THE TALL TOWER DATASET TECHNICAL NOTE

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Summary

A database containing quality controlled wind observations from 222 tall towers has been created. High resolution wind speed and wind direction measurements have been collected from existing tall towers around the world within the context of the INDECIS project (GA 690462) in an effort to boost the utilization of these non-standard atmospheric datasets. Wind observations taken at several heights greater than 10 meters above ground level have been retrieved from various sparse datasets and compiled in a unique collection with a common format, access, documentation and quality control. For the latter, a total of 18 Quality Control checks have been considered to ensure a high quality of the wind observations. Non quality-controlled temperature, relative humidity and barometric pressure data have been also obtained and made available.

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1. Introduction

Renewable energies have experienced the fastest growth among all electricity sources in the last few years (OECD/IEA, 2018) and they are expected to account for more than the 70% in the global electricity generation during the 2018-2023 period. Together with solar PV, wind power will lead this development. In this way, the number of installed capacity and new wind farms is currently facing an important increase worldwide (WindEurope, 2018; AWEA, 2018).

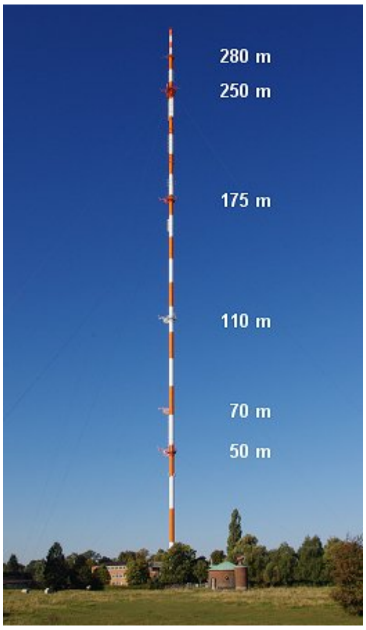


Figure 1. *Hamburg university meteorological mast. Source: https://icdc.cen.uni-hamburg.de*

With higher shares of electricity generation depending on wind speed conditions, it is crucial to advance understanding of wind speed conditions at heights between 50 and 150 meters above ground -where current wind turbines are installed- and at multiple time-scales from turbulence to mesoscale circulations, seasonal oscillations and climate change impacts. To do so, meteorological observations are highly needed. Most surface meteorological stations measure wind at 10 meters above surface level. However, observations at higher elevations are needed for wind power applications. Some of the potential usages of those high-elevated observations can be: a) study local wind shear and turbulence of the Planetary Boundary Layer (Li et al., 2010); b) evaluate wind resource characteristics and derive generation estimates (Brower et al., 2013); c) enhance or verify reanalysis products (Decker et al., 2012); d) correct meteorological forecasts (Baker et al., 2003) and climate predictions (Torralba et al., 2017); or e) adjust wind atlas products (Troen et al., 1989).

Energy companies erect instrumented tall towers prior the construction of a new wind farm to characterize the wind speeds in the area in order to ensure the return of the initial investment. Local wind flows, turbulence effects and vertical wind shear can have a strong impact on the electricity production (Hansen et al., 2012). The basic structure of these masts consists of a high vertical tower reaching heights of 100 to 200 meters above ground, with several platforms distributed along the vertical structure. It allows the placement of several wind sensors (i.e. anemometers and wind vanes) at different heights so that the vertical wind shear can be profiled. In addition, it is also typical to install several booms at each height oriented to different directions. It allows the installation of more than one sensor per measurement level so failures in the measurement by a sensor, either because it has entered a shadow zone produced by the mast itself or by a technical failure, can be corrected by replacing these observations by those of a redundant sensor at a same height. The physical structure of a tall tower is illustrated in Figure 1. Within the context of the energy industry, tall towers only take measurements for a relatively short period (1 or 2 years commonly). Then, they are decommissioned and the wind speed measurements used to correlate against reanalysis data and reconstruct wind time series over a climate period of 30 years by means of a statistical model (Brower et al., 2013).

Fortunately, there are other meteorological or research initiatives that install and maintain instrumented tall towers for longer periods of time. Derived from these diverse efforts, there exist various sparse datasets containing measurements from instrumented tall towers. Although most private companies are reluctant to share data with third parties, a quite large amount of tall tower data from public institutions can be freely accessible for non-commercial and research purposes. Nevertheless, they are difficult to find or access. Furthermore, the lack of coordination in terms of formats, metadata, data access and quality control hinder their further usage.

The INDECIS project (GA 690462) is putting efforts to collect existing non-standard meteorological observations. Within this framework, the Earth Sciences Department of the Barcelona Supercomputing Center (ES-BSC) has been working to identify, collect, format, document and quality control existing high-elevated wind observations. Providing an easier and unified access to quality-controlled wind observations from tall towers will boost the utilization of those measurements. This technical report goes through the different stages in order to build a unique dataset containing quality-controlled tall tower wind measurements. Section 2 describes the data collection process. Then, the quality control checks are presented in Section 3. General results obtained after the application of the quality control tests are presented in Section 4. Finally, some conclusions are presented in Section 5.

2. Data collection

The compilation of the tall tower raw wind measurements is divided in two phases. First, several institutions and observational sites that could potentially own and share tall tower wind observations have been identified. Then, if the data is accessible the observations and its metadata are downloaded and processed to a standardized format.

2.1. Identification of tall towers

Most wind energy companies install tall towers prior to construction of wind farms to characterize wind resource in the area. However, most companies are reluctant to share this information. Luckily, many public institutions, research centers and even government administrations own and maintain instrumented tall towers which can be used for research purposes.

These data are owned by institutions with very diverging goals. Most of them are public institutions that install one or two meteorological masts and use these data for their own internal research. But in some cases they manage several tall towers. Several types of institutions have been identified and are described in the following.

Meteorological weather services, such as MetÉireann, Korea Meteorological Administration, South African Weather Service, Météo-France, Agencia Estatal de Meteorología, Finnish Meteorological Institution, Royal Netherlands Meteorological Institute or Deutscher Wetterndiens, manage some tall towers that are used for operational meteorology and for boundary layer investigation. Energy research centers such as the National Renewable Energy Laboratory or the Energy Research Centre of the Netherlands also maintain some towers specifically designed and instrumented for wind power research. Some universities across the globe also own some towers. The Ohio State University, Hamburg University, Helsinki University or the Technical University of Denmark are some examples.

The World Bank has provided funds to some government administrations to implement national wind resource assessment campaigns in order to boost renewable energies at national level. Those projects typically include the installation of several met masts in the country. This is the case of South Africa or Iran. Although those campaigns have a good spatial coverage, masts are dismantled after a short period of one or two years only. Some international research projects, either ongoing or already finished, manage or collect tall tower data for their own purposes. Eventually, these data can be distributed outside the framework of the project. The New European Wind Atlas project (NEWA, http://www.neweuropeanwindatlas.eu), funded by the European Commission, aims to create a wind atlas covering the European Union with a resolution of 2-3 km. Within the context of this project, some met masts have been installed and measurements will be used to verify dynamical downscaling simulations. The FINO project (https://www.fino-offshore.de/en/), funded by the Federal Government of Germany, installed three offshore tall towers in the Baltic and North seas to boost the exploitation of renewable energy by means of offshore wind turbines. The Department of Energy of the United States launched the WFIP and WFIP2 projects, in order to enhance short-term meteorological prediction with the inclusion of new observational systems, including some tall towers.

In the United Kingdom, the institution that leases developments of new offshore farms (the Crown Estate) enforces the companies to share their offshore wind measurements. These observations covering the North Sea and coastal regions in the British islands are publicly accessible through the Marine Data Exchange website (http://www.marinedataexchange.co.uk/).

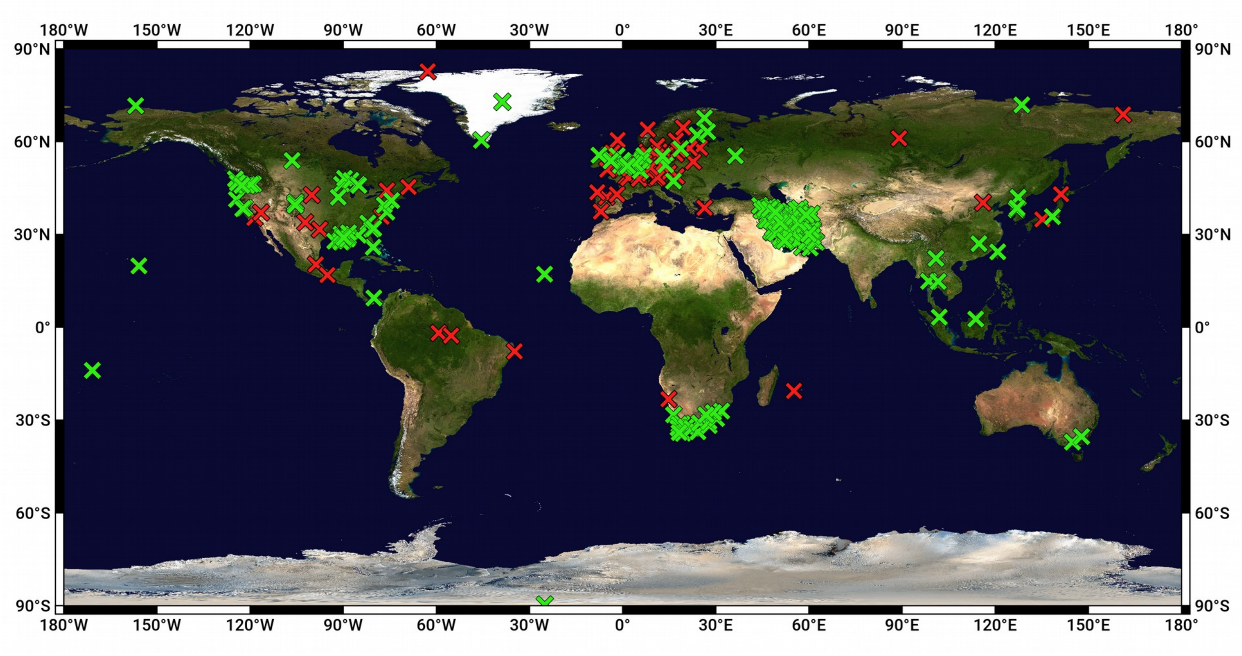


__Figure 2.__ Global distribution of the 311 identified tall towers. Green crosses indicate data that have been obtained for formatting and processing whereas red crosses depict tall towers which data have not been approached yet .

Other initiatives not directly related to wind energy also provide wind speed measurements at heights above ground. This is the case of the many flux towers that are used across the globe to monitor greenhouse gas fluxes. The Integrated Carbon Observation System (ICOS, https://www.icos-cp.eu/) or the World Data Centre for Greenhouse Gases (WDCGG, https://gaw.kishou.go.jp/) allow the access to towers specifically instrumented to monitor carbon fluxes, and typically contain anemometry at multiple levels. Also, the National Data Buoy Center from NOAA maintains an extensive database of offshore measurements from lights, buoys and ocean platforms such as oil stations. Some of these data are available at heights above 10m and have been identified here.

After all this process, a total of 311 instrumented tall towers from these institutions and databases have been identified around the world (Figure 2). The density of towers is higher in north and Western Europe, United States, Iran and South-Africa. The last two groups come from national wind resource assessment databases. Masts have been identified sparsely in some parts of south-eastern Asia, South-America and Australia. Some tall towers cover insular regions such as Hawaii, American Samoa, Cape Verde or Reunion. As mentioned before, some offshore towers have been found as well.

2.2. Retrieval and formatting of the data

Due to the fact that these tall towers are owned by different initiatives and centers, the data are spread in several different platforms and storage systems and provided in a diversity of formats and quality control. Some datasets are directly downloadable from *http* or *ftp* sites, whilst others require a registration through the owner institution. Some of them cannot be downloaded and are only available after sending a formal request to the institution.

