rapid network expansion since the 1990s was unforeseen), but it was also designed for more flexible changes to formats, such as reporting higher precision. Any format could be expressed as BUFR variables (such as the variables reported at each radiosonde level), operations (such as a variable stating the number of levels reported in that sounding), and table values (some variables simply define units and precision, such as temperature, but the instrument code table is a common code table used by TAC and BUFR. The 2-digit TAC instrument code is 8 bits in BUFR, allowing 256 values, but that is still an inadequate number of instrument codes for the long term because obsolete codes are kept, so with the latest code tables, any current or historical BUFR observation can be decoded.

One feature of BUFR is that much more metadata can be reported. About a dozen variables are set up to identify temperature, humidity, and other sensors, software versions, ground stations and tracking radars or other equipment, specific correction schemes, and radiosonde serial numbers. However, even managing Common Code Table C-2 is a difficult task, so other tables have been neglected, with code values only identifying generic characteristics (such as “thermistor”) or specific equipment or sensors used in the 1980s. Many of the defined variables were set up with only 4 or 5 bits (16 or 32 possible values), so their expansion is very limited. There have also been many problems in incorporating BUFR soundings into operational forecast systems, with different issues arising in each country.

So, the conclusion is that there will be an indefinite need for checking all upper air station and instrument metadata.

Validating or Inferring Instrument Histories

USEFUL DATA VARIABLES

A “sensitive variable” is a variable that is most likely to show steplike differences when a radiosonde model changes. Any such unnatural data change is considered to be a radiosonde change including a change in the ground station, other radiosonde equipment (even the balloon), operational or computational procedures, or software can change readings reported in a sounding. For example, a new radiation correction should change the reading by the amount of difference between the old and new schemes. Since the radiosonde swings across the balloon wake as it ascends, lengthening the line from the balloon to the radiosonde allows the radiosonde to swing in a larger arc with less time in the balloon wake. From April 1973 to September 1993, NWS stations reported relative humidity <20% as an artificial dew point depression of 30°C. Any such change can be treated as an instrument change.

Basic sounding variables are pressure, height (of certain pressure levels), temperature, and humidity (reported as dew point from 1949-1967 and dew point depression since 1968), and also wind direction and speed. These variables are reported at mandatory levels (currently surface and 1000, 925, 850, 700, 500, 400, . . . hPa) and significant levels (including the tropopause and any other levels where data values differ noticeably from a straight-line interpolation of the reported levels). With BUFR, these variables can be reported at every level, along with additional variables at every level such as elapsed time since launch, latitude, longitude, and height.

Sensitive variables are derived from basic variables and may need to be customized for different suspected or reported instrument types, since the nature of discontinuities depends on processing and other practices, as well as the original sensor responses. Examples shown here focus on typical sensitive variables at stations before the instrument type code was reported, so instrument changes are inferred solely from time series of archived soundings. Because sensitive variables represent extremes of sensor responses, many discontinuities are so large and abrupt that they cannot be natural changes. Most sensitive variables have no real climate use, so they have generally not been studied. A partial list of sensitive variables is as follows:

* Number of reported levels in transmitted soundings. A sudden increase may indicate improved processing, such as changing from manual computations to a calculator or computer.
* Lowest reported (or computed) relative humidity (RH) or highest dew point depression (DPD reported since 1968), and also highest reported (or computed) RH. Since it was difficult to produce very dry RH in a calibration chamber, some RH algorithms were tuned to never compute an RH below a value such as 10 or 20 percent. Slow-responding sensors often would report RH considerably below 100% (or ice saturation) in clouds, would not detect thin dry (or moist) layers, and also would not measure dry conditions in the upper troposphere and stratosphere.
* Coldest reported dew point. Some instruments have dry biases at upper levels, seen by dew points < -100 °C, which should never occur at radiosonde altitudes. At the South Pole, Air-5A radiosondes used from 1999-04-09 to 2002-08-11 often reported DP < -110 C at all levels including the surface in winter, due to a defective response at temperature <-40°C.
* Lowest pressure, highest altitude, or coldest temperature with reported RH (or DPD). Due to the above-mentioned RH cold insensitivity, for some radiosondes it was a policy to not report RH or DPD below a chosen temperature or pressure (such as -40°C or 200 hPa), and some radiosondes were wired to disconnect the RH sensor at a temperature or pressure threshold.
* Lowest reported temperature, or temperatures at certain levels such as 500 hPa, 100 hPa, or the tropopause. Usually these variables are not sensitive enough to detect discontinuities in individual sounding data, but monthly averages may show discontinuities caused by factors such as an introduced or changed radiation correction.
* Number of reported wind levels, or maximum height or lowest pressure with wind data. A discontinuity does not necessarily indicate a change in the radiosonde itself, except if the wind reporting is changed due to a change in the entire ground system. In some cases, wind data was obtained by a separate balloon launch, not necessarily at the time or location of the radiosonde launch, so such wind observations would not be at all related to radiosonde changes.

