AUTOMATIC MONITORING OF WEATHER AND CLIMATE AT MOUNTAIN AREAS. THE CASE OF PEÑALARA METEOROLOGICAL NETWORK (RMPNP)

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Abstract. Mountains have a very peculiar climate, are an essential factor in the climate system and are excellent areas for monitoring weather and climate. Nevertheless there is still a lack of long term observations at these areas, mainly due to their harsh conditions for instruments and humans. This work describes the results obtained in the design, installation and operation during more than a decade of a mountain meteorological network located in *Sierra de Guadarrama* (Iberian Central System, Spain). This work includes information about the measuring strategy, objectives and performance of the network with some technical and operational conclusions that might be useful for the mountain meteorology observation community. Discussions about the representativeness of the observations are shown in order to be taken into account by future users of this data base. Some basic statistics of the available data are shown as a framework for further and deeper analysis. Finally, some recommendations are made about mountain meteorology observation which could be taken into account for future improvements of this network or for other mountain meteorological networks.

1. Introduction

Despite the importance of mountains in climate, meteorological observations at mountains were not intensively made until the mid nineteenth century. Since then, and mostly in the last decades, progress to conduct continuous observations have been made according to the generalization of standardized methods for observing the atmosphere not without difficulties (Auer et al., 2007, Hiebl et a., 2009). It is commonly accepted that a better understanding of the climatic characteristics of mountain regions is limited by a lack of observations adequately distributed in time and space.

The very specific conditions of mountain environments make them excellent indicators of climate change, whether or not this is due to internal climate variability or anthropogenic origin (Barry, 1990; Diaz and Bradley, 1997; Hauer et al., 1997; Jungo and Beniston, 2001; Bosch et al., 2007; Anderson et al., 2009; Lurgi et al., 2012; Lepi et al., 2012; Fuhrer et al., 2012).

As done in similar situations with high deficit of observations, some climatic information for mountains could be retrieved remotely through the use of satellite information, radiosonde or observations obtained at closer but lower observatories. But, in this case, the differences between these observations and ground observations are expected to be significant due to decoupling of the boundary layer from the free troposphere (Seidel et al., 2003; Hazeau et al., 2010; Barry 2013). It seems like in situ mountain observatories are imperatively required.

There are several reasons that explain the lack of reliable and long meteorological observations at mountains. Some of them are: remoteness, extreme environmental conditions, difficulties on having powerful energy sources and reliable telecommunications. On the other hand, due to the high spatial variability of the meteorological fields at mountains (Buytaert et al., 2006), a mountain observatory is expected to be representative of a very small area. This makes necessary a higher density of stations than at lower elevations, increasing the overall cost of installation and operation.

Peñalara Massif is located in Sierra de Guadarrama, which is part of the Iberian Central System (De Pedraza-Gilsanz, 2000). This mountain range lies over two extensive plateaus in the center part of the Iberian Peninsula and shows excellent conditions for conducting weather and climate observations (Figure 1.a). It has been kept unaltered for centuries, even though it is relatively close to the city of Madrid. This area shows some particular conditions due to its complex orography and a strategic location that exposes the mountain to the advection of the humid air masses coming from the Atlantic (Durán et al., 2015). This area is under an Alpine climate immersed in a Continentalized Mediterranean climate. Temperature and precipitation mean values are comparable to other mountain areas in southern Europe, but with some peculiarities like a strong summer drought and a high inter-annual variability (Durán et al., 2013).

In the last years, this area has been subject of numerous scientific and multidisciplinary studies: geomorphology (Palacios, 1997; Palacios et al., 2000; Palacios et al., 2003; Palacios et al., 2011, Álvarez and Sierra, 2011), limnology (Granados, 2000; Granados et al., 2006; Granados, 2007), ecology (Montouto, 2000), zoology (Juez, 2001; Pérez, 2001; Horcajada, 2001; Ortiz-Santaliestra et al., 2011), botanics (Sancho L.G., 2000; Moreno, 2001; Sancho et al., 2007; Gómez González et al., 2009; Mera et al., 2012; García-Fernández et al., 2013; Amat et al., 2013; Schwaiger and Bird, 2010; García-Romero et al., 2010; García-Camacho et al., 2012; Ruiz-Labourdette et al., 2013; Gutiérrez-Girón and Gavilán, 2010; and meteorology and climate (Durán, 2003; Bosch et al., 2006; Bosch et al., 2007; Palacios et al., 2003; Durán, 2007; Ruíz Zapata et al., 2009; Granados, 2011; Ruiz-Labourdette et al., 2011; Génova, 2012; Durán et al., 2013; Sánchez et al., 2013; Durán et al., 2015; Durán and Barstad, 2016).

This increasing scientific interest during the last decade made necessary to have local meteorological observations of high quality for the scientific community working on this area. The first step was taken in 1998 with the installation of one of the first fully automatic meteorological stations above 2000 m.a.s.l. of scientific quality and with a long term horizon in the

Iberian Peninsula. Since then, other four automatic meteorological stations have been installed forming what is known as *Red Meteorológica del Parque Natural de Peñalara (*RMPNP hereafter) (Figure 1.b).

The next sections outline some concepts taken into account during design, installation and operation of this network along with some results and discussions about the representativeness of the data. Some technical and operational procedures are outlined so can be helpful for the mountain meteorology observing community and for future mountain networks planned in this area (Rath 2012; Rath et al., 2014; Santolaria-Canales et al., 2015). This work is also expected to be a framework for future users of RMPNP data base.

This paper is organized as follows. Next, the method used for the design and installation of the network will be described. It also includes some details of the organization, the maintenance procedures, the quality assurance program, a description of the sites and some discussions about the representativeness of the data. Next section shows a preliminary analysis of the data which are able to give preliminar climatic features of this complex region. Last section summarizes the conclusions.

2. Method

Since 1998 the number of observatories in the area has increased in order to take into account the complexity of the area and the new resources available. The process has been sequential following a measuring strategy, in terms of siting criteria of new sites at macro and micro scale levels. Nowadays, the network consists of 5 automatic weather stations, one manual observatory and some fixed sites for ancillary measurements and prototype testing (Figure 1.b).

2.1 Measuring objective

The objective of a meteorological network determines its design and configuration. Depending on the potential use of the data, different network designs are possible (Frei, 2003). For this network, the main objective is to obtain representative and high quality meteorological data at Peñalara Massif and its area of influence.

The representativeness of an observation is the degree to which it accurately describes the value of the variable needed for a specific purpose (WMO, 2008). Thus, representativeness depends strongly on the measuring objective and also on other factors like the measuring technique (manual or automatic), instrumentation used (quality of the sensors, calibration, sample time, averaging time), exposure (macro-scale and micro-scale siting criteria), and also maintenance protocols (data handling, collection intervals, post-processing and storage) (Brock and Richardson, 2001).