Table 1. *Original and final standard formats of the tall tower data*

	Original	**Final**
File formats	ASCII (csv, tab, custom formats), NetCDF	NetCDF
Time resolution	From 1-minutely to 1-hourly	Preserve native resolution
Time stamps	Start/middle/end of average period time stamp	Middle of average period time stamp
Time zone	UTC, local time	UTC time
Units	Wind speed: km/h, kt, mph, cm/s, m/s Wind direction: degree Temperature: ºC, K Relative humidity: % Pressure: mbar, mmHg, Pa	Wind speed: m/s Wind direction: degree Temperature: K Relative humidity: % Pressure: Pa

The availability and quality of documentation and metadata varies considerably between providers. This dispersion hinders the usage of the datasets. Therefore, a common format, documentation and single access point to all this data are proposed and described here to facilitate the usage of these data.

Regarding the data policies that regulate the usage of the different datasets, most of masts measurements are made freely accessible and open to be used for any purpose so there is no restriction affecting the distribution to third parties. Regrettably, some centers prefer to restrict the usage of their data or the distribution to third parties, limiting the possibility to provide these data in this collection. Also, it has been impossible to obtain data or information from some of the identified towers.

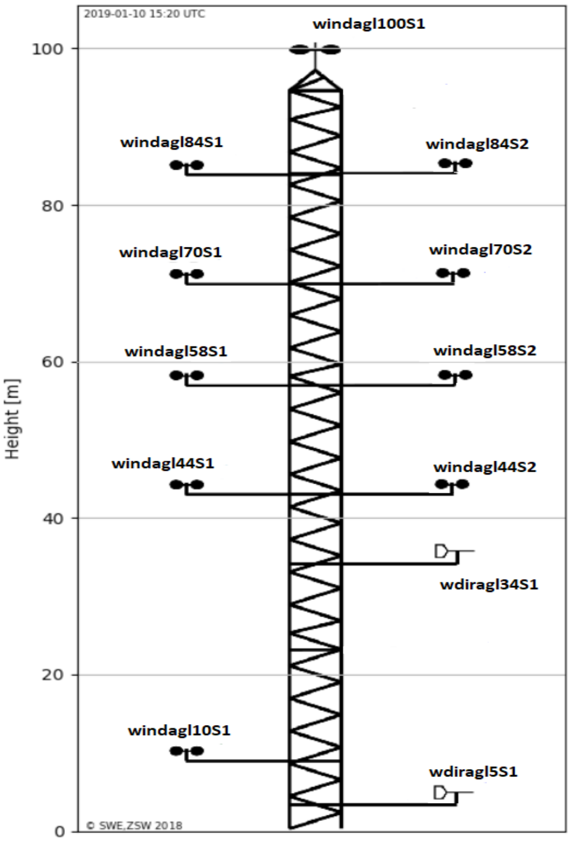


Figure 3. *Schematic representation of an instrumented lattice tall tower. Anemometers have been named using the convention 'windagl[height in meters]S[sensor id]'. Wind vanes are identified with 'wdiragl[height in meters]S[sensor id]. Adapted from: https://www.windfors.de/en/projects/test-site/winsent-weather/*

Another aspect that differs significantly between the retrieved datasets is their quality. It is noted that some institutions perform automatic or manual quality control tests over their observations -or a fraction of them- in order to ensure their proper further usage. However, these checks can be more or less effective in removing erroneous data. Because of that, we have considered all the data as raw, and we have designed and applied a unique quality control software over all the tall tower measurements, no matter whether they were previously checked or not.

Wind measurements from 222 tall towers have been obtained so far (Figure 2), representing a percentage of 73% of the 311 sites that have been previously identified. A total of 181 of these tall tower data is made publicly accessible at https://b2share.eudat.eu/records/159158152f4d4be79559e2f3f6b1a410 within the EUDAT data repository. Observed variables include wind speed, wind direction, temperature, barometric pressure and relative humidity (although those last three parameters are not always available). The total size of all the original files is 146 GB. Apart from meteorological observations, some towers often include other variables such as heat flux measurements that have been discarded to be included in the Tall Tower Dataset.

Table 2. *Metadata included in the NetCDF files*

Attribute	Definition
tower_name	Name of the tall tower or observatory
institution	Owner organization of the tall tower
boom_direction	Orientation of the horizontal booms. Often missing, but usually provided for redundant sensors.
location	Country where the tower is placed. Using the Country Codes List ISO Alpha-2
offshore	Indicates whether the tall tower is placed over oceanic areas or continental regions
tower_type	Main usage of the tall tower (e.g.: meteorological mast, TV transmitter, etc.)
creation_time	UTC time indicating when the file was generated in format: YYYY-MM-DD-THH:MM:SSZ
links	Main web pages containing information or data of the tall tower
history	Track of changes of the NetCDF file

All the obtained data has been encoded as NetCDF4 files with a unique storage format and naming convention for each these five meteorological variables. The standards are based on the guidelines provided by the World Meteorological Organization (WMO, 2015), CORDEX archive design (Christensen et al. 2014), ECA&D metadata (Klein-Tank et al., 2002) and the NetCDF Climate Forecast (CF) Metadata conventions (Eaton et al., 2009). The specific nature of this dataset requires the distinction between the multiple sensors installed along the tall tower at different measuring heights over ground, and those placed at different boom orientations (see Figure 3 for a schematic example). Table 1 shows the different characteristics of the original datasets as they were obtained. The final convention and format are also presented. In addition, all the collected metadata for each tower site has been compiled and included in the NetCDF files as global attributes (see Table 2).

2.3. Anatomy of the Tall Tower Raw Dataset

Data from 222 tall towers have been included so far in the Tall Tower Raw Dataset (although it is expected to enlarge this dataset by adding new observations, especially in the European continent). The heights, instrumentation and length of records of these structures is quite diverse, and depends on the purpose they were designed for. On the one hand, masts placed in historical observatories (i.e. often having more than 20 years of data) tend to be short, ranging between 20 and 50 meters of height above ground. On the other hand, modern towers often reach 100 to 200 meters of height, and exceptionally up to 400 meters. The period of record of the 222 time series is depicted in Figure 4. Although some records reach 37 years of length, most of the time series do not span more than 20 years. Nevertheless, several of these masts have been recently installed and measurements are currently ongoing. The resolution of data ranges from 10-minute observations to hourly data. Regarding the location of the towers, 80% of them are found inland whilst the other 20% are placed offshore. The main characteristics of the tall towers are specified in their metadata, which has been uniformed for all the sites even though the original information is sometimes sparse or even missing.

Several types of towers have been identified. Each tower has been classified according to the intended usage of the instrumented tower. Most of the towers are typically installed with the aim to provide in situ observations for experimental field campaigns within the research or industry fields. In this case, the tall towers are commonly referred to as meteorological masts or met masts. They represent up to 77% of all the tall towers in the dataset. A group of 26 (11%) tall towers are installed over marine platforms along coastal areas in the United States. Indeed, most of them belong to the Coastal-Marine Automated Network (C-MAN) and are managed and maintained by the National Data Buoy Center (NDBC) of the National Oceanic and Atmospheric Administration (NOAA). In some cases, they are petrol and oil drilling platforms in the Gulf of Mexico. Another group of 23 tall towers (which represent the 10% of all the processed datasets) are located within wind farms, either onshore or offshore. They are usually referred to as meteorological masts too and are permanently installed to measure the meteorological conditions and monitor the performance of the wind turbines. Two coastal lighthouses taking meteorological records on the top of the building have been also included and considered as tall towers since they can reach heights up to 50 meters above ground level. Finally, two of the tall towers are instrumented communication transmitters and take meteorological measurements at several platforms along the antenna.

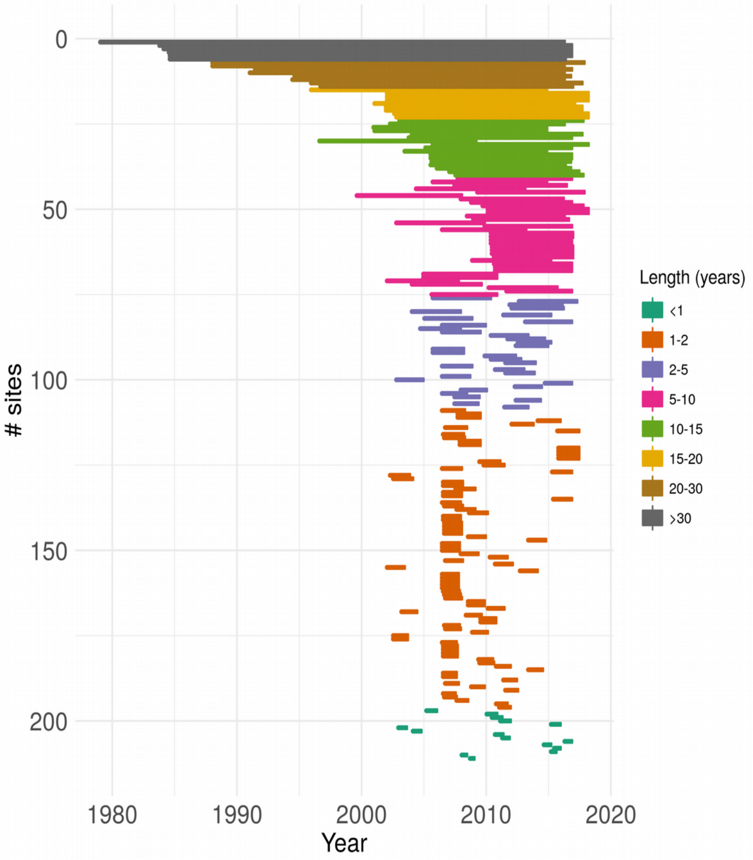
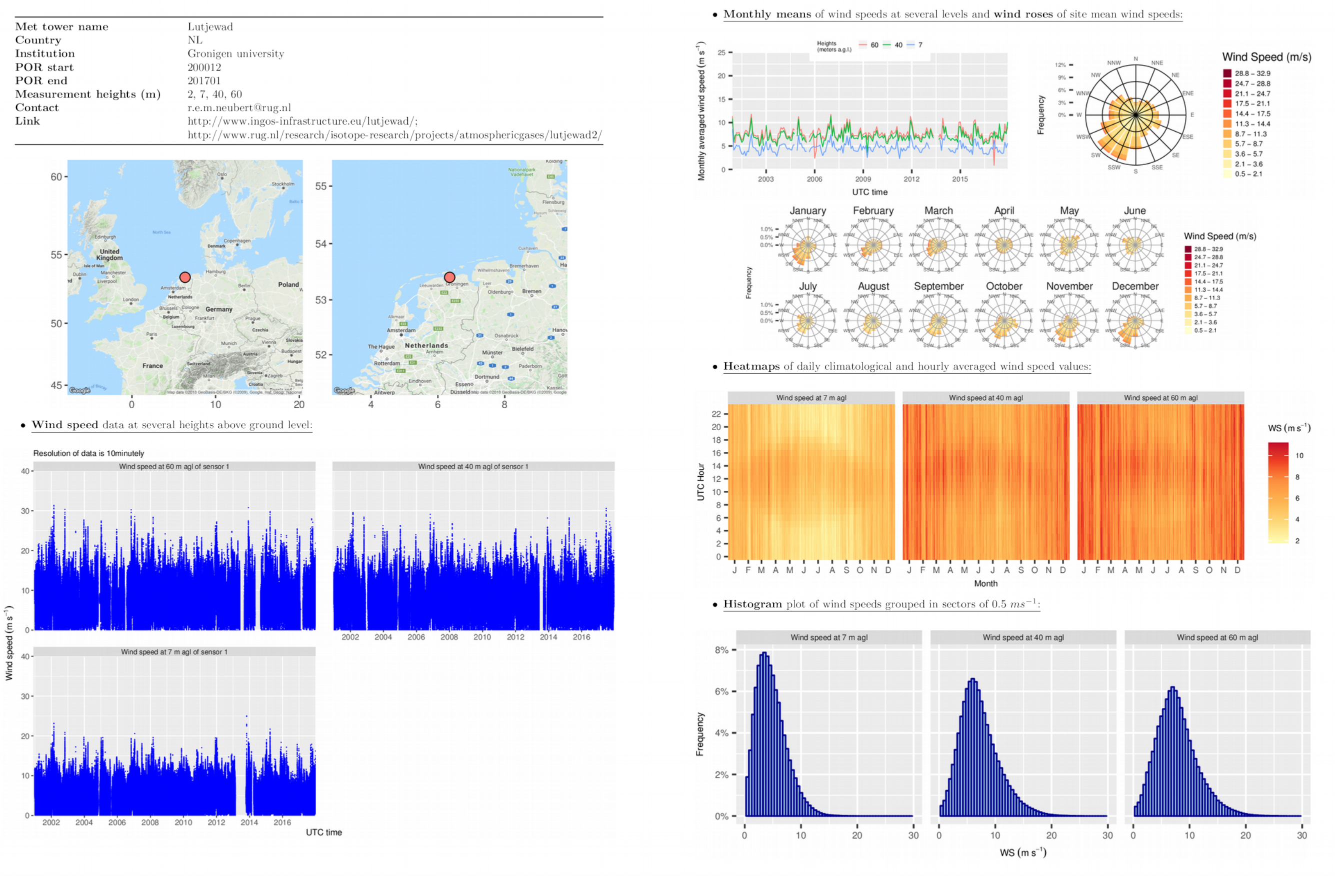