ARCHIVED DATA PROCESSING STEPS

An initial data preparation step is to **hydrostatically compute the surface elevation** using the reported surface pressure and all levels up to the first above-surface height. Alphanumeric code formats report pressure to the whole hPa, so individual computed surface elevations vary by about +/- 4 m, but in most cases an elevation change of ~1 m can be detected in averages. An elevation change is likely to coincide with a station move and possibly an instrument change. As shown to the right, additional information may identify station locations corresponding to the computed surface elevations. Even if locations are not accurately determined, elevation needs to be considered due to effects on bulk variables such as precipitable water, or boundary layer characteristics, that may falsely imply an instrument change. After determining the elevation (and hopefully location) history, finding instrument changes is a **repetitive two-stage process**:

First, examine **monthly averages** of appropriate variables to identify reported (or hypothesized) instrument changes and their approximate timing.

Second, search sensitive variables in **individual soundings** for steplike discontinuities that may show instrument transitions to the exact or almost exact observation.

Both steps should consider whether a fluctuation may have a natural cause, such as ENSO or a large volcano. The repetitive nature of this process means that multiple stations with the same hypothesized instrument types need to be carefully compared, possibly repeatedly, because an instrument type should show a high degree of commonality in characteristics at each station. Data signals in individual soundings may indicate frequent alternations between instrument types. Evidence of an unreported instrument type with different characteristics can also be found, even when the same instrument code is reported. For example, Russia MRZ (code 27 or 75) is ordinarily moist (goldbeaters skin humidity sensor), but reported dry conditions at some stations in the late 1990s. From personal communications (A. Kats, 2010), these were experimental radiosondes with MRZ electronics and more modern sensors, including RF95 (using Vaisala RS80 temperature and humidity sensors) and MRZ-3AM (with a domestic capacitive humidity sensor). So, the use of an unreported radiosonde often can be detected, although the identity of the instrument model is not immediately known.

SOME EXAMPLES

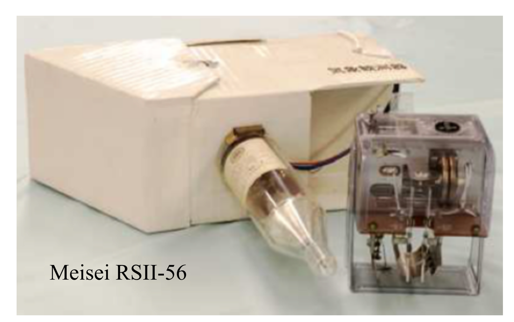
The examples shown here focus on Japan prior to the beginning of reporting the instrument type code in soundings, which started at these stations early in November 1995. There were only three basic Meisei models involved,

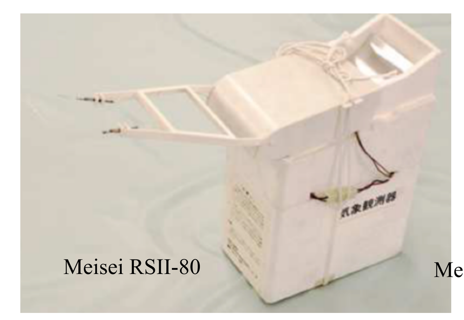
RSII-56 (mostly used 1957-1981):
Bimetal thermometer, hair hygrometer