2.2. Specific difficulties to overcome at mountains

All the technical and human issues that affect the performance and representativeness of a meteorological network can be applied also at mountain networks (WMO, 2008). Nevertheless, the following specific difficulties to overcome at a mountain environment have been identified:

i. Remoteness. Mountain environments have been kept unperturbed for centuries and are distant from anthropogenic activity. This is one of the reasons why mountain observations are so valued. On the contrary, remoteness might be the main source of data gaps and measuring errors. The difficulties start during the installation since logistics are more complex and the materials and structures to be potentially used are also very limited due to environmental reasons. It also decreases the frequency and duration of the maintenance procedures and increases the vulnerability to the elements, fauna and vandalism. It also reduces the public radio based communication signal coverage, something that turns crucial for these kinds of unattended networks. Remote sites usually do not have power available for powering the electronic systems or for heating the sensors. Remoteness has probably the highest impact on the cost of installation and operation of these networks.

ii. Extreme environmental conditions. Low temperatures can last for many days at these areas. This seriously compromises the correct functioning of the powering systems. Scientific quality instruments are normally able to handle these low temperatures, but batteries drop their efficiency drastically at low temperatures. A power loss affects directly the completeness of data, and consequently, the representativeness of the data set. Persistent low clouds or fog is also more frequent that at lower altitudes, so the solar power resource is also lower. Frequent saturating conditions also affect temperature measurements, especially when condensed drops form over sensors and then evaporate. Most of the conventional sensors are designed and calibrated for regular ambient temperatures and accuracy normally decreases when reaching their limits of operation, something that is frequent at mountains. In summer, solar radiation is very high, especially short wave radiation, accelerating the degradation of plastics and paints. This, combined with rain and snow, accelerates corrosion of structures and sensors protections. In winter high radiation during a sunny day with snow covering the ground, increases temperature measurements, due to reflection, when using regular solar radiation shields. Snow and rime are also a difficult problem to overcome when depose over sensors like pyrometers, temperature radiation shields, rain gauges and solar panels. Rime icing has a devastating effect on mountain meteorological networks. It forms when supercooled water drops transported by the wind make contact with an obstacle and freeze immediately. Data from a sensor covered with rime is useless and sometimes it is hard to find a method to detect when rime starts and ends to affect the measurements. Rime is also responsible, in combination with high wind, of tearing down towers and breaking supporting cables and sensors. Other factors that are specially enhanced at mountains and also affect reliability are strong winds and lightning.

iii. Micro-climate. Complex orography originates a great variety of micro climates in a small area. This makes mountains very valuable from a scientific point of view but has a direct impact on representativeness. At mountain environments, It is difficult to find a location that is not too influenced by local conditions or perturbed by obstacles, projected shades, stagnation, cold pools, and other local effects. Thus, a mountain weather station is usually representative of a very small area compared with stations at lower lands. For a correct assessment, a higher density of stations is necessary.

iv. Security and environment. Mountains can be very dangerous and maintenance personnel need to increase their security protocols, especially in winter. Also, higher precautions need to be taken in order to minimize the environmental impact of towers, sensors and equipment since these areas usually have a high degree of environmental protection.

2.3 Measuring strategy

Once established the measuring objective, assessed the difficulties of conducting observations at mountains and considering the resources available, the following measuring strategy was defined:

i. Measuring technique. Automatic measurements are the base of this network. Additional manual measurements for calibration and data quality control are performed at a limited number of sites.

ii. Density of stations. Considering the size and orographic complexity of the area, five sites are considered enough to cover the elevation range going from 1102 m.a.s.l. to 2079 m.a.s.l.. Since highest point of the area is 2414 m.a.s.l., this makes an average of one site per 260 m of altitude. Density of stations is higher at higher altitudes.

iii. Siting criteria. Recommendations from the World Meteorological Organization (WMO, 2008) will be followed when possible. Additional criteria applied are: the site needs to be representative of a broader area of similar elevation, environmental impact will have to be minimized during installation and operation; the site needs to be relatively accessible mostly of the year in safe conditions for personnel, and good signal coverage from public telecommunication networks is desirable for data downloading and control.

2.4 Quality Assurance and Quality Control

Quality assurance and control (QAQC) of meteorological networks deserves even more resources and attention than installation itself (Shafer et al., 2000). The lack of a clear, continuous and realistic QAQC program is probably the main reason for the frequent data gaps found in mountain networks data sets. Sustainability of the network needs to be guaranteed. Even the best infrastructures, sensors and powering systems will not last much without a proper QAQC program. There is an extended and wrong thought that automatic networks are fully automatic, and consequently, not enough human resources are normally planned.

Quality of data does not only depend on quality of sensors. It also depends on the quality of every aspect that intervenes in the measuring chain (Brock and Richardson, 2001). This chain starts at the installation, it continues during the maintenance and finishes with the data management, storage and dissemination. Considering only the measurement process, the accuracy of a measurement depends on a sum of factors that accumulate one after the other. The first one is the sensor itself, which needs to have a valid calibration. Another common source of errors at mountains is a wrong exposure, it is difficult to guarantee that the sensor will be correctly exposed to the measurand all over the year, especially in winter. Distance to ground changes due to snow height and obstacles can project rain shadows on sensors. Wind can also affect rain catchment due to aerodynamic effects (underestimation) or turbulence can hurry the tipping bucket process (over estimating). Snow can deposit on top of pyrometers and collapse non heated rain gauges. Snow can melt afterwards, giving spurious precipitation under clear sky. These errors could be acceptable if they were random like, but they are weather dependent and can lead to wrong climatic conclusions if this bias is not corrected.

The quality assurance program has evolved through the years of operation of this network since there has been a progressive acquisition of knowhow. During the first years of operation most of the resources available were invested in the installation and instrumental consolidation of the network. In the last years, once the number of sites reached the optimum number, a higher effort was given to define and apply the following QAQC program:

i. Preventive maintenance. Consists of regular visits to the sites before any problem is detected. The expected frequency of these visits has been between one to two months, depending on the weather conditions and resources available. Works done include: cleaning panels and sensors, structures checking, parallel measurement for checks of performance and extension of calibration times given by manufacturer. On site rain gauge calibration once a year using a rain gauge calibrator. Electrical and telecommunications checks are also performed. All these tasks are recorded in a control chart.

ii. Corrective maintenance. Reparation of a malfunctioning part of the automatic station. Sometimes it requires a previous visit for diagnostic and evaluation of damages. The correction should be made as soon as possible in order to minimize data loss, but it depends on availability of spare parts and weather conditions. Sometimes broken sensors during winter cannot be substituted until next spring.

iii. Data validation. During this procedure is decided whether or not an observation is valid and becomes part of the variable time series (Salvati and Brambilla, 2008). This process is done following a two phase protocol. A first level validation is done almost at real-time during the importing process. The objective of this phase is to detect impossible values, outliers and very clear malfunctions. We had found that many of the wrong observations are due to total breakeage of the sensors. Under these circumstances, observations are either full scale, Not-A-Number or impossible values. When telecommunications where available with certain reliability, it was possible to do the downloading daily, and also the first phase validation. The purpose of this phase is to trigger alarms for corrective maintenance and to filter out suspicious data that will be otherwise reported to the public in daily graphs and maps. A second phase validation is made after some moths, when information from all sites has been collected, maintenance reports are finished and observations from other networks are available. At this phase, climatological site specific thresholds are used and internal consistency checks are performed. Spatial coherence checks using information from neighboring stations and data from other networks or reanalysis are also made yearly. Long term drift tests are also made for the long time series. As a result of this process, data are individually tagged with the following codes: V: valid data, D: not valid data, C: corrected data and T: temporal not validated data. At this point, data is now ready for dissemination.

iv. Storage and Reporting. As long as the volume of data increases with new data and new sites, the storage technology becomes more important (Table III). This has been evolving through the years from individual ASCII (American Standard Code for Information Interchange) files to spreadsheets to finally a PostgreSQL based data base (Momjian, 2001; PostgreSQL Global Development Group,1996-2014). A PHP (Achour et al., 2006) graphical user interface accessible remotely through the web has been developed for data storage, validation and reporting to users, public and organizations. Validation and graphics routines are programed with Python (Van Rossum and Drake, 1995). Last evolutions of this software is relying more on Python newer versions of PosgreSQL.