Figure 4. *Periods of record of the 226 tall towers.*

In order to facilitate a preliminary understanding of the wind resource at each tower, a summary sheet has been designed for each tall tower. An example is shown in Figure 5 for Lutjewad met mast in The Netherlands. After a short metadata overview, several plots have been employed to characterize the main local wind characteristics. Firstly, a plot of the wind speed observations at the different measurement levels is displayed. Then, the monthly averaged wind speeds at several heights are plotted on the same panel. Monthly wind roses and an annual wind rose depict the preferred wind directions. Heat maps containing hourly averaged wind speeds for each day of the year and at different heights have been plotted to help understand and visualize the seasonal and daily cycles. Lastly, histograms of wind speed values have been represented. These summary sheets are available in *pdf* format prior request or in a website visualization -which will be available soon-.



Met tower name	Lutjewad
Country	NL
Institution	Gronigen university
POR start	200012
POR end	201701
Measurement heights (m)	2, 7, 40, 60
Contact	r.e.m.neubert@rug.nl
Link	http://www.ingos-infrastructure.eu/lutjewad/; http://www.rug.nl/research/isotope-research/projects/atmosphericgases/lutjewad2/

- **Wind speed** data at several heights above ground level:
- **Monthly means** of wind speeds at several levels and **wind roses** of site mean wind speeds:
- **Heatmaps** of daily climatological and hourly averaged wind speed values:
- **Histogram** plot of wind speeds grouped in sectors of 0.5 ms^{-1}:

Figure 5. Summary sheet for a meteorological mast at Lutjewad, the Netherlands (53.40º N, 6.35º E, 60 m).

3. Quality Control of the Tall Tower Dataset

In order to ensure a minimum quality of tall tower wind data and guarantee the accuracy of any results derived from these records, a set of sequential Quality Control (QC) tests have been designed and coded to be performed over wind speed and wind direction measurements. Each of these QC routines flags each observation according to a level of confidence. Hence, every single measurement will have their associated flag. No record will be removed or modified by the QC routines, and is up to the user to filter the data basing upon the QC flags.

Table 3. Flags and their corresponding meaning

Flag	Means that the observation...
1	has passed all QC tests successfully
2	is potentially correct, but could need further check
4	has failed at least one of the tests
5	is a calm wind. Wind speeds below 0.5 m s^{-1} are not considered in the majority of the tests.
9	is missing
10	has not been evaluated by three or more QC tests

Three different categories have been defined depending on whether an observation passes the test successfully (indicated with '1'); passes the test but could need further check (hereafter referred to as 'Suspect' and numbered with '2'); or fails the test (categorized as '4'). Three more levels have been added to indicate if the observation was not evaluated by three or more tests ('10'), corresponds to a calm period ('5') or is missing ('9'). Flag levels are summarized in Table 3. The classification has been done by setting different threshold values based on the world Meteorological Organization standards (WMO, 2008), QC software manuals (Brower, 2013; IEC, 2005; IOOS, 2017) or scientific articles (Jimenez et al., 2010) and after testing them over observations from more than 200 tall towers.

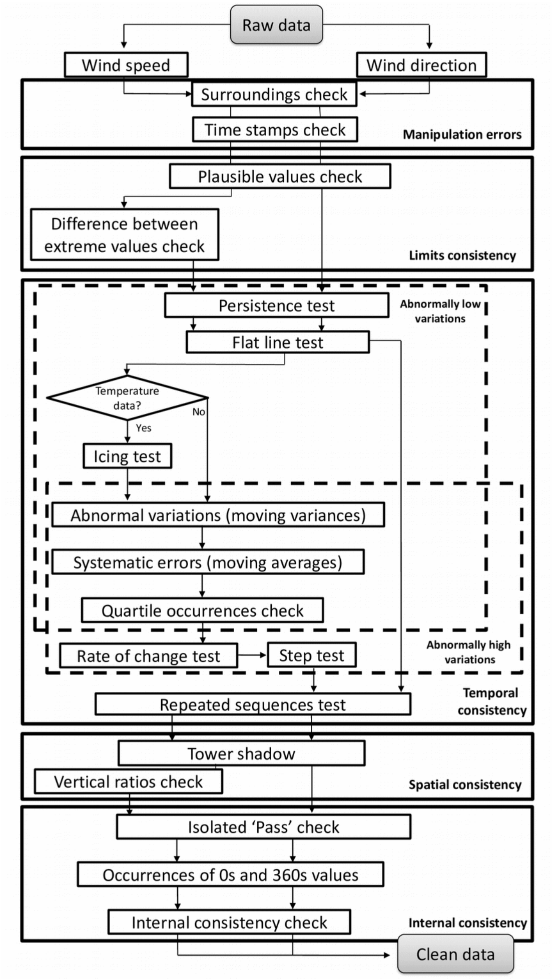


Figure 6. *Flux diagram of the QC routines applied over tall tower wind data.*

A total of eighteen QC tests have been considered and sequentially applied over the Tall Tower Raw Dataset. The flux diagram of the process that has been followed is shown in Figure 6. Potentially erroneous observations have been detected and marked accordingly. The first two tests (*Surroundings check* and *Time stamps check*) are preliminary and have been applied before and during the formatting process, respectively. The *Surroundings check* is carried out manually by a visual inspection of the surrounding area where the tall tower is placed, either with pictures or satellite images. Nearby obstacles that could perturb the wind flow and produce unreal records are identified. However, this information is not always available since it is rarely provided and the impact of the obstacles usually changes over time or even disappears. Figure 7 shows the wind speed series at 10, 20, 45, 90 and 110 meters above ground level for the Wallaby Creek tall tower in Australia. The entire QC software suite has been run and data are flagged according to their level of confidence. In the 10-meter level, several values in a row fail at least one of the QC tests. A closer inspection reveals that the wind speed values are extremely weak, especially when compared with simultaneous records at the other heights. Indeed, the canopy of the forested encircling area reaches heights over 10 meters. Therefore, the lowermost level of this tower is shadowed by the surrounding forest and all the observations from this level should be flagged as erroneous.

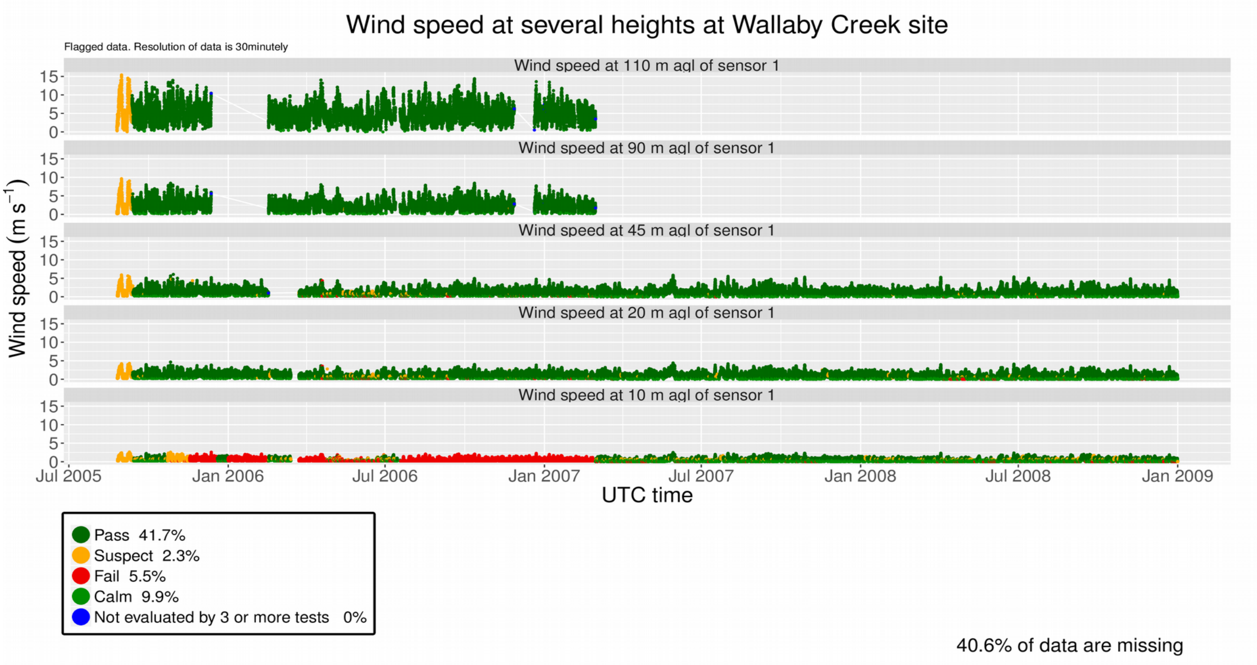


__Figure7.__ Wind speeds at 10, 20, 45, 90 and 110 meters above ground level at Wallaby Creek site, Australia (37.42º S, 145.19º E, 720 m).

The *Time Stamp check* ensures that all the timestamps are present once and only once in the time series and are correctly ordered. This is especially important if daily averages are derived from hourly or 10-minutal series. Any missing timestamp is set to Not Available (NA).

Aside of the two preliminary tests, the code of the remaining 16 QC routines have been provided within the frame of the INDECIS project through a Git repository: https://earth.bsc.es/gitlab/jramon/INDECIS-QCSS4TT. Complete information on the code as well as a guided example on how to run the QC checks (hereafter referred to as Quality Control Software Suite for Tall Towers, QCSS4TT) are included in the repository. With the exception of the *Isolated pass* and *quartile occurrences* tests, the QC routines can be run independently. Hence, any user of this software can redefine the order and decide whether a test is applied or not. In addition, as different levels of confidence have been considered, the user can decide their own level of restriction by filtering the records according to their associated flags. In the following subsections each of the 16 QC checks is described further.

3.1. Plausible values

Wind speed and wind direction records falling outside a physically possible range of values are commonly found within the time series. They are mainly produced by gross errors in the data loggers or storage. This test detects and flags unrealistic values such as negative wind speed values or observations above a maximum allowed threshold. The absolute maximum limit has been chosen from the maximum wind gust measurement ever recorded on earth surface, which is 113.3 m s^{-1} measured in Barrow Island (Australia) produced by Olivia cyclone in April 1996 (Courtney et al., 2012). A lower threshold can be selected from which wind speed values can be flagged as 'Suspect'. We used the value 75 m s^{-1}, which is Vaisala's sensors highest measurable value. Wind direction values falling outside the range from 0 to 360 degrees are also flagged as erroneous.

3.2. Difference between extreme values of the wind distribution

One of the potential usages of the Tall Tower Dataset is the detection of severe weather events by looking at the extreme values of the empirical distribution. However, some of these measurements might be erroneous and need to be detected and flagged correspondingly. This QC check detects and flags unrealistic extreme wind speed values of the time series by checking the difference between the maximum and the second maximum values of the distribution of wind speed values. If the difference between them exceeds the absolute value of the second maximum, the first maximum is flagged as 'Suspect'. This test is run iteratively until the previously mentioned condition is not satisfied.