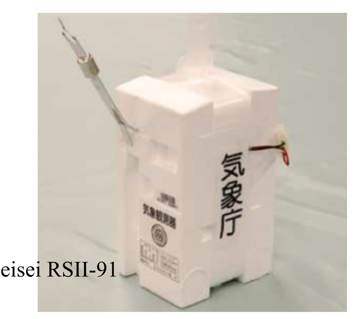
RSII-80 (mostly used 1981-1992):
White coated rod thermistor, carbon hygristor

RSII-91 (mostly used 1992-2009):
Bead thermistor, capacitive humidity sensor

(photos from Kizu et al. 2018)


Meisei RSII-56

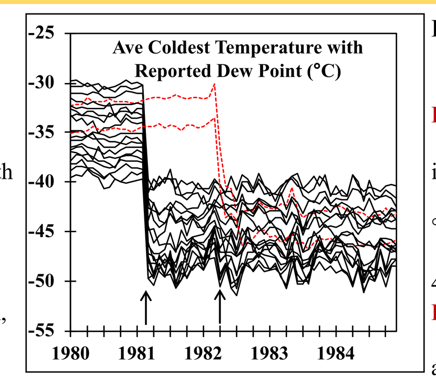

Meisei RSII-80



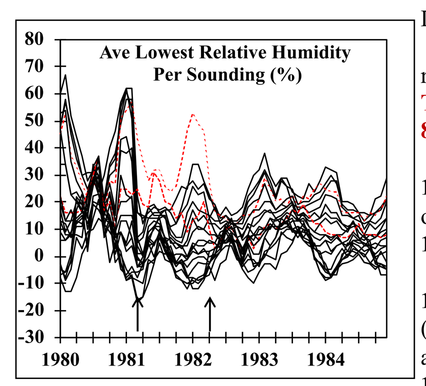
Meisei RSII-91

1981 or 1982 – Transition from RSII-56 to RSII-80

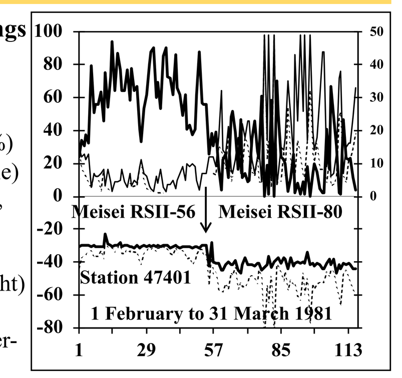
Monthly averages
20 Japan stations, 47401-47991
Offset from top line (left scale) in numerical order, mostly north to south
Red dashed lines = military 47580,47681
Transitions early 1981-03 civilian, 1982-04 military

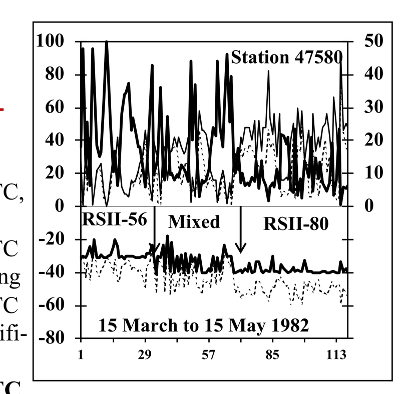


Same stations and offsets
Northern stations more moist winter, southern stations more moist summer
Exact month of change hard to see
Military stations moist 1 year longer than civilian stations