3. Results and discussion

At present time RMPNP consists of five automatic meteorological stations that cover the area of Massif of Peñalara and the lower lands of Valle del Lozoya (Figure 1.b). Additionally, a manual observatory of temperature and precipitation has been installed near one of the automatic sites for calibration purposes and research.

Next sections describe some characteristics of the sites that future data users might find relevant for their applications. Also, some discussions about the representativeness of temperature, wind and precipitation data is shown along with some comments on the rest of the variables measured.

3.1 Description of the network

Table I shows the RMPNP code, name, coordinates, starting year, variables codification, magnitudes measured and sensor used at the present time.

Even though location of sites have been chosen in order to be as much representative as possible, sometimes this is difficult at mountain areas, especially for some variables and seasons. Table II includes some general comments about the representativeness of each individual site. Metadata information has been taken and archived. Such information should be always be taken into account before using an observational data base like this (Woodruff et al., 1998). The brief information showed in Table II, should not substitute an in-situ visit of the site, something that is always recommended.

Since first stations (Zabala and Cabeza Mediana) were installed in 1999 at an elevation of 2079 and 1691 m.a.s.l. the network has suffered a set of changes as a result of technological evolution and acquisition of know-how (Durán, 2003). Regarding changes in sensor and data logging system technology, the evolution has been less marked than in telecommunications and quality assurance procedures. Data logging was made first using a NRG9000 data logger (renewablenrgsystems.com). With the generalization of GSM (Global System for Mobile communications), loggers were progressively substituted with Gantner IDL101 loggers (gantner-instruments.com) and Wavecom (sierrawireless.com) modem was used for data transfer.

Table III shows the annual average data completeness of the stations based on the availability of air temperature data. This table shows fairly well the performance of the network in relation to problems related with power failures, general malfunction due to a general breakage of the stations and also human errors. This table shows also the increment of data volume through the years and also the technology change that the network has suffered from first years to present, especially in relation with telecommunications and data storage systems.

Before 2005 data collection was made through in-situ access to the sites walking and downloading data directly from the logger to a portable computer. This method was proven to be very robust since power requirements of the systems were very low and loggers could be operated by small power panels and batteries. This option should not be rejected nowadays for this kind of very remote networks. Nevertheless this was unsustainable with more sites needed to be visited (Table III). GSM opened a new horizon, since stations could be accessed remotely for data downloading, configuration and status control. But poor quality of the signal at these mountains and problems due to a still incipient technology with not many automation software possibilities made this technology not very reliable. GPRS (General packet radio service) and evolution of GSM oriented to data transfer through the cellular network was the ultimate solution that gave the needed reliability to the communications at RMPNP. Telecommunications not only gave the possibility to have data at the desktop, saving man power and resources, but also made possible to have an almost on line diagnostic of the station status. It really made a difference on data completeness and compensated the extra work due to the increment in the number of sites (Table III).

Another important technological evolution was the way data was stored. With a few stations and during the first years, individual ASCII was simple and useful. Nevertheless, soon it was found necessary to tag data individually as result of the QAQC process and ASCII files were not found very optimum. This was first solved using spreadsheets which also offered an easy solution for calculation of some statistics, wind roses and daily and monthly time series using macros. But again, it turned not to be very practical with the rapid increment of volume of data needed to be stored (Table III). The solution was found using PosgreSQL data base environment which brought new possibilities and saving man power. This made easier the use of functions and algorithms programmed in Python for data validation, automation of reports and exchange of information with third parties. Also, gave reliability to the system thanks to the powerful capabilities of this environment for backups and remote access for management.

Next sections discuss more deeply the representativeness of temperature, wind and precipitation observations.

3.2 Representativeness of Temperature Time Series

The measurement of temperature using automatic techniques has shown to be very robust at RMPNP. Data gaps at temperature time series is mainly due to general failure problems of the station, like power failures. Drift of sensors has shown to be under factory specifications and regular replacement of sensor filters showed to be less necessary than in other more contaminated atmospheres. The progressive substitution with new sensors have not affected its homogeneity.

In order to check the homogeinity of the temperature data sets, an Alexandersson (Alexandersson, 1986) test has been performed to Zabala and C.Mediana temperature data sets for the period 2000-2014. A reference station located at less than 10 km distant temperature observatory belonging to the Spanish Meteorological Agency has been used. Puerto de Navacerrada (1893 m.a.s.l.) observatory uses professional staff and follows standardized observation methods. Since this observatory is operated by independent staff from RMPNP, using completely different methods, a homogeneous behavior with this observatory should be robust enough. Figure 4 shows the results obtained. As can be seen the T value of this test on the annual mean temperature is below the critical value (6 for 13 points) and can be concluded that the time series at these two sites are homogeneous.

Temperature time series recorded at RMPNP show to be a reliable estimation of the real temperatures at this area through all these years. Nevertheless, there are some factors that could be influencing the representativeness of these measurements and should be considered when using the data for certain applications. These are:

- effect of rime freezing on the naturally aspirated radiation shield. Under this situation, a decoupling of the sensor from the measurand is expected (Leroy et al., 2002; Appenzeller et al., 2008; Heimo et al., 2009) and probably the observation differs from real temperature;

- effect of down-up short wave radiation reflected from ground due to snow cover. Radiation shields are designed for an up-down direction of direct radiation;

- effect of raised ground level due to snow height in winter;

- effect of evaporation of water drops condensed over temperature sensor;

One aspect that has shown to be useful for data validation is the relationships between values observed simultaneously at different sites (spatial coherency checks) and the local lapse rate. Figure 5 shows the mean hourly temperature for every site and season and for the common period. Considering the difference between mean maximum and minimum temperature as mean daily temperature amplitude, this figure shows how the temperature amplitude decreases with elevation, as expected, due to a lower influence of the soil at higher altitudes. Bottom valley sites show the higher temperature amplitude. This decoupling between elevations produces episodes of temperature inversion, specially during the first hours of the day. Differences between maximum temperature at higher site (Zabala, 2070 m.a.s.l.) and lower site (Alameda, 1102 m.a.s.l.) are around 10 ºC, what gives a value very close to dry adiabatic lapse rate. In winter this value is around 7 ºC km^{-1}, which is closer to moist adiabatic lapse rate.

Figure 6 shows the correlation between the hourly air temperatures for all the sites and for their common period. As expected the correlation is high since the sites are relatively close. Higher correlations are found among the higher altitude sites (Zabala, Cotos and C.Mediana) and the valley bottom sites (Ontalva and Alameda).