3.3. Persistence test

Wind time series are usually characterized by a strong variability, alternating periods of high and low fluctuations. Nevertheless, the presence of relatively long periods of extremely low variability can be unrealistic since they can be produced by errors in the measuring sensors or instrumental drift. The *Persistence test* detects and flags sequences of wind speed and wind direction observations with abnormally low variability. However, it is important to take into account that relatively long periods with very low variability and mean wind speed values close to zero are typical of the observed natural variability (e.g., produced by a static high pressure systems during several days in a row and thus producing weak winds). Hence, these data cannot be considered erroneous. The *Persistence test* does not introduce any flag to wind speeds weaker than 0.5 m s^{-1}. These measurements are then flagged as calms.

Wind speed periods are flagged as 'Suspect' if the wind speed does not change more than 0.7 m s^{-1} in 60 consecutive values. Wind direction values will be considered suspicious if the range between the maximum and the minimum values in a sequence of 60 records is lower than 5 degrees.

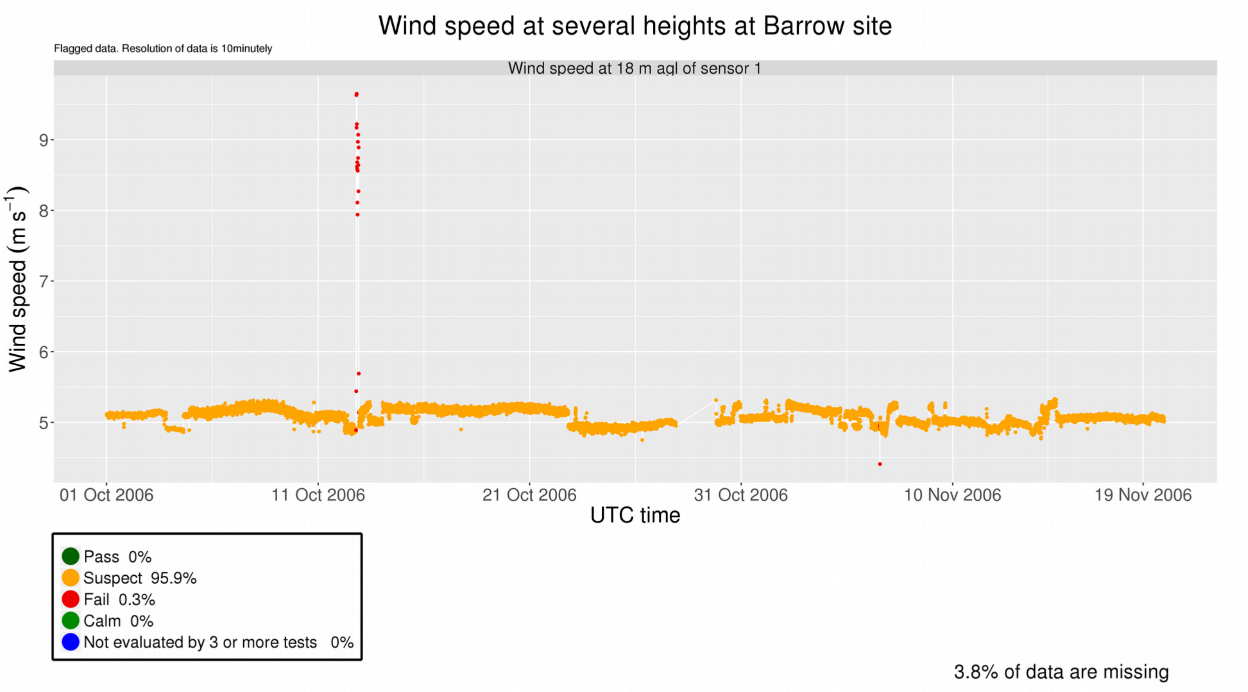


Figure 8*. Wind speed time series at 18 meters above ground level at Barrow site, USA (71.32ºN 156.61ºW, 11 m)*

The example plotted in Figure 8 shows wind speed observations measured at 18 meters on the top of the Barrow tower (Arctic Circle) during a period of 51 consecutive days. In except of the two spikes on 14th October and 3rd November, wind speed values range from 4.8 to 5.3 m s^{-1}. This variability is significantly low when compared with the rest of the wind series (not shown). Although the 'Persistence test' flags the records as 'Suspect', it is very likely they are erroneous and should not be used as reliable data.

3.4. Flat line

A sequence of numbers with null standard deviation is the extreme case of a low variability period and indicates that several constant values are observed consecutively. The probability of recording repeated values in a row decreases with the number of significant figures that the sensor can record, being almost unlikely to have more than 6 successive exact matches for wind speed and 40 for wind direction measurements. In this sense, data fail the test when there exist 6 -or more- constant wind speed values in a row. This threshold is increased to 40 for the wind direction variable. Observing 3, 4 or 5 exact consecutive matches is more likely for wind speed values, but still unlikely to happen frequently. Therefore, the tests flags as 'Suspect' those flat sequences. Making an analogous assumption for wind direction data, flat sequences containing 20 to 40 wind direction records are flagged as 'Suspect'. It is also not uncommon to observe an alternation of no data periods with null speed values, which are usually produced by failures in the sensors or data loggers. If the period containing this alternating pattern exceeds 30 days, all the measurements within this period are flagged as erroneous.

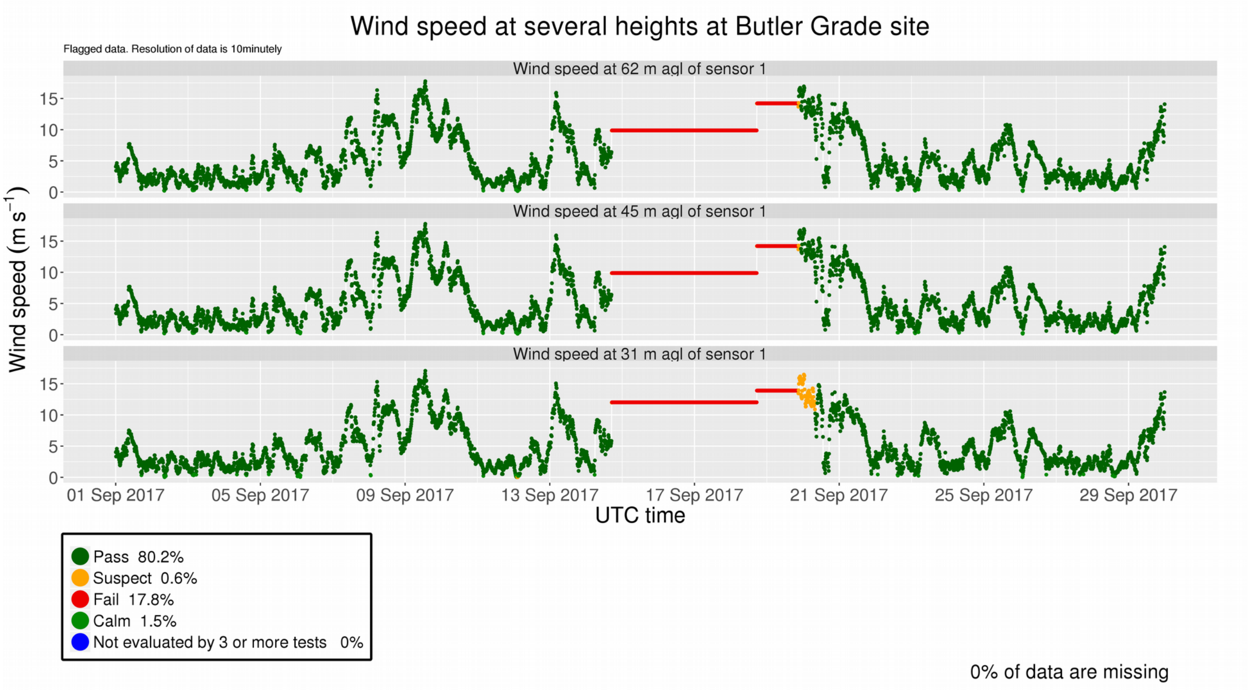


Figure 9. Wind speed time series at 31, 45 and 62 meters above ground level at Butler Grade site, USA (45.95° N, 118.68° W, 545 m).

A detection of a flat line is shown in Figure 9. Various sequences of constant values are encountered at the three different levels between September 14th and September 20th. Flat lines are often detected simultaneously at all levels of the tower.

3.5. Icing

Freezing rain or fog usually frosts the anemometers or vanes placed along the tall tower preventing them from measuring non-zero wind speed values and changes in the wind direction. Hence, these records should be detected by checking wind and temperature observations simultaneously. Data are considered bad when the test detects 4 or more days with 0 m s^{-1} as the maximum wind speed value and below zero temperatures during all the suspicious period.

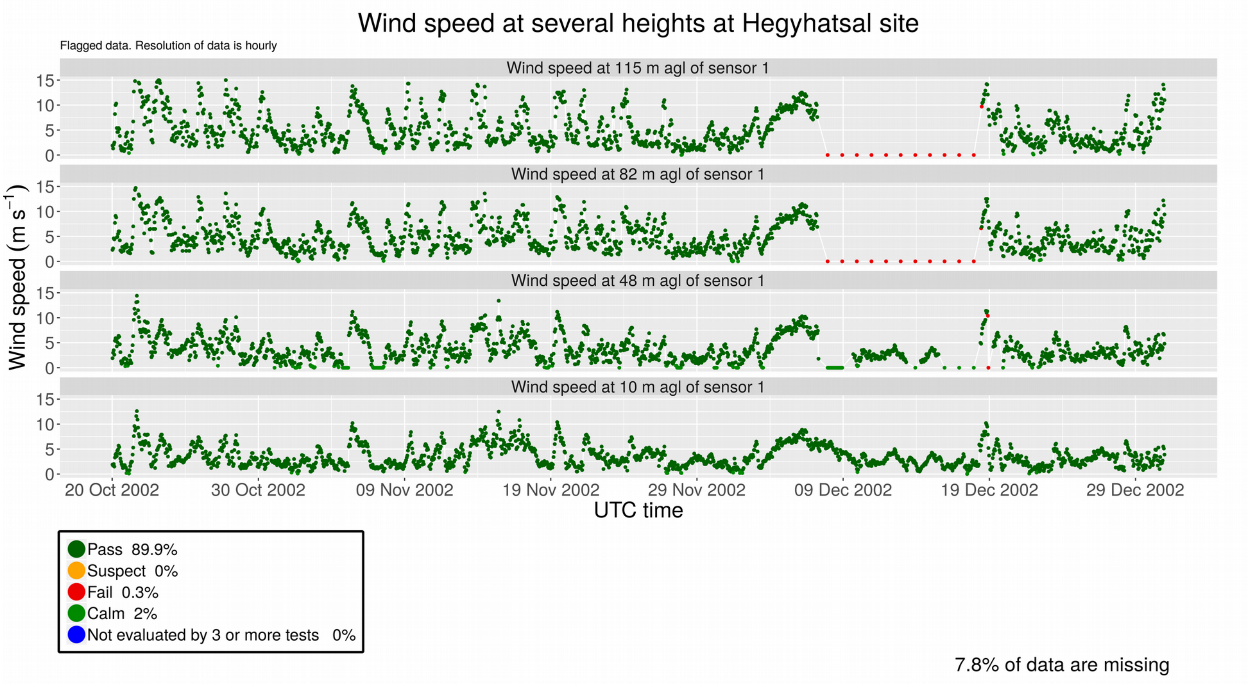


Figure 10. *Wind speed time series at 10, 48, 82 and 115 meters above ground level at Hegyhatsal tall tower, Hungary (46.96° N, 16.65° E, 248 m).*

Wind speed series at different heights at Hegyhatsal tower are represented in Figure 10. An flat line is observed in the two uppermost levels from December 8th to December 18th 2002. However, the air temperature observations (Figure 11) reveal that negative Celsius temperatures occurred during all the 10-day period in the two top levels of the tower. Given these conditions, an icing event that frosted the two upper anemometers is highly possible.