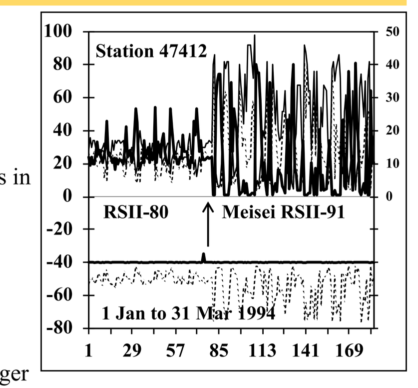
Individual soundings
(top) station 47401
(bottom) 47580
Lines >0:
Bold, lowest RH (%) in sounding (left scale)
Solid, highest DPD, °C (right scale)
Dashed, ave DPD 400-600 hPa, °C (right)
Lines <0:
Bold, coldest temperature with reported DPD (°C)
Dashed, coldest reported DP (°C)
Transitions to RSII-80:
47401, starting **1981-03-02 0000** UTC, one prior RSII-80 at **1981-03-01 0000** UTC
47580, mixed starting **1982-04-01 1200** UTC (each sounding identifiable), only RSII-80 **1982-04-19 0000 UTC**

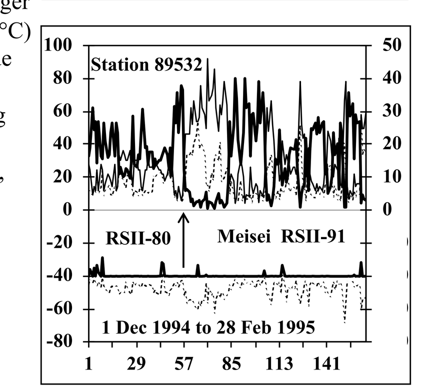




1992 to 1995 – Transition from RSII-80 to RSII-91

Individual soundings
(top) station 47412
(bottom) 89532, Syowa, Antarctica
Lines >0, <0:
Same meanings and scales as in panels at left
Transitions to RSII-91:
47412, RSII-91 starts **1994-02-07 1200** UTC
89532, RSII-91 starts **1995-01-03 1200** UTC
Both stations show much larger RH variability (surface to -40°C) with RSII-91 than RSII-80 due to more sensitive RH sensor
Antarctica has RH remaining lower in moist atmospheres, compared to stations in Japan, due to ice saturation being considerably < 100% RH





References

Only a few references are listed here. Additional references are included in the online paper to be prepared for this poster soon after this meeting.

Gaffen, D. J., 1993: Historical Changes in Radiosonde Instruments and Practices (WMO/TD-No. 541, IOM-50). WMO, 127 pp. plus 4 microfiche (Library of Congress Catalog Number = QC875.5 .I58 #50).

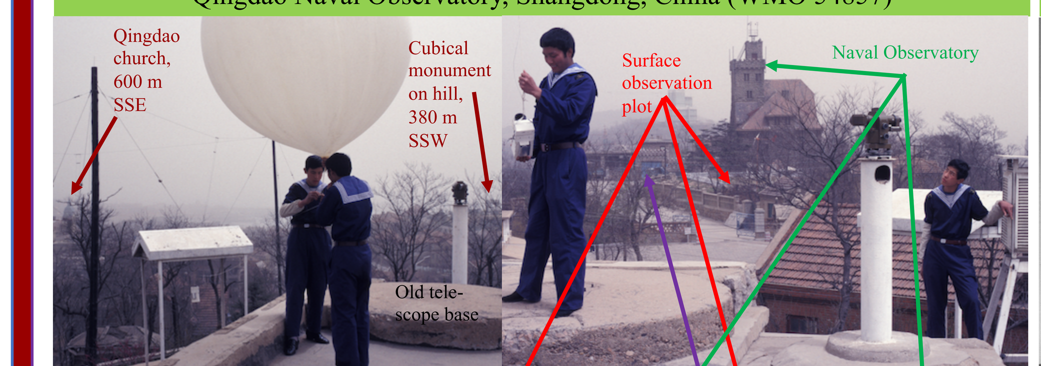
Gaffen, D. J., 1996: A Digitized Metadata Set of Global Upper-Air Station Histories (NOAA Technical Memorandum ERL ARL-211). NOAA Air Resources Laboratory, Silver Spring, MD, 38 pp. (available at ftp://ftp.ncdc.noaa.gov/pub/data/images/gaffen1996.pdf).