One advantage of having such high density of stations highly correlated is that it might be feasible to complete the data gaps of one site out of the observations from the others. Figure shows an example of such simple data completion procedure calculating a temperature lapse rate between Zabala and C.Mediana. This lapse rate is then used to calculate air maximum, minimum and average temperature at Cotos. Figure 7.a shows the scatter plots of calculated versus observed temperature using this simple lapse rate method. Figure 7.b shows the root mean square error (RMSE) between these two data series. It is shown how this method gives higher RMSE for summer and lower values for the rest of the year. Surely a more sophisticated method would give better results (Henn et al., 2013).

3.3 Representativeness of Wind Time Series

For wind speed and wind direction, mechanically driven sensors have been chosen. In the last years cup anemometers and wind vanes have been substituted by four blade helicoid propeller wind and direction sensors which has shown to be more reliable and robust. Both kinds of sensors are susceptible of being blocked and broken frequently by rime acting together with high winds (Makkonen et al., 2001; Fortin et al., 2005). Figure 8.a shows the wind speed measured at Zabala during some days in winter along with the standard deviation in the same period. This is just an example of the effect of rime on anemometers. Supercooled water freezes immediately when touching the anemometer that finally lose its mobility after a certain time. This process occurs under freezing conditions and can last for some days (Figure 8.b). When temperature rises, ice melts and very often the anemometer recover functionality. Often, an asymmetrical melting process on the rotor of the anemometer can cause it to break and lose functionality. Since this is a winter phenomenon, substitution of sensor delays in time waiting for safe conditions for the maintenance crew, increasing the data gaps considerably.

Figure 9 shows completeness of wind data for some sites at different elevations and for all seasons. The number of wind measurements taken under freezing conditions is also shown. This graph shows the strong relationships between both variables and how higher elevation sites are more susceptible to this kind of phenomena. Figure 10 reinforces this elevation dependency and shows the percentage of valid data and data gaps due to general failure of the powering system, effect of rime and sensor breakage. It seems clear how it is still difficult to have good data coverage in winter and at high elevation sites without heated sensors.

Besides the complexity of measuring wind under these conditions, and taking into account that the loss of data is causing a bias that would need further evaluation, a first assessment of wind at this area of Guadarrama can be obtained using C.Mediana site wich showed 70% of completeness for more than a decade. For illustrating purposes the seasonal wind distribution has been calculated (Figure 11.a) and the wind roses for this excellent wind monitoring site (Figure 11.b).

3.4 Representativeness of Precipitation Time Series

Regarding precipitation, this quantity has shown to be extremely difficult to measure at these mountains and with the systems used. Under the absence of wind, rain gauges perform fairly well since precipitation falls down vertically and is collected by the effective area of the collector. But in real field conditions the catching process is less efficient and depends on other factors, mainly on wind speed and precipitation rate. Even neglecting other sources of errors, only the influence of wind at the upper part of the rain gauge can be responsible of more than 15% losses in the case of rain and of 30% for snow, depending on wind speed and precipitation rate (Groisman and Legates, 1994; Sevruk, 1996; Goodison et al., 1997; Sieck et al., 2007; Paulat et al., 2008; Cheval et al., 2011). Thus, it is generally accepted that rain gauges tend to underestimate no matter the measuring principle.

Besides the loss of precipitation due to the aerodynamic effect of wind, the non-heated rain gauge used at RMPNP have been blocked with snow during many winter, fall and spring precipitation events. When temperatures rise, the blocking snow at the funnel melts and spurious precipitation is recorded at the tipping-bucket under clear sky. This double effect of erroneous precipitation measurement is shown in Figure 12.a where manual observations made at Cotos using a Hellman manual rain gauge combined with the automatic measurements made possible to make a deep analysis of this effect. During the 27th and 28th of October snow precipitation is collected manually. During these days, nothing is detected by the tipping bucket rain gauge, which is collapsed with the snow. The 2nd of March, the sky is clear as shown by the radiation sensor, and temperature rises above zero degrees (Figure 12.b). Snow starts to melt during the central hours of the day giving precipitation at a very constant and artificial rate (Figure 12.b). This process is confirmed by the snow depth sensor installed at the same site (Figure 12.a). Normally the total amount of this spurious rain is very similar for other episodes and it stops at night, when temperatures go again below zero. This pattern is repeated with every snow storm, so proper validation algorithms can be programmed to filter them out.

At Guadarrama, most of the total precipitation that falls in winter, spring and fall is snow (Durán et al., 2013), so this is something that needs special attention in the future.

Figure 13.b shows a scatter plot of days with precipitation below 1 mm (orange), days with snow precipitation higher than 1 mm (light blue) and days with rain precipitation higher than 1 mm (dark blue) against mean daily relative humidity and mean air temperature observed at Cotos. Precipitation is measured using a manual rain gauge. It seems clear how precipitation occurs more frequently with mean daily relative humidity values higher than 80%. This graph has been used as a three phase diagram with curves has been used for precipitation data validation like detection of false precipitation events or tipping bucket malfunction. Refinements of this algorithm are expected to be done in the future discriminating between seasons and hour of the day, since relative humidity follows a clear daily cycle.

Some precipitation events with low mean relative humidity have been found related with convective storm activity. These episodes are characterized by a sudden and isolated increase of relative humidity lasting only some hours. This repeated pattern opens again possibilities for using relative humidity as a good variable for precipitation data validation.

Figure 13.a also shows how snow, as expected, occurs mainly under freezing conditions, but again some exceptions are found and probably attributable to a cooling process due to evaporation of the snowflakes on their falling down. Obviously this deserves deeper investigation.

In order to establish if the effect of precipitation underestimation of non-heated tipping bucket rain gauges is also affecting the rest of the rain gauges, the mean zero isotherm has been calculated using hourly temperature and elevation of the sites. A linear adjustment of this pair of data gives an hourly lapse rate that is used to find the height for temperature equal to 0 ºC. Figure 14 shows the median, 75^{th} percentile and 25^{th} percentile of elevations of the zero isotherm for winter months. This figure shows how during winter, partly fall and spring most of the sites (except Ontalva and Alameda) have average freezing temperatures. It is them expected that underestimation of precipitation is potentially occurring at all these sites. The precipitation observations for the winter period should be used with certain precaution.

As a result of the experience through all these years certain rules of thumb have been developed for precipitation validation. These rules are summarized in Figure 15 and should be taken as guidelines, sometimes real cases are much more complex.

Automatic precipitation observations using non-heated tipping-bucket rain gauges are shown not to be valid for a complete year long assessment of precipitation at Guadarrama. For some cases, like convective episodes and under non-freezing conditions manual and automatic measurements are comparable. Future users of this data base might have to use other techniques, like modeling for completing the observations. In order to give an estimation of the potential use of models for completing these data sets and also to give an order of magnitude of the missed precipitation, Figure 16 shows results of a Linear Orographic Model (Smith and Barstad, 2004) applied to this region (Durán and Barstad, 2016). This Figure shows an estimation of the climograms for each site and for each available period. Comparisons between sites should be made with precaution. Manual observations at Cotos (LL10) show how this method, is giving realistic results.

4. Conclusions

Automatic techniques for measuring weather and climate at mountains are feasible but there are important factors that affect representativeness, including data completion, which are strongly weather dependent. This dependency might induce biases that need to be taken into account.

Manual methods of observing the atmospheric conditions at only one site have shown to be very practical for understanding the reliability of the network and to outline future improvements. Despite the low temporal resolution of this kind of measurements, it has shown to be very reliable and gave a solid base for building validation algorithms.