3.6. Abnormal variations

Periods of abnormally high or abnormally low variability can be produced by random errors in the measurements and usually appear embedded in the wind speed time series. Differently from the persistence check, the abnormal variations check compares the variability (computed as the variance) of 30-day periods with the mean variance of all 30-day periods of the time series by means of moving variances. If the standard deviation of a specific 30-day period departs more than 4 standard deviations from the mean standard deviation, records within this 30-day period are flagged as 'Suspect'.

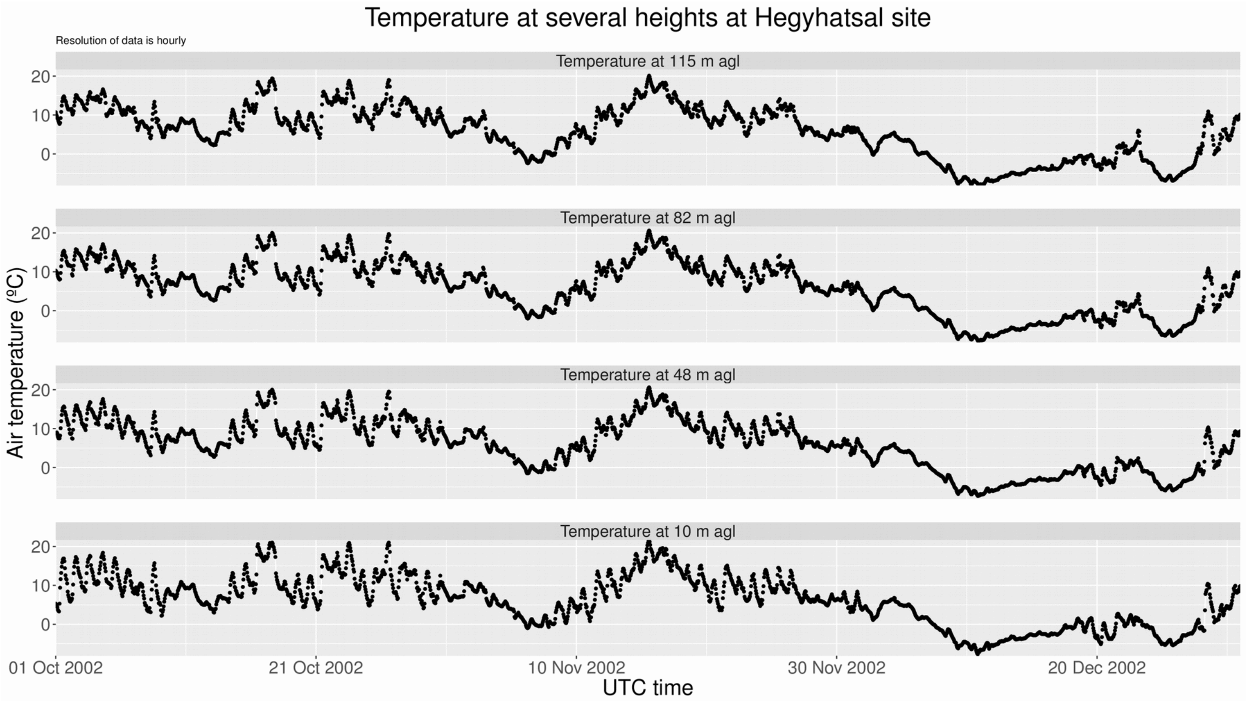


Figure 11. *Temperature measurements at 10, 48, 82 and 115 meters above ground level at Hegyhatsal tall tower, Hungary (46.96° N, 16.65° E, 248 m).*

3.7. Systematic errors

Another method to detect random and systematic errors in the experimental measurements is based on the computation of moving averages. Similar to the abnormal variations check, this QC routine computes the mean wind speeds over a 30-day moving window. Wind speed values within a 30-day period whose average departs more than 4 standard deviations from the mean value of all 30-day moving means are flagged as 'Suspect'.

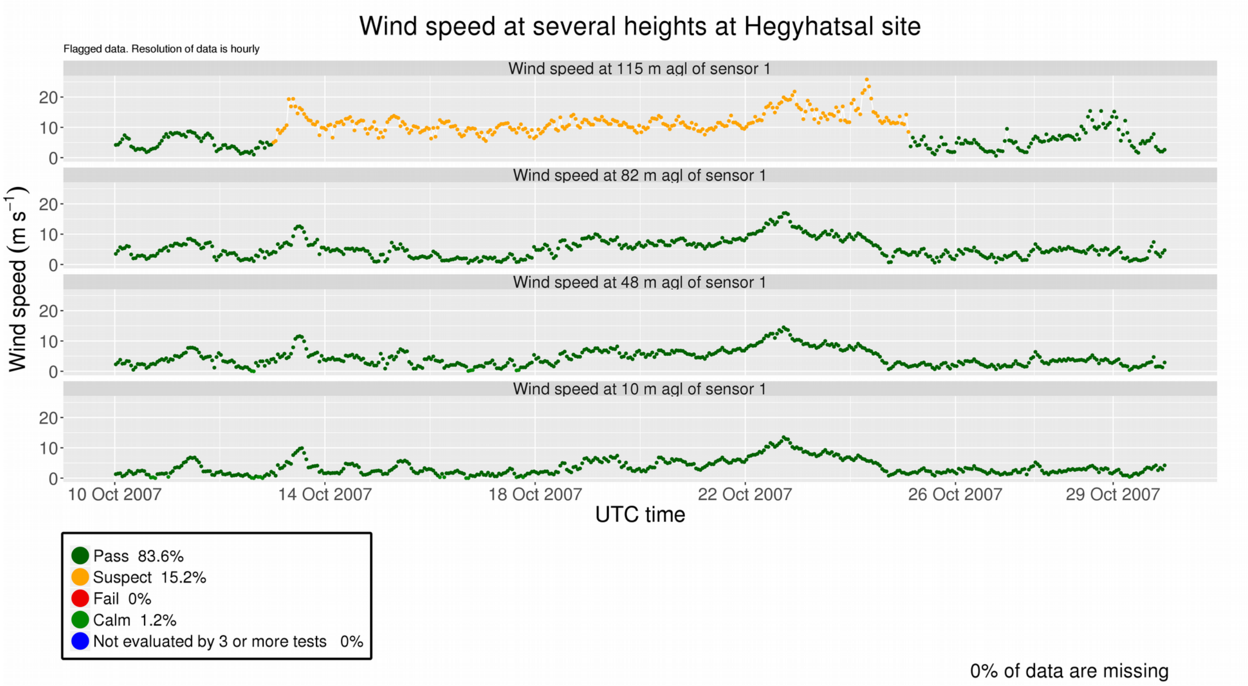


Figure 12. *Wind speed time series at 10, 48, 82 and 115 meters above ground level at Hegyhatsal tall tower, Hungary (46.96º N, 16.65º E, 248 m).*

In Figure 12, the *Systematic Errors* check flags as 'Suspect' a period of 12 consecutive days of wind speed measurements taken at the top of Hegyhatsal tower. A close inspection reveals that the minimum wind speed record is over 5 m s^{-1}, which is considerably high when compared with the wind speeds measured at the lower levels. Indeed, the three anemometers located at 10, 48 and 82 meters measure weaker winds or even calms during this 12-day period. An offset could have been inserted in the data logger and produced the inconsistency observed in the uppermost wind speed measurements. In this case, this 12-day period of winds at 115 meters should not be considered reliable. Figure 13 shows a false detection of a systematic error at WLEF tall tower. Although the test flags as 'Suspect' a period of 2 months of wind speed data at 122 meter level, a visual inspection and comparison with winds at other levels does not discern any inconsistency in these observations. Hence, these data should not be discarded unless a sensor failure is reported in the metadata.

3.8. Quartile occurrences

A third method to detect periods containing gross errors in the measuring process is suggested here by looking at the number of consecutive days where no value is above or below the first, second and third quartiles of the empirical wind speed distribution. Table 4 summarizes the different thresholds (in days) that define the success flags (i.e., 'Pass', 'Suspect' and 'Fail'). As an example, the first row indicates that if all the observations in a

30-day period are above the first quartile of the whole distribution, data within this time period will be flagged as 'Fail' and considered erroneous. Observations are flagged as 'Suspect' when the period without any appearance of the first quartile ranges between 15 and 30 days. They ‘Pass’ the test when the duration is shorter than 15 days.

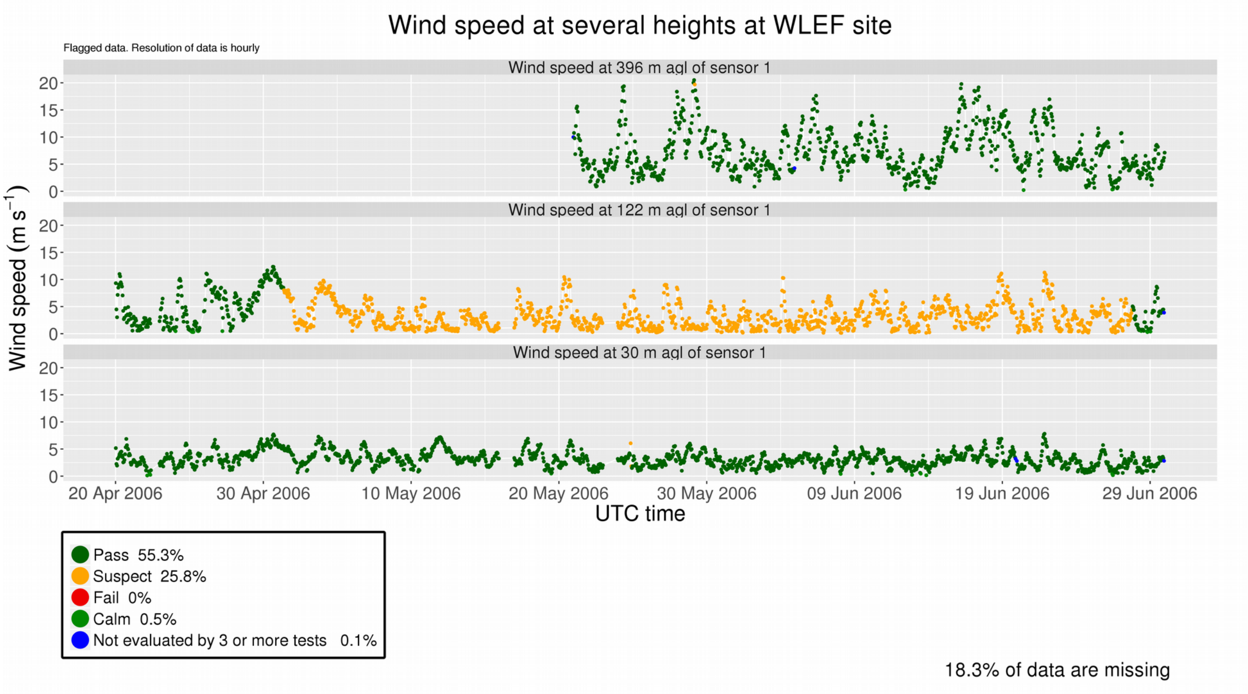


Figure 13. *Wind speed time series at 30, 122, 396 meters above ground level at WLEF tall tower, USA (45.95ºN, 90.27º W, 472 m).*

3.9. Rate of change

The presence of spikes in wind series are usually observed during extreme wind phenomena events. However, the magnitude of these peaks is constrained to a specific allowable range of values since wind data are the result of an average over a period of several minutes of high frequency records (usually less than one second). This test compares each observation with the adjacent. To pass the test successfully, differences between consecutive values must be lower than three times the value of the interquartile range (IQR) defined as the difference between the 3rd and 1st quartiles. When this condition is not satisfied, both values are flagged as ‘Fail’. If the difference falls between two and three times the IQR, the pair of observations is considered ‘Suspect’.

Table 4.- Threshold values that set the different levels of confidence for the quartile occurrences check.