Kizu, N., et al., 2018: Technical Characteristics and GRUAN Data Processing for the Meisei RS-11G and iMS-100 Radiosondes (Publication GRUAN-TD-5 Rev 1.0 (2018-02-21)). Gruan Lead Centre, Deutsche Wetterdienst, 152 pp. (available at https://www.gruan.org/gruan/editor/documents/gruan/GRUAN-TD-5_MeiseiRadiosondes_v1_20180221.pdf).

WMO, ----: WMO Manual on Codes (WMO-No. 306). WMO (available at http://www.wmo.int/pages/prog/www/WMOCodes.html, “Manual on Codes (WMO-No. 306)”.
Volume I.1: Part A – Alphanumeric Codes.
Volume I.2: Part B – Binary Codes, Part C – Common Features to Binary and Alphanumeric Codes.

Determining Accurate Station Location and Elevation Histories

Qingdao Naval Observatory, Shangdong, China (WMO 54857)



Photos from Eckart Dege, showing 1988-04-03 2300 UTC launch (04-04 0700 local)
(left) Facing south, GZZ-2 radiosonde under white roof while balloon is being prepared
(right) Facing east, Qingdao Naval Observatory building is “castle”, sfc obs site inside white fence

* Note tile roof building in right photo above and just SE of blue arrow tip in both photos below.
* Slab and old telescope base in photos above apparently removed before oldest Google Earth photo (2001-08-01)
* New dome NW of blue arrow tip first seen in 2004-08-22 photo
* 1988 launch location identified within ~10 m relative to tile roof building, which is unchanged

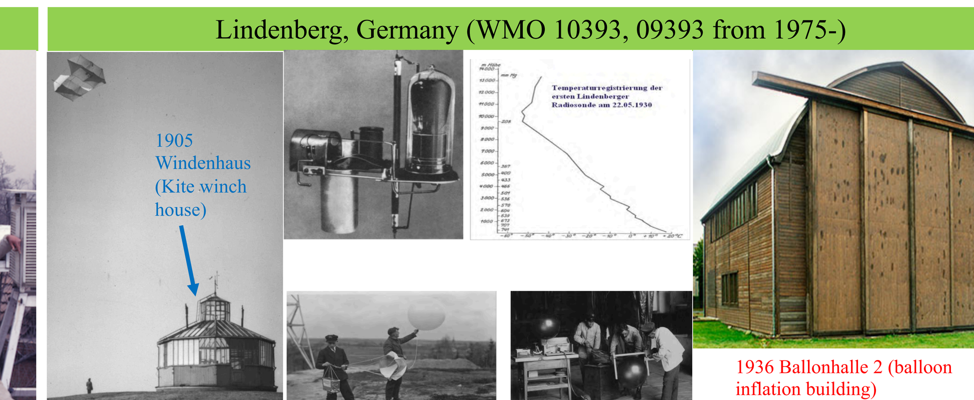
Conclusion: Launch site in 1988 (probably 1966-01 to 1991-08-23) = **36.0698N 120.3211E 76 m** (hydrostatic elevation)

Google Earth photos: (left) 2001-08-01, right (2019-03-15)

* In data, computed elevation decreases from 76 to 75 m approximately 1991-08-23, constant to at least 2007
* WMO catalog location in 1958 = 36 04N 120 19E 78 m (surface catalog only)
* NOAA, USAF, and WMO location starting 1966-01 = 36 04N 120 20E 75.6 to 77 m, might not indicate actual move due to small changes in reported elevations
* Upper left building in both photos is now Qingdao Old Observatory Youth Hostel, and removal of old concrete launch location before 2001 photo and addition of new dome implies new location
* Little flat area on remaining property, most likely new launch site is from paved area, balloon inflation possibly in building with blue door in right 1988-04-04 photo, probably not launched from surface observation plot

Conclusion: Launch site since probably 1991-08-23 inferred (almost definitely within 50 m) = **36.0697N 120.3227E 75 m**