Five monitoring sites covering altitudes from 1104 m.a.s.l. on the bottom of the valley to 2079 m.a.s.l. have shown enough to find relevant altitudinal differences. Whether or not this station density is enough for accounting for all spatial and temporal variability depends on the objectives. For a finer assessment of the conditions at higher altitude and more complex terrain, more sites would be necessary.

After trying several communication techniques, GPRS has shown to be very reliable and cost effective saving a considerable amount of man power. It also allows to have a daily diagnostic of station status reducing the data gaps since it decreases significantly the time response for the solution of break downs.

A data base structure for data storage has found to be crucial after a certain volume of data has been stored. This not only made simpler data management but also made possible the development of more efficient data quality routines, exchange of information, remote access for users and backups.

A two phase validation process, one based on automatic algorithms that are executed almost on line and useful for on line publication and triggering maintenance alarms, and a second phase based on more sophisticated checks and expertise has shown to be very useful and operative.

Individual tagging with quality tags of every observation as valid, corrected, null and temporal has shown to be simple but efficient for data dissemination to third not weather expert users.

Temperature and relative humidity automatic measurements have shown to be very robust. Even though no indications of interferences have been found, some aspects might need further investigation using artificially aspirated radiation shields and a rime detection sensor.

Horizontal axes four blade helicoid propeller wind anemometer and wind vane has shown to be more robust and less rime influenced, giving better availability statistics. Ice free or ice repellent anemometers might also need to be investigated and compared with regular cup anemometers.

Non-heated tipping bucket rain gauges do not record precipitation under 5 ºC. This is very frequent at Sierra de Guadarrama, so this kind of rain gauge is not advised for this area. On the contrary, manual observation using a regular Hellmann rain gauge, proved to be very efficient and helpful. Wide collection area rain gauges with no funnel might perform well even without heating. Also wind shields are recommended to minimize wind induced underestimation.

Snow height measurement will help to evaluate snow precipitation and dynamics but also is important for establishing the surface level in order to correct the measurements.

Automatic precipitation measurement at mountains is one of the biggest challenges for automatic surface meteorological monitoring. Due to the difficulties and high spatial variability of this parameter in this kind of areas, a combination of surface measurements, remote detection techniques and modelization is necessary for a correct assessment of precipitation at mountains.

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Table I. Description of the location and characteristics of the observing sites of Peñalara Meteorological Network. Instrumentation has changed since first installation but last one is included in this table.

Code	Name	Coordinates (City, Province)	UTM (m) Altitude (m.a.s.l.)	Starting year	Variable code	Magnitude (Units)	Sensor (in 2014)
001	Ontalva	40º52'20''N 3º53'1'' W (Rascafría, Madrid)	X: 424736 Y: 4524980 Z: 1190	2008	TA01	Air temperature at 2m (ºC)	Vaisala HMP45
				2008	HR01	Relative humidity at 2 m (%)	Vaisala HMP45
				2008	LL01	Liquid precipitation at 3 m (mm)	NovaLynx 260-2500
				2008	VV01	Wind velocity at 6 m (m/s)	NRG #40
				2008	DV01	Wind direction at 6 m (º)	NRG
002	Cabeza Mediana	40º50'13''N 3º54'15''W (Rascafría, Madrid)	X: 423450 Y: 4521790 Z: 1691	1999	TA01	Air temperature at 2m (ºC)	Vaisala HMP45
				1999	HR01	Relative humidity at 2 m (%)	Vaisala HMP45
				1999	LL01	Liquid precipitation at 3 m (mm)	NovaLynx 260-2500
				1999	VV01	Wind velocity at 6 m (m/s)	Young Wind monitor
				1999	DV01	Wind direction at 6 m (º)	Young Wind monitor
				2008	PA01	Atmospheric pressure 1.75m (hPa)	NovaLynx
003	Refugio Zabala	40º50'20''N 3º57'1'' W (Rascafría, Madrid)	X: 419300 Y: 4521330 Z: 2079	1999	TA01	Air temperature at 6m (ºC)	Vaisala HMP45
				1999	HR01	Relative humidity of air at 6 m (%)	Vaisala HMP45
				1999	LL01	Liquid precipitationat 4m (mm)	Young Wind monitor
				2008	LL02	Liquid precipitation at 4m (mm)	Lambrecht
				1999	VV01	Wind velocicity at 10m (m/s)	Young Wind monitor
				1999	DV01	Wind direction at 10m (º)	Young Wind monitor
				2008	PA01	Atmospheric pressure 2m (hPa)	NovaLynx
004	Cotos	40º49'31''N 3º40''' W (Rascafría, Madrid)	X: 418955 Y: 4519800 Z: 1857	2008	TA02	Air temperatute at 2m (ºC)	E+E Elektronic
				2005	TA01	Air temperature at 10 m (ºC)	E+E Elektronic
				2008	HR02	Relative humidity of air at 2m (%)	E+E Elektronic
				2005	LL01	Liquid precipitation at 1.5 m (mm)	Nova Lynx
				2005	VV01	Wind velocity at 10 m (m/s)	NRG #40
				2005	DV01	Wind Direction at 10m (º)	NRG
				2008	HN01	Snow heigth (m)	Judd Comunicatio
005	*Alameda*	40º54'53''N 3º50'39'' W (Alameda, Madrid)	X: 428934 Y: 4529640 Z: 1102	2009	TA01	Air temperature at 4m	E+E Elektronic
				2009	HR01	Relative humidity of air at 4m	E+E Elektronic
				2009	LL01	Liquid precipitation at 4 m	Nova Lynx

Table II. Some comments on representativeness of sites.

Code	Name	Comments on representatives of measurements
001	Ontalva	This station is located in the lower land of the valley. Land use is natural grass immersed into a pine forest in a sheltered clear. Wind observation is not very representative of the boundary layer wind due to obstacles, much higher than tower. The not heated rain gauge might under sample in winter due to snow blocking. Minimum temperatures are lower than expected due to this location is immersed in *Valle de la Umbría*, a north oriented valley within Lozoya Valley. Cold air drainage from higher elevations is also expected.
002	Cabeza Mediana	Mountain site. Land use is natural pasture with some small trees. Excellent location in top of a flat and round ended hill in the middle of *Valle del Lozoya*. Very good representatives of wind measurements. Not heated rain gauge is surely under sampling real precipitation in winter.
003	Refugio Zabala	Very High mountain environmental conditions. Land use is mainly bare rock with snow cover during many months. Sensors are located in the top of small construction for security and impact reasons, so some impact is expected in wind an precipitation measurements. Good representatives of temperature at 4 meters but rime might be influencing temperature measurements in winter. Not heated rain gauge, so precipitation measurements are surely under sampled in winter.
004	Cotos	High mountain site. Land use is natural pasture with tall pine trees at 100 meters. Good representatives but the site is located not in a very flat area. Local effects of catabatic cold air drainage from higher terrain is expected due to the slope. Not heated rain gauge, so precipitation measurements are surely under sampled.
005	Alameda	Good representatives of all measurements. Land use is natural grass. Even though rain gauge is not heated, under sampling might be less important due to less snow precipitation at this altitude, but needs to be taken into account in winter.