All the observations are…	Pass	Suspect	Fail
> 1st quartile	< 15	[15,30]	> 30
> 2nd quartile	< 10	[10,20]	> 20
> 3rd quartile	<5	[5,10]	> 10
< 1st quartile	< 5	[5,10]	> 10
< 2nd quartile	< 10	[10,20]	> 20
< 3rd quartile	< 15	[15,30]	> 30

3.10. Step test

The step test uses the same methodology as the rate of change test in order to detect spurious peaks of wind speed data. This spike test uses a fixed maximum threshold instead of a statistic derived from the series. The absolute permissible high limit is set to 20 m s^{-1} (WMO, 2007). Although the WMO indicates this limit as a possible threshold for 2-minute averaged data, we have used it also for all the observed time stamps samplings in the Tall Tower Database.

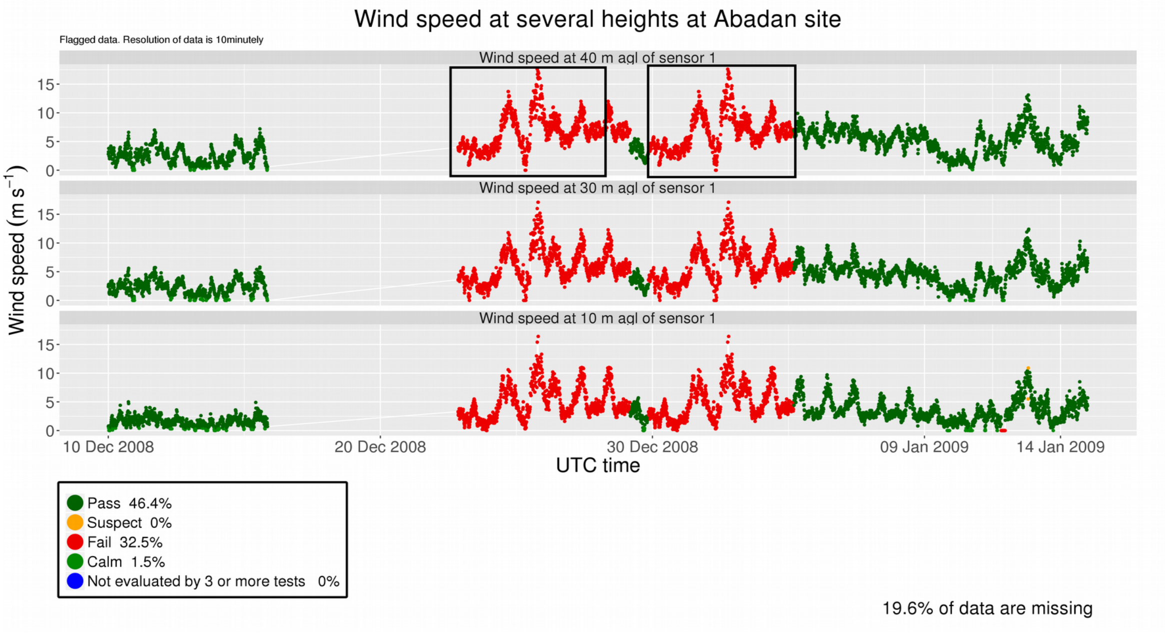


Figure 14. *Wind speed time series at 10, 30 and 40 meters above ground level at Abadan met mast, Iran (30.45º N, 48.31ºE, 4 m). The two black boxes in the upper graph represent two duplicated sequences of wind speed values within the same time series.*

3.11. Repeated sequences test

This check looks for series of consecutive observations that are repeated in the same order more than one time within a time series. Duplicate sequences of 30 wind speed values are flagged as wrong if data do not contain any decimal places. The threshold is decreased to 20 wind speed observations if data are measured with one or more decimal digits. Wind direction series are also checked for duplicate sequences and they are flagged when containing 30 or more records.

Duplicated sequences have been found in three parallel time series at Abadan tall tower time series (Figure 14). A cautious inspection reveals that data contained in the black rectangles in the top time series matches perfectly. An analogous situation is noticed for the two lower levels. Filling in no-data periods with previously observed wind speed sequences of data is a common technique to avoid gaps produced by a sensor failure.

3.12. Tower shadow

One of the singularities of the tall tower data is that meteorological measurements are not recorded at the top of a pole where a sensor is placed. Instead, anemometers and wind vanes are distributed along the vertical structure of the tall tower (see Figure 3). The mast usually consists of a solid vertical cylinder or a lattice structure that produces an inherent wind shadow in the downwind area where winds can be reduced significantly. If an anemometer is measuring in the shadow area, these wind speed records cannot be reliable whatsoever.

To help overcome this handicap, a common practice in the instrumental installation is to place redundant sensors in different booms. As mentioned in Section 1, shadowed records can be replaced by those from a sensor not affected by this reduction. In this way, this test locates first the shadowed directions and anemometers by dividing wind speeds from two sensors at the same level. Ideally, they should measure the same values so the ratio is expected to be equal to the unity unless there is a shadow. All wind speed ratios are grouped in wind direction sectors of 1 degree. Then, the 5th and 95th percentiles of the distribution generated by all the quotients are calculated. Those directions showing ratios below the 5th percentile and above the 95th are considered to be in the wake of the tower. In this way, the shaded directions for each anemometer can be inferred. The test marks as ‘Suspect’ those wind speed values affected by this reduction produced downwind of the mast.

Figure 15 exemplifies the previous explanation by means of the ratios between simultaneous wind speeds observations measured by redundant sensors at 60 and 100 meters at the FINO3 met mast the North Sea. For most of the wind directions, the quotient between wind speeds is approximately the unity, showing a good agreement between the parallel measurements. However, wind speeds coming from 50±5 and 170±5 degrees of direction are reduced by the vertical pole of the mast and then measured by each of the anemometers in the respective shadow area. These wind speed values should not be considered valid and only data measured by the complementary anemometer that is not affected must be used.

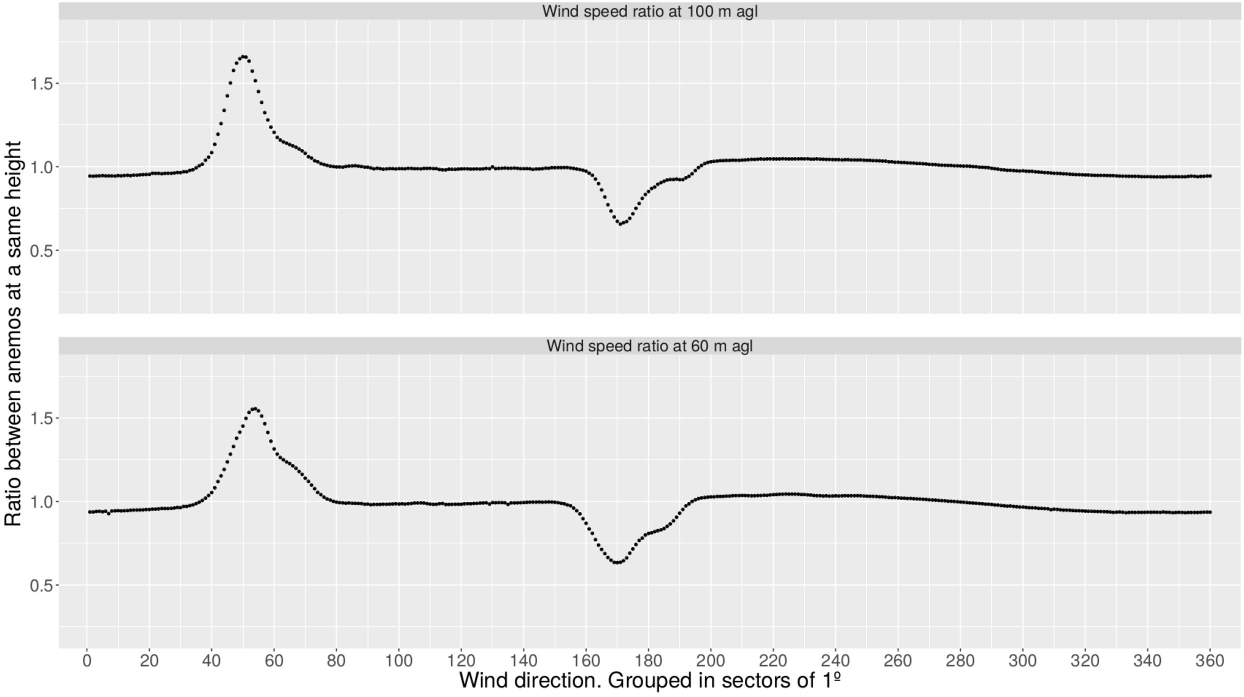


Figure 15. *Ratio between simultaneously measured wind speed values at 60 and 100 meters at FINO3 met mast, Germany (55.20º N, 7.16º E, 0 m).*

3.13. Vertical ratios

QC checks that employ nearby stations are not suitable for meteorological variables with remarkably localized features such as precipitation or wind speed, due to the fact that the correlation between neighbor series is considerably lower when compared to temperature or pressure time series (Dunn et al., 2012). In addition, these tests require a dense network of stations, which is not the case for this dataset (see Figure 2 again). However, another particularity of tall tower data is the simultaneous records taken at different heights along the mast. These series can be compared among them as they are highly correlated. This is a special test which takes pairs of time series from different heights and computes the mean ratio ($\bar{r}$) of all the pair-wise tower measurements ratios

(r_i). To avoid duplication and save computation time, the test only computes the ratio between one level an all the lower levels. In except of local effects, wind speeds tend to increase in height so the mean ratio is expected to be greater or equal to unity. Taking this assumption into account, the test will detect and flag as erroneous those pair of values which ratio (r_i) satisfies the following condition:

$$r_i \geq \bar{r} + 30$$

Dubious values are considered when r_i satisfies the condition:

Wind speeds under 1 m s^{-1} are not considered in this test.

3.14. Isolated pass

A QC test may flag as wrong or dubious several sequences of data within a time series. These sequences can be found close in time and encircle values that passed successfully the test. However, these apparently correct values might not be as so since a prolonged sensor failure may have occurred but the QC check missed. The isolated pass check attempts to detect those correct observations surrounded by wrong or suspiciously wrong values and change the flag into 'Fail' or 'Suspect'. It is important to note that this test must be performed after running at least one of the previous routines.

Table 5. Explicit definition of the sequences to be searched within the wind time series which central value or values will be changed from 'Pass' flag to 'Fail'.

$Fail, Fail, Fail, Pass, Fail, Fail, Fail$
$\underbrace{Fail, \ldots, Fail}_{5}, Pass, Pass, \underbrace{Fail, \ldots, Fail}_{5}$
$\underbrace{Fail, \ldots, Fail}_{10}, Pass, Pass, Pass, \underbrace{Fail, \ldots, Fail}_{10}$
$\underbrace{Fail, \ldots, Fail}_{15}, Pass, Pass, Pass, Pass, \underbrace{Fail, \ldots, Fail}_{15}$
$\underbrace{Fail, \ldots, Fail}_{25}, Pass, Pass, Pass, Pass, Pass, \underbrace{Fail, \ldots, Fail}_{25}$
$\underbrace{Missing, \ldots, Missing}_{50}, Pass, \underbrace{Missing, \ldots, Missing}_{50}$
$\underbrace{Missing, \ldots, Missing}_{50}, Calm, \underbrace{Missing, \ldots, Missing}_{50}$

A total of 12 predefined sequences (see Table 5) containing data flagged as correct but surrounded to the left and right by either wrong or dubious records have been defined. The central 'Pass' values of this sequence will be changed from correct to erroneous (i.e. 'Fail'). Table 6 defines similar sequences but their central records will be changed from 'Pass' to 'Suspect'.