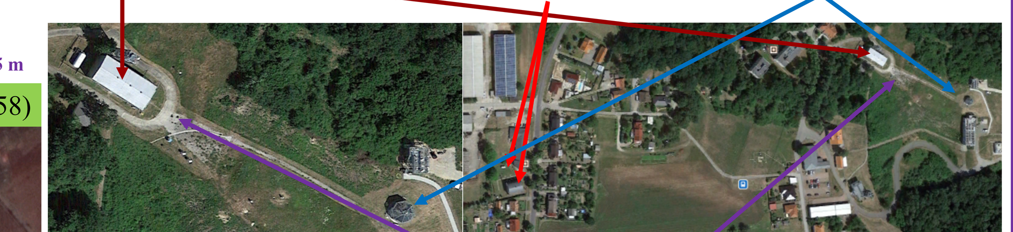
Lindenberg, Germany (WMO 10393, 09393 from 1975-)



Historical photos (https://www.gruan.org/gruan/editor/documents/meetings/icm-10/pres/pres_SV05_Dirksen_MOL3.pdf) (https://www.wettermuseum.de/index.php/museum/ballonhalle-2)
(left photo) Kite (1905 to 1944) and kite winch house
(middle photos and profile) First radiosonde launch, Duckert type, 1930-05-01
(right photo) Ballonhalle 2 (built 1936) used for balloon inflation and launches with wind from east

(http://twelveoclockinlondon.wordpress.com/page/83/)
(left) 1905 ballonhalle, photo facing NW, balloon for 2005-06-02 1800 UTC launch

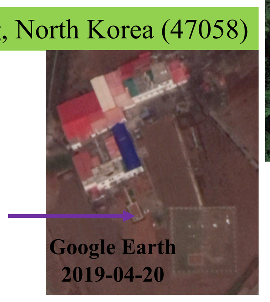
(https://www.wettermuseum.de/index.php/museum/radiosondenaufstieg)
(right) Facing SE from in front of balloon inflation building, unstated summer date probably about 2016



Google Earth photos 2018-06-05
Left panel is enlargement of upper right part of right panel
1905 Ballonhalle and Windenhaus in upper right, 1936 buildings about 500 m WSW
Conclusion: Radiosonde launch site since at least 1971 = **52.2094N 14.1203E 112 m** (within 10 m)

Nagqu, China (WMO 55299) — Pyongyang, North Korea (47058)

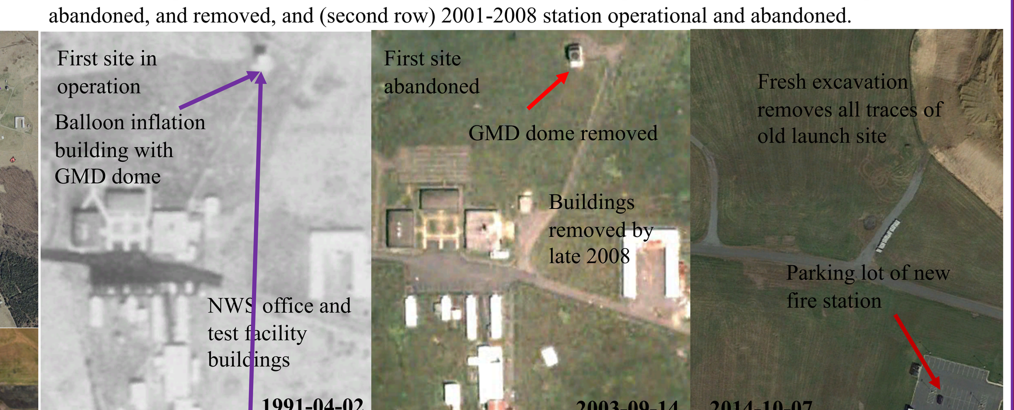
Inferred radiosonde launch locations
Naqu: Most likely = **31.4798N 92.0614E 4515 m** (balloon inflation building)
Pyongyang: Most likely = **39.0343N 125.7952E 37 m** (balloon inflation probably in adjacent building with large door)



Sterling, VA - NWS Forecast Office (WMO 72403)

This station has an unusual station history: 3 locations between 2000 and 2010 due to construction of runway 1L-19R (opened late 2008), causing the existing office to be in the runway safety zone.