Table III. Annual average of data completeness of the stations based on availability of air temperature observations (Blue for completeness>=75%, orange for completeness <75%, and white for not fully operative). Collection method are Local that stands for in-situ downloading of data, GSM for analog GSM data collection using modem and GPRS for GPRS TCP/IP protocol using dynamic IPs. Regarding Storage, ASCII stands for individual raw files from datalogger, S. Sheet stands for spread sheets for every variable organized in years with individual validation code and SQL stands for PosgreSQL database storage.

Year	Collection method	Volume of data in bytes	Storage	Station				
				001-Ontalva	002- C.Mediana	003-Zabala	004-Cotos	005-Alameda
1999	Local	202039	ASCII		34	42		
2000	Local	722874	ASCII		98	100		
2001	Local	1015623	ASCII		96	94		
2002	Local	1698549	ASCII		83	73		
2003	Local	2198111	ASCII		63	61		
2004	Local	2850198	ASCII		84	89		
2005	Local	3613656	S. Sheet		91	85	96	
2006	GSM	4219771	S. Sheet		55	58	51	
2007	GSM	5375096	S. Sheet		66	80	56	
2008	GPRS	7510050	SQL	84	92	90	96	
2009	GPRS	9911400	SQL	88	87	88	98	21
2010	GPRS	12634429	SQL	81	100	75	95	99
2011	GPRS	15261155	SQL	95	80	83	98	88
2012	GPRS	18022734	SQL	97	93	84	99	100
2013	GPRS	20629862	SQL	100	80	79	100	82
2014	GPRS	21966337	SQL	99	77	75	99	55
Average				92	80	79	89	75

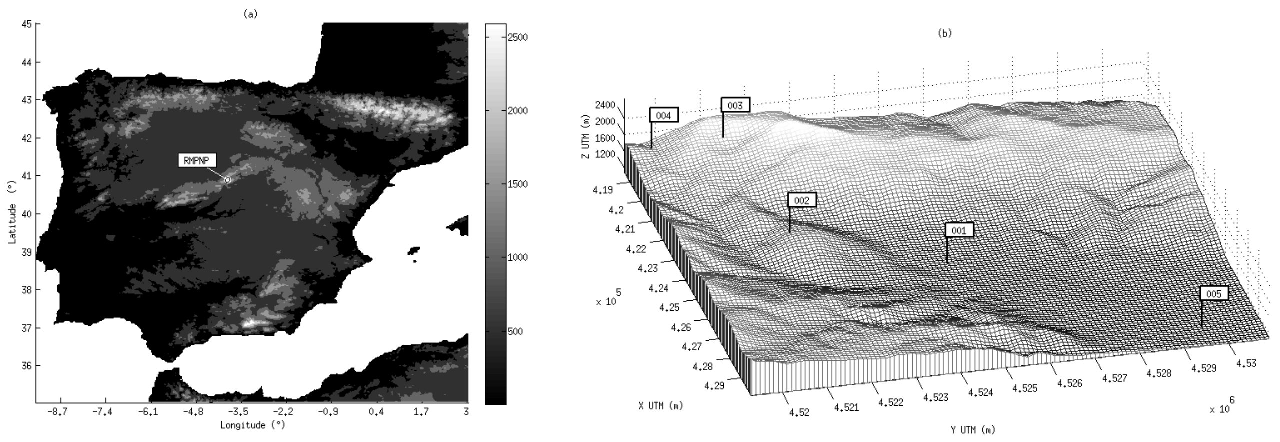


Figure 1. (a) Location of the Peñalara Natural Park Meteorological Network in Sierra de Guadarrama. (b) Location of the automatic monitoring stations.

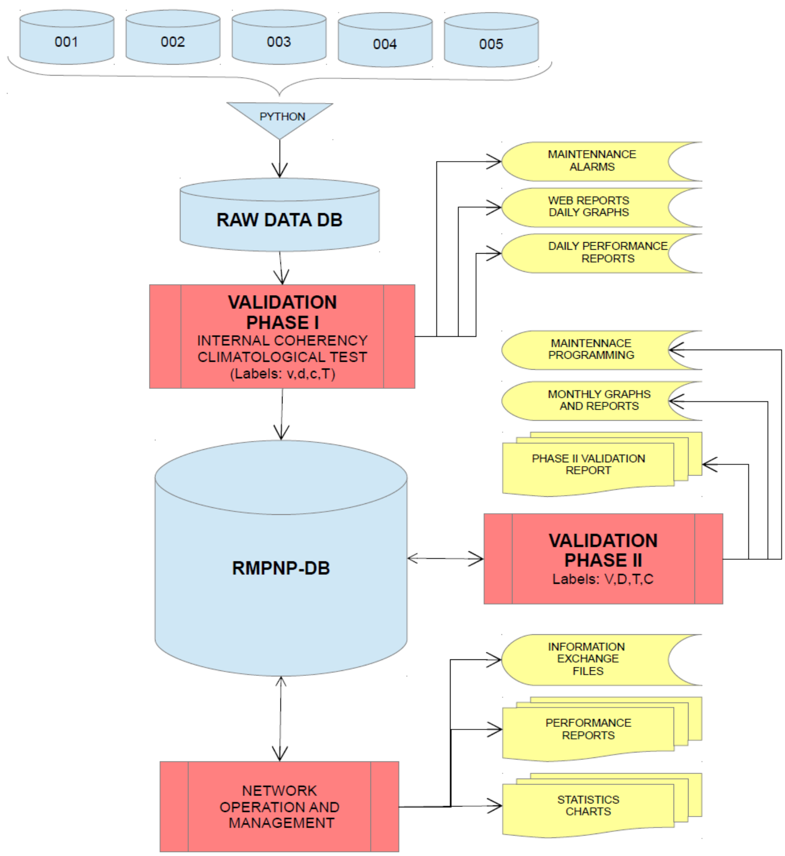
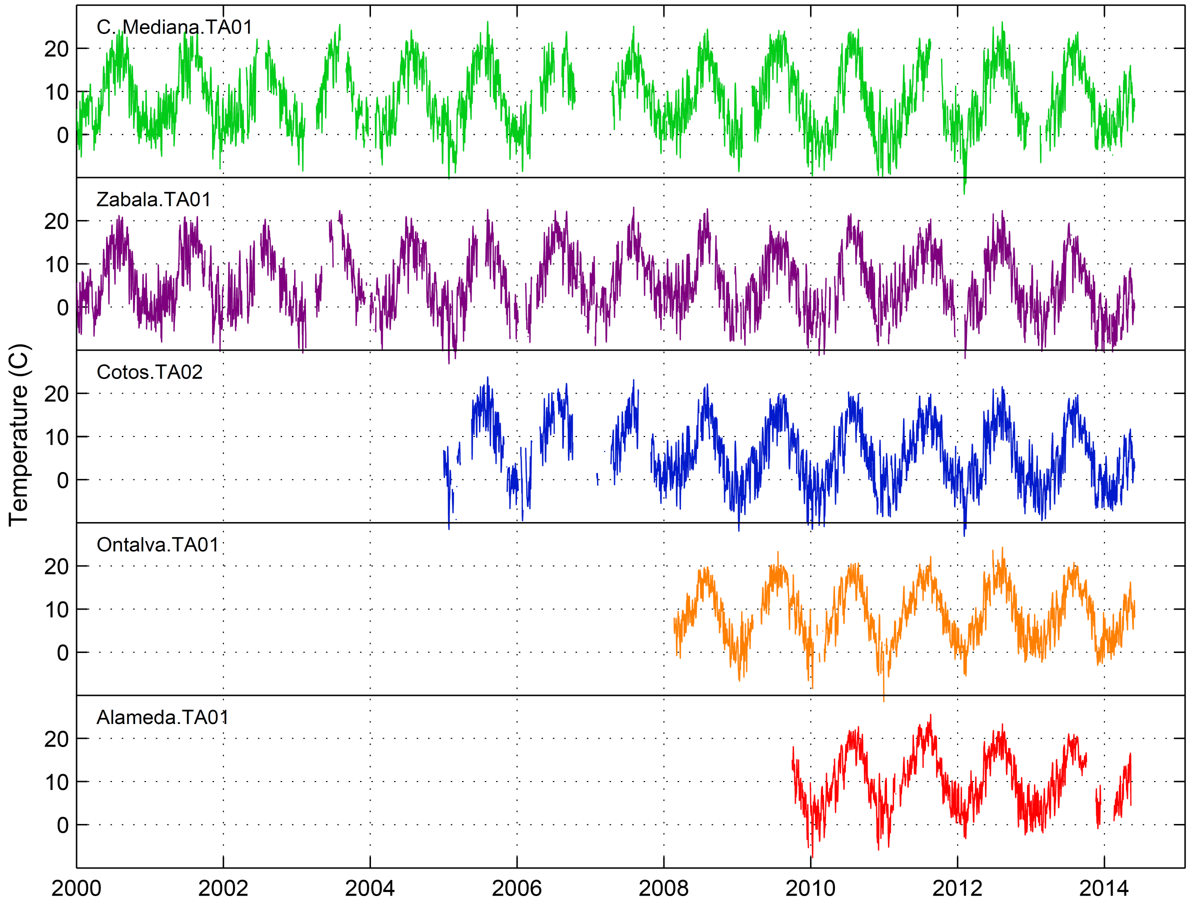