Table 6. *Explicit definition of the sequences to be searched within the wind time series which central value or values will be changed from 'Pass' flag to 'Suspect'.*

$Suspect, Suspect, Suspect, Pass, Suspect, Suspect, Suspect,$
$\underbrace{Suspect, \dots, Suspect}_{5}, Pass, Pass, \underbrace{Suspect, \dots, Suspect}_{5}$
$\underbrace{Suspect, \dots, Suspect}_{10}, Pass, Pass, Pass, \underbrace{Suspect, \dots, Suspect}_{10}$
$\underbrace{Suspect, \dots, Suspect}_{15}, Pass, Pass, Pass, Pass, \underbrace{Suspect, \dots, Suspect}_{15}$
$\underbrace{Suspect, \dots, Suspect}_{25}, Pass, Pass, Pass, Pass, Pass, \underbrace{Suspect, \dots, Suspect}_{25}$

3.15. Occurrences of 0s and 360s values

The lack of coordination concerning the data storage and formatting conventions in the original data may produce some issues that must be detected. For example, in the wind speed time series, missing records are sometimes set to zero. This can lead to a spurious increase in the occurrence of the zero value. Similarly, some conventions use the value 0 degrees to refer to the northern wind direction whilst others identify this direction with 360 degrees. This routine computes the percentage of occurrence of each of these three cases:

- Occurrences of 0s within the wind speed time series,
- occurrences of 0s within the wind direction series and
- occurrences of 360s within the wind direction series.

A further visual inspection of these percentages should shed some light on the original conventions and standardize the storage format of the Tall Tower Dataset.

3.16. Internal consistency

Whenever wind speed is 0 m s^{-1}, the wind vane tends to point to the last wind direction that pushed the vane, but this direction does not have a physical meaning. Therefore, for wind speed records equal to zero wind direction should be NA. The condition must be only applied for wind measurements taken at the same height above ground level. Internal consistency test ensures this condition is satisfied for every pair of wind speed and wind direction values measured at a same height.

4. Application of the QC software and analysis

The QCSS4TT has been sequentially applied over the Tall Tower Dataset following the order stated in Figure 6. In except of the *Surroundings check*, wind speed and wind direction values have been analyzed individually by each of the QC routines. As a first preliminary step, the *Time Stamp test* has filled with NA's wind values which time stamps were missing so that monthly files contain ordered data ranging from the first to the last day of the month and equally sampled according to the original interval sampling provided in the original datasets. These missing values have been added to the ones originally missing so a total of 12.1% of the time stamps contain missing observations.

Then, a total of 240 371 908 of non-missing individual wind speed and wind direction values which represent the 85.7% of the dataset have been analyzed by each of the other 16 QC routines. After all this process, 228 780 679 values -representing up to 95.2% of the total non-missing data- passed successfully all the checks and can be considered reliable. On the contrary, 6 827 880 observations (i.e. the 2.8% of the total non-missing data) have been considered erroneous at least by one of the 16 QC tests. Potentially suspicious data which could need a further manual check represent the 1.8% of the total non-missing observations. Other group of data -which represents the 0.2% of the existing values- could have not been evaluated by 3 or more QC tests mainly because they have been found within periods with poor number of observations and the QC test was disabled to run over periods with huge amounts of missing data. Finally, the percentage of calm wind data is highly dependent on the geographical location of the tall tower. Met masts located in Southeast Asia contain the largest percentage of calms -reaching up to 24% of the total data-. The *Flat line* check has flagged as erroneous the largest amount of data, whilst the *Differences between extreme values of the wind distribution* test did not flagged as erroneous any individual value. It is also worth noting that several duplicated sequences have been observed within the same time series. Although it can be a usual and efficient practice to fill in missing data periods, we deemed appropriate flagging these duplicated data as erroneous.

Given that most of the data have passed successfully all the QC checks, it can be considered that the quality of the original data is rather good. Nevertheless, it is important to take into account that the selected thresholds have been chosen conservatively so that we minimize the flagging of potentially correct the data (also known as Type I errors). This conservative procedure prevents from flagging as 'Fail' -and eventually remove- extreme wind speed data produced during severe phenomena events which are usually subject of study.

The performance of the QC tests as seen from the computational view is also diverse. Some routines are run and finished in a few seconds (such as *Plausible value* check or *Occurrences of 0s and 360s*) whereas others might need several hours to be completed. The tests that need more computational time are those that compute moving averages or variances such as the *Systematic errors* or the *Abnormal variations* tests. In addition, for longer and high resolution time series they may require bigger RAM memory (up to 30 GB in some cases).

5. Conclusions

A dataset containing wind observations from existing 222 tall towers distributed around the world has been created within the context of the INDECIS project. A total of 181 of these towers is made available through EUDAT repostory at https://b2share.eudat.eu/records/159158152f4d4be79559e2f3f6b1a410. These data belong mainly to public institutions such as universities, meteorological weather services or research centers. High resolution wind speed, wind direction, temperature, pressure and relative humidity observations measured at different heights along the tall towers have been retrieved from their archives and have been stored in a dataset with a common access and format. To this end, a compilation of climate data storing conventions has been previously performed to design a unique storage format. Observations are stored in compressed NetCDF4 format in monthly files. Common attributes have been set detailing the metadata of each tower despite the fact that the provided metadata is usually sparse and sometimes missing.

In order to assure the high quality of the tall tower wind data, several QC routines have been prepared and applied to the dataset. The QCSS4TT checks the spatial, temporal and internal consistency of the wind series. A total of 16 (plus 2 additional preliminary checks) have been considered to be applied sequentially over tall tower wind speed and wind direction data. The code of the 16 main QC checks is made available through a Git repository: https://earth.bsc.es/gitlab/jramon/INDECIS-QCSS4TT. The execution order of the QC tests can be redefined as these functions can be run independently, except the *Isolated Pass* and *Quartile Occurrences* checks, which feed from the output of previous test runs. After running the QCSS4TT over the Tall Tower Dataset, each individual wind speed and wind direction value is flagged according to its quality. Three different quality levels have been defined by setting different thresholds in each QC check. A special flag is assigned to those records that have not been evaluated, are missing or correspond to calm winds. Flagging data instead of modifying or removing potentially incorrect data allows the user to select his own choices regarding the level of confidence depending on the application needs.

The QCSS4TT has been applied over the Tall Tower Dataset and 95.2% of the data contained in the dataset passed all the tests successfully. Important differences in the performance of the tests have been noticed, as well as special requirements in terms of memory consumption. The QC checks have been run using the servers installed at the Barcelona Supercomputing Center, which allow the capacity to request big sizes of RAM memory.

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Appendix A: List of the tall towers in the Tall Tower Dataset

Table 7. List of tall towers rescued in the Tall Tower Dataset. The availability of data will depend on the data policy indicated by the owner. Countries are specified using the ISO ALPHA-2 Country Codes convention. Latitudes and longitudes are presented in degrees. POR stands for Period Of Record and they are shown using the format YYYYMM, where YYYY is the year and MM the month.

Tower name	Institution	Country	Longitude	Latitude	POR start	POR end
42361	Shell International E&P	US	-92.49	27.55	200507	201612
42362	Enven Energy Corporation	US	-90.65	27.80	200507	201612
42363	Shell International E&P	US	-89.22	28.16	200507	201606
42364	Shell International E&P	US	-88.09	29.06	200709	201612
42365	Shell International E&P	US	-89.12	28.20	201201	201311
42369	BP Inc	US	-90.28	27.21	201005	201612
42370	BP Inc	US	-90.54	27.32	201005	201211
42375	BP Inc	US	-88.29	28.52	201005	201612
42394	Shell International E&P	US	-89.24	28.16	201409	201612
42887	BP Inc	US	-88.50	28.19	200911	201612
Abadan	SATBA	IR	48.31	30.45	200709	200908
Abadeh	SATBA	IR	52.25	31.09	200606	200711
Abarkooh	SATBA	IR	53.66	31.30	200608	200801
Abhar	SATBA	IR	49.39	36.11	200706	200907
Afriz	SATBA	IR	58.96	33.45	200608	200802
Agh Ghala	SATBA	IR	54.47	37.11	200607	200710
Ahar	SATBA	IR	47.22	38.59	200811	201504
American Samoa	ESRL	AS	-170.56	-14.25	199406	201605
Ardakan	SATBA	IR	54.27	32.59	200609	200802

Asfestan	SATBA	IR	47.60	37.93	200503	200602
BAO	ESRL	US	-105.00	40.05	200706	201607
Bardkhoon	SATBA	IR	51.49	27.98	200606	200802
Barro Colorado Island	Princeton Environmental Institute	PA	-79.85	9.17	200112	201710
Barrow	ESRL	US	-156.61	71.32	198801	201605
Barzook	SATBA	IR	51.14	33.81	201506	201601
Behabad	SATBA	IR	56.12	31.78	200606	200801
Binalood	SATBA	IR	59.39	35.99	200212	200309
Bojnoord	SATBA	IR	57.25	38.14	200608	200805
Bonab	SATBA	IR	46.03	37.40	200607	200710
Boroojen	SATBA	IR	51.31	31.97	200606	200711
Boseong	Yonsei University	KR	127.35	38.27	201404	201610
Braschaat	INBO	BE	4.52	51.31	199512	201412
BURL1	NBDC	US	-89.43	28.91	198402	201612
Butler Grade	Bonneville Power Administration	US	-118.68	45.95	200208	201804
bygl1	NOAA's National Ocean Service	US	-90.42	29.79	200502	201612
Cabauw	KNMI	NL	4.93	51.97	198602	201703
Cape Point	South African Weather Service	ZA	18.48	-34.35	200701	201311
Cardington	UKMO	GB	-0.42	52.10	200405	201303
Chabahar	SATBA	IR	60.66	25.33	200807	200912
Chaldoran	SATBA	IR	44.45	39.05	200607	200710
Changbaishan	Institute of Applied Ecology	CN	127.72	41.70	200212	200511
Chinook	Bonneville Power Administration	US	-119.53	45.83	200601	201611
CHLV2	NBDC	US	-75.71	36.91	198408	201606

CVO	Cape Verde Atmospheric Observatory	CV	-24.87	16.85	201110	201807
Davarzan	SATBA	IR	56.81	36.27	200607	200803
Dehake Saravan	SATBA	IR	62.67	27.14	200606	200712
Deilaman	SATBA	IR	49.91	36.88	201001	201012
Delgan	SATBA	IR	59.46	27.49	200608	200712
Delvar	SATBA	IR	51.05	28.84	200609	200801
DESW1	NBDC	US	-124.49	47.68	198408	201612
Docking Shoal	Centrica	GB	0.65	53.16	200606	200908
Eghlid	SATBA	IR	52.62	30.89	200606	200805
Egmond aan zee	ECN	NL	4.39	52.61	200508	201012
Enjilavand	SATBA	IR	50.67	34.94	201105	201207
Esfaryen	SATBA	IR	57.40	37.05	200608	200803
Eshtahard	SATBA	IR	50.69	35.73	200807	200912
Fadashk	SATBA	IR	58.79	32.78	200608	200802
Falideh	SATBA	IR	49.40	36.81	200207	200403
Fino1	Fino Project	DE	6.59	54.01	200401	201710
Fino2	Fino Project	DE	13.15	55.01	200707	201711
Fino3	Fino Project	DE	7.16	55.20	200909	201711
fmoa1	NOAA's National Ocean Service	US	-88.02	30.23	200810	201612
fsnm2	NOAA's National Ocean Service	US	-76.53	39.22	201604	201612
Fuji Hokuroku	NIES	JP	138.76	35.44	200512	200911
FWYF1	NBDC	US	-80.10	25.59	199106	201612
Ganje	SATBA	IR	49.46	36.86	200207	200310
Gardaneh Almas	SATBA	IR	48.67	37.59	200906	201009