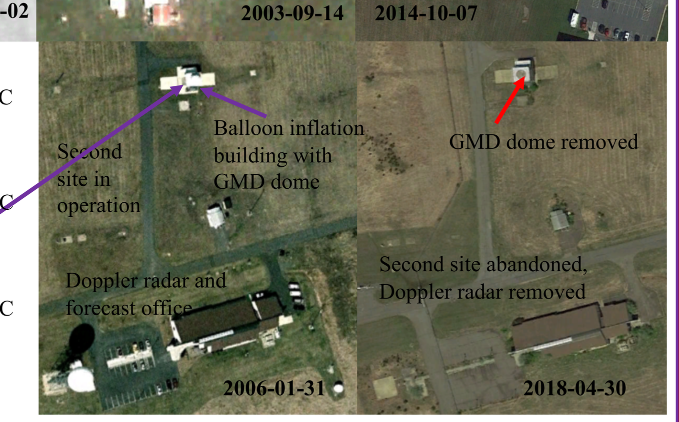
Google Earth photos (date shown on each panel) below show (top row) 1960-2000 station operational, abandoned, and removed, and (second row) 2001-2008 station operational and abandoned.



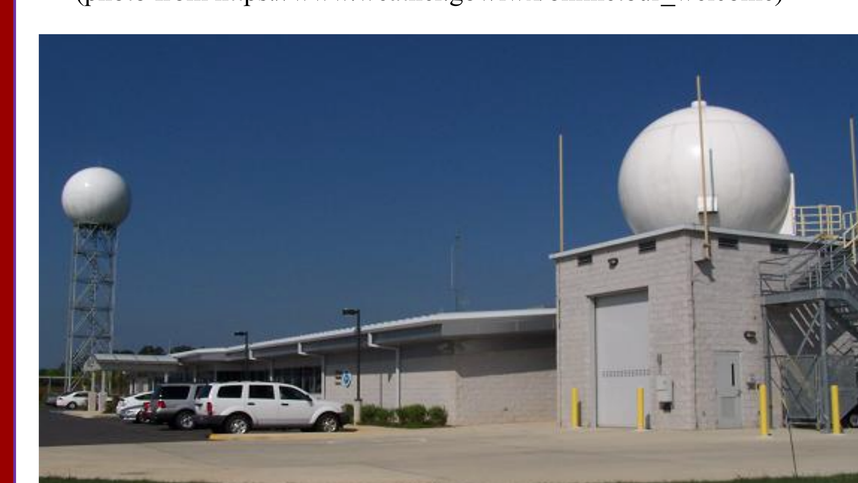
First launch location:
starting 1960-10-11 0000 UTC
38.9773N 77.4712W 84 m

Second launch location:
starting 2001-09-24 0000 UTC
38.9768N 77.4771W 86 m

Current launch location:
starting 2008-09-19 0000 UTC
38.9767N 77.4858W 88.4 m



Current Sterling NWS Forecast Office with Doppler radar and radiosonde launch facility
(photo from https://www.weather.gov/lwx/onlinetour_welcome) (Google Earth photo 2018-04-30)



Some conclusions about station location metadata
* Computed elevation change may indicate a station move
* Other reasons may be corrected survey, change in definition of “station elevation”, or elevation change without station move
* A few stations may operate 2 sites, indicated by different elevations at different observation times
* Erratic elevations may indicate inaccurate computations or possibly missing surface level in soundings
* Some countries have distinct station designs (such as certain radar domes, or nearby traditional surface observing plots) that may be clues to correct radiosonde launch sites
* However, identifying modern radiosonde locations may not always be possible without additional information because equipment may not appear distinctive or is too small to be visible on satellite photos
* ASOS is rarely a launch location clue because it is usually in the middle of an airfield for surface observations
* Published catalogs disagree, sometimes have large errors for years or decades, rarely identify metadata sources or dates of actual changes, and usually assume radiosonde and surface locations are the same