Figure 2. Flow chart of RMPNP data management and QAQC system.



577 Figure 3. Time series of air temperature at the sites from 2000 to 2014.

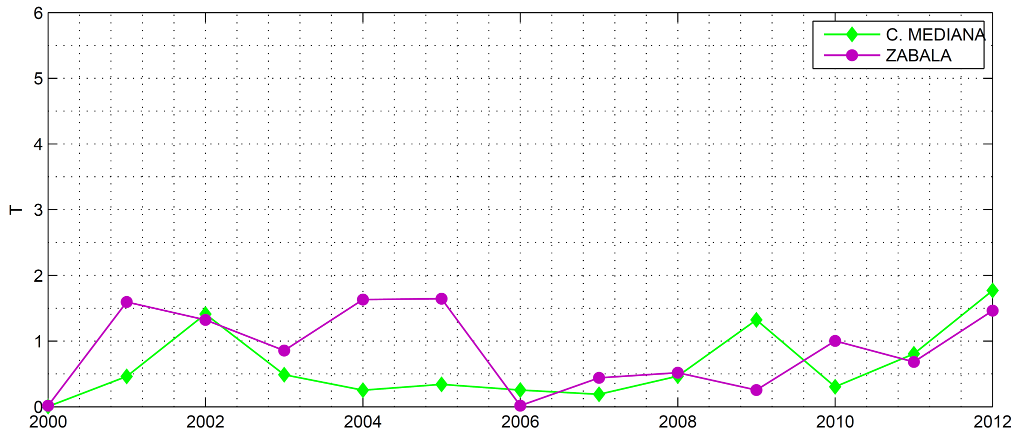
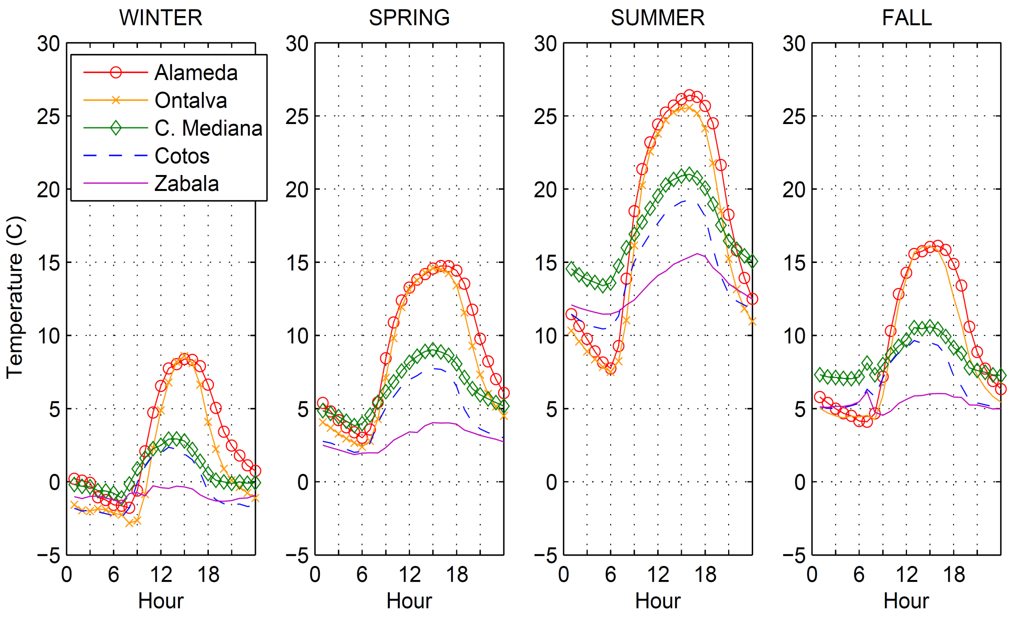


Figure 4. Values of T of an Alexandersson test for annual mean temperature observed at Cabeza Mediana and Zabala using Puerto de Navacerrada AEMET observatory as a reference station. The critical T value for 5% confidence level and 14 samples is 6.



583 Figure 5. Mean hourly temperature for every site and season. Differences between maximum and minimum

584 temperatures represent the mean seasonal temperature amplitude.

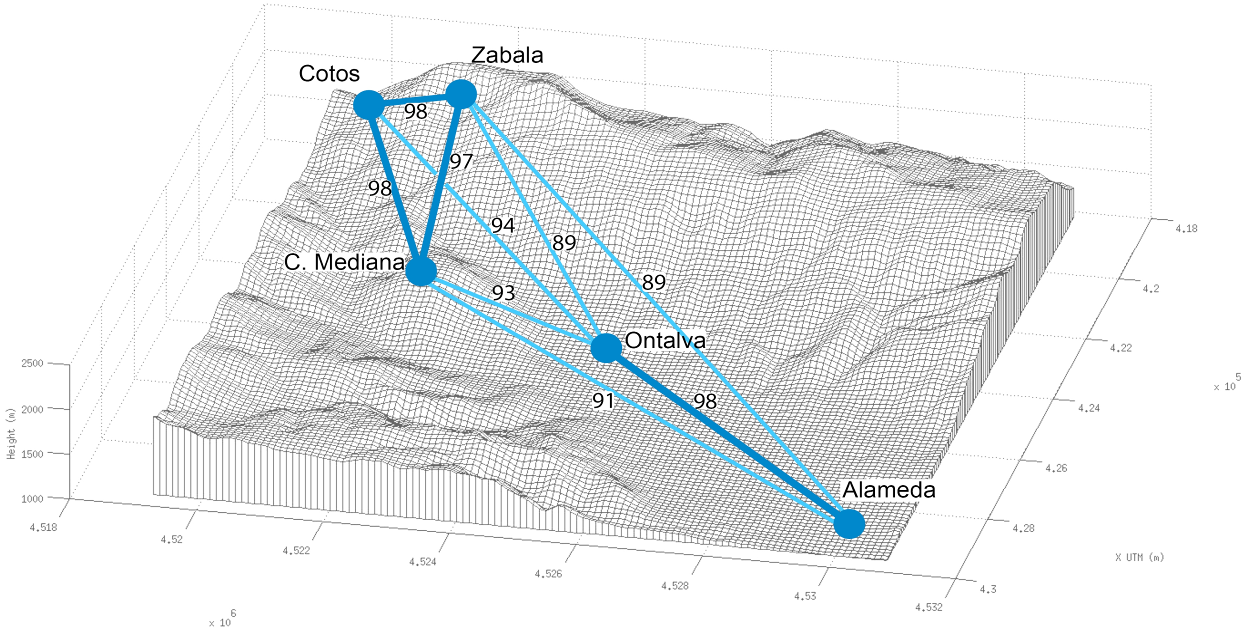
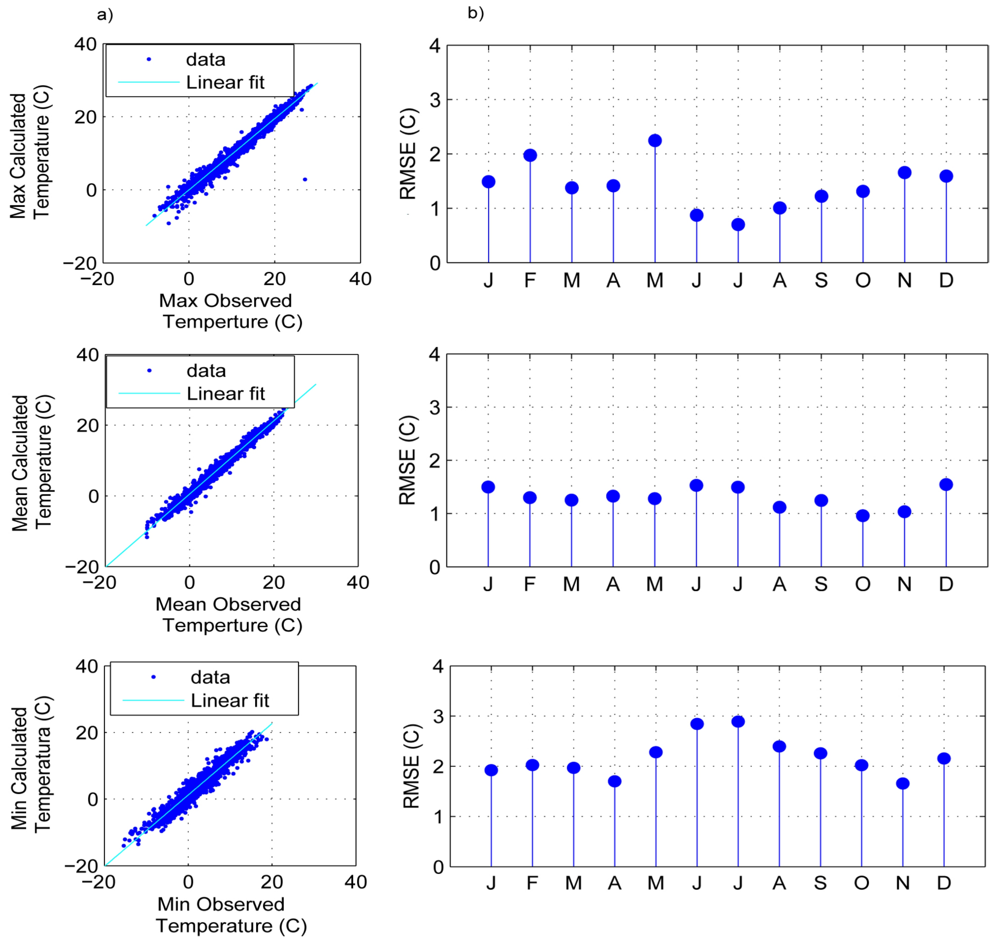


Figure 6. Correlation coefficients of air temperature 10 minutes time series between all the sites of the network. Width of the lines is proportional to the Pearson correlation factor value.



587 Figure 7. (a) Scatter plot of observed and calculated time series of daily maximum (up), average (center) and minimum (bottom) temperatures at Cotos site (b) Monthly RMSE of the calculated maximum (up), average (center) and minimum (bottom) temperatures.

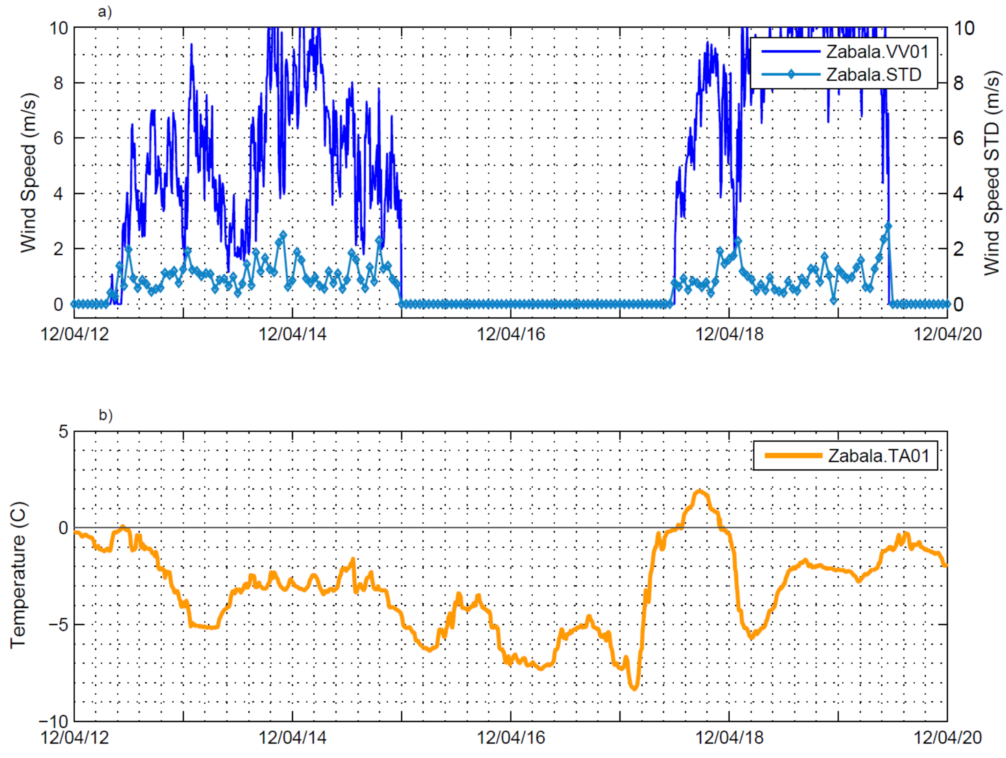