Ghadamgah	SATBA	IR	59.01	36.06	200609	200803
Ghoroghchi	SATBA	IR	51.00	33.59	201305	201408
Ghorveh	SATBA	IR	47.75	35.18	200810	200912
Goodnoe Hills	Bonneville Power Administration	US	-120.55	45.78	200201	201804
Greater Gabbard MMX Mast	Innogy SE; SSE Renewables	GB	1.90	51.86	201205	201501
Greater Gabbard MMZ Mast	Innogy SE; SSE Renewables	GB	1.92	51.94	200509	201412
Gunfleet Sands	Development Back of Japan;Marubeni Corporation;Dong Energy	GB	1.20	51.73	200201	200711
Gwangneung Deciduous Forest	Seoul National University	KR	127.15	37.75	200312	200811
Gwynt Y Mor	UK Green Investment Bank	GB	-3.51	53.48	200509	200804
Hadadeh	SATBA	IR	54.73	36.25	200608	200802
Haft Chah	SATBA	IR	52.43	27.72	201002	201107
Halvan	SATBA	IR	56.30	33.96	200607	200802
Hamburg University	Hamburg University	DE	10.10	53.52	200401	201812
Hegyhatsal	Hungarian met service	HU	16.65	46.96	199408	201611
Hendijan	SATBA	IR	49.77	30.12	201004	201110
Hesarak	SATBA	IR	51.32	35.80	201102	201201
Hormozgan University	SATBA	IR	56.44	27.26	201402	201601
Hoseinieh	SATBA	IR	48.18	30.80	200711	200908
Huisun	National Chung Hsing University	TW	121.13	24.08	201012	201311
Humber Gateway	E.ON	GB	0.27	53.64	200910	201210
Hyytiala	Helsinki university	FI	24.29	61.85	199512	201710

Ijmuiden	ECN	NL	3.44	52.85	201111	201603
Inner Dowsing	UK Green Investment Bank	GB	0.44	53.13	199908	200802
Jangal	SATBA	IR	59.21	34.70	200607	200803
Jask	SATBA	IR	58.11	25.69	200608	200709
Javim	SATBA	IR	54.09	28.19	200606	200711
Jirandeh	SATBA	IR	49.78	36.71	200303	200407
Juelich	Research Center Juelich, Institute for Energy and Climate research (IEK-8)	DE	6.22	50. 93	201110	201712
Kaboodar Ahang	SATBA	IR	48.75	35.35	200607	200710
Kahak Garmsar	SATBA	IR	52.32	35.12	200607	200802
Kahrizak	SATBA	IR	51.32	35.47	200708	200903
Kennewick	Bonneville Power Administration	US	-119.12	46.10	200201	201804
Kentish Flats	Vatenfall AB	GB	1.09	51.46	200210	200501
Kerend Gharb	SATBA	IR	46.19	34.43	201204	201407
Khaf	SATBA	IR	60.31	34.49	200707	200903
Khalkhal Bafrajerd	SATBA	IR	48.57	37.54	201109	201410
Khalkhal Eilkhichi	SATBA	IR	48.25	37.63	200906	201103
Khash	SATBA	IR	61.06	28.10	200606	200712
Khomein	SATBA	IR	50.16	33.80	200607	200709
Kohein	SATBA	IR	49.71	36.34	201105	201504
Korit	SATBA	IR	56.95	33.44	200607	200801
Langrood	SATBA	IR	50.23	37.26	200607	200804
Larijan	SATBA	IR	52.22	35.98	201006	201105
Latman	SATBA	IR	51.23	35.77	200708	200808
Likak	SATBA	IR	50.12	30.86	201009	201106

Lindenberg	DWD	DE	14.12	52.17	199901	201701
London Array	E.ON; Caisse; Dong Energy; Masdar	GB	1.39	51.59	200412	201012
Lootak Zabol	SATBA	IR	61.39	30.73	200606	201001
lopl1	Louisiana Offshore Oil Port	US	-90.03	28.89	201108	201612
Lutjewad	Gronigen university	NL	6.35	53.40	200012	201701
Mae Klong	National Institute of Advanced Industrial Science and Technology	TH	98.84	14.58	200212	200411
Mahidasht	SATBA	IR	46.73	34.39	200606	200709
Mahshahr	SATBA	IR	49.09	30.58	200709	200908
Malin Head	Met ├ëireann	IE	-7.33	55.35	198801	201712
Manjil	SATBA	IR	49.40	36.74	200402	200411
Marvdasht	SATBA	IR	52.92	29.98	200606	200711
Mauna Loa	ESRL	US	-155.58	19.54	199101	201605
Mayan	SATBA	IR	46.05	38.09	200607	200801
Megler	Bonneville Power Administration	US	-123.88	46.27	200210	201804
Meshkin Shahr	SATBA	IR	47.73	38.27	200811	201003
mhrn6	NOAA's National Ocean Service	US	-74.16	40.64	201505	201612
Mil Nader	SATBA	IR	61.16	31.09	201009	201203
Mir Javeh	SATBA	IR	61.44	29.03	200905	201008
Mir Khand	SATBA	IR	49.40	36.67	200207	200310
Moalleman	SATBA	IR	54.57	34.87	200608	200802
Moghar	SATBA	IR	52.18	33.57	200606	200711
Nahavand	SATBA	IR	48.21	34.27	200607	200709
Namin	SATBA	IR	48.38	38.38	200607	200712
Nanortalik	DTU	DK	-45.23	60.14	200706	200906

Naselle Ridge	Bonneville Power Administration	US	-123.80	46.42	201002	201804
Nikooye	SATBA	IR	49.53	36.31	200911	201206
Nir	SATBA	IR	47.98	38.03	201305	201411
NOAH	FoundOcean	GB	-1.49	55.14	201209	201403
Nosrat Abad	SATBA	IR	60.16	29.81	200606	200712
NWTC M2	NREL	US	-105.23	39.91	199609	201701
NWTC M4	NREL	US	-105.23	39.91	201201	201604
NWTC M5	NREL	US	-105.23	39.21	201208	201705
Obninsk	Institute of Experimental Technology	RU	36.60	55.11	200712	201604
Oestergarnsholm	Uppsala university	SE	18.98	57.43	200306	201412
Ohio State University	Ohio State University	US	-84.71	45.56	200701	201707
Old Aspen	UCAR	CA	-106.20	53.63	200210	200912
Palangkaraya	Hokkaido Universit	ID	114.04	2.35	200112	200511
Papooli	SATBA	IR	50.06	36.08	200907	201011
Pasoh	Kyoto University	MY	102.30	2.97	200212	200911
Puijo	Finnish Meteorological Institute	FI	27.65	62.91	200510	201512
Qianyanzhou	Northwest Plateau Institute of Biology	CN	115.07	26.73	200212	200411
Race Bank	Race Bank	GB	0.75	53.31	200606	201304
Rafsanjan	SATBA	IR	56.22	30.32	200606	200807
ROAM4	NBDC	US	-89.31	47.87	198310	201612
Roodab	SATBA	IR	57.35	36.05	200808	201003
Rostamabad	SATBA	IR	49.49	36.90	200201	200307
Sakaerat	National Institute of Advanced Industrial Science and Technology	TH	101.92	14.49	200012	200311

Sanar	SATBA	IR	51.31	36.50	200607	200708
Sarakhs	SATBA	IR	61.14	36.31	200609	200711
Saravan	SATBA	IR	62.26	27.42	201010	201110
Saveh Site	SATBA	IR	50.40	35.08	200805	200909
Semnan	SATBA	IR	53.45	35.62	200907	201011
Seven Mile	Bonneville Power Administration	US	-121.27	45.63	200201	201804
SGOF1	NBDC	US	-84.86	29.41	200310	201612
Shahr Abad	SATBA	IR	56.20	37.65	201104	201112
Shahr Babak	SATBA	IR	55.22	30.09	200609	200807
Shandol	SATBA	IR	61.66	31.15	201010	201201
Shell Flats Mast 1	Centrica UK	GB	-3.29	53.86	201107	201312
Shell Flats Mast 2	Centrica UK	GB	-3.20	53.87	201107	201401
Sheykh Tapeh	SATBA	IR	45.08	37.52	201207	201504
Shiraz Site	SATBA	IR	52.61	29.37	200712	200906
Shooshtar	SATBA	IR	48.76	31.79	200711	200908
Shorjeh	SATBA	IR	49.44	36.07	200807	201001
skmg1	Skidaway Institute of Oceanography	US	-80.24	31.53	200409	200801
Sodankyla	FMI	FI	26.64	67.36	200012	201412
South Carolina	Savannah River National Laboratory	US	-81.83	33.41	200904	201712
South Pole	ESRL	US	-24.80	-89.98	197901	201605
spag1	Skidaway Institute of Oceanography	US	-80.57	31.38	200401	200909
STDM4	NBDC	US	-87.23	47.18	198407	201612
Summit	ESRL	GL	-38.48	72.58	200806	201605
Tafresh	SATBA	IR	50.06	34.68	201009	201302

Taleghan Site	SATBA	IR	50.57	36.12	200712	201002
Tange Hashi	SATBA	IR	52.96	29.18	201503	201509
Tarom	SATBA	IR	49.03	36.66	201106	201306
Tiksi	Roshydromet; Finnish Meteorological Institue; U.S. National Oceanic and Atmospheric Administration	RU	128.89	71.60	201008	201809
Too Takaboon	SATBA	IR	49.52	36.91	200204	200312
Trinidad Head	ESRL	US	-124.15	41.05	200204	201605
Troutdale	Bonneville Power Administration	US	-122.40	45.56	201002	201804
Tumbarumba	CSIRO Marine and Atmospheric Research	AU	148.15	-35.66	200101	201412
tybg1	Skidaway Institute of Oceanography	US	-79.93	31.63	200401	200801
upbc1	NOAA's National Ocean Service	US	-122.12	38.04	201302	201612
Varzaneh	SATBA	IR	52.62	32.46	200606	200810
Vasf	SATBA	IR	50.93	34.19	200809	200902
Vielsalm	Universit├® Catholique de Louvian	BE	6.00	50.31	199608	200904
Wallaby Creek	University of Western Australia	AU	145.19	-37.43	200501	200812
Walnut Grove	ESRL/DOE	US	-121.49	38.27	200508	201611
Wasco	Bonneville Power Administration	US	-120.77	45.50	200509	201804
wdel1	Shell International E&P	US	-89.55	28.66	200812	201609
West Branch	ESRL; IOWA university	US	-91.35	41.72	200801	200807
WLEF	ESRL	US	-90.27	45.95	200301	201711
WM01	Republic of SouthAfrica - dept. of Energy	ZA	16.66	-28.60	201006	201701
WM02	Republic of SouthAfrica - dept. of Energy	ZA	19.36	-31.52	201006	201701
WM03	Republic of SouthAfrica - dept. of Energy	ZA	18.42	-31.73	201006	201701

WM04	Republic of SouthAfrica - dept. of Energy	ZA	18.11	-32.85	201005	201306
WM05	Republic of SouthAfrica - dept. of Energy	ZA	19.69	-34.61	201005	201701
WM06	Republic of SouthAfrica - dept. of Energy	ZA	20.69	-32.56	201009	201612
WM07	Republic of SouthAfrica - dept. of Energy	ZA	22.56	-32.97	201005	201701
WM08	Republic of SouthAfrica - dept. of Energy	ZA	24.51	-34.11	201008	201701
WM09	Republic of SouthAfrica - dept. of Energy	ZA	25.03	-31.25	201009	201612
WM10	Republic of SouthAfrica - dept. of Energy	ZA	28.14	-32.09	201008	201612
WM11	Republic of SouthAfrica - dept. of Energy	ZA	28.07	-30.81	201510	201707
WM12	Republic of SouthAfrica - dept. of Energy	ZA	30.53	-29.85	201510	201707
WM13	Republic of SouthAfrica - dept. of Energy	ZA	32.17	-27.43	201510	201707
WM14	Republic of SouthAfrica - dept. of Energy	ZA	29.54	-27.88	201510	201707
WM15	Republic of SouthAfrica - dept. of Energy	ZA	27.12	-28.62	201509	201707
wslm4	Great Lakes Environmental Research Laboratory	US	-85.14	45.84	201504	201612
Xishuang-banna	Xishuangbanna Tropical Botanical Garden	CN	101.20	21.95	200212	200511
Zahedan	SATBA	IR	60.81	29.47	201101	201201
Zarrineh2	SATBA	IR	46.93	36.06	201503	201601
Zartoshtabad	SATBA	IR	48.50	37.61	201408	201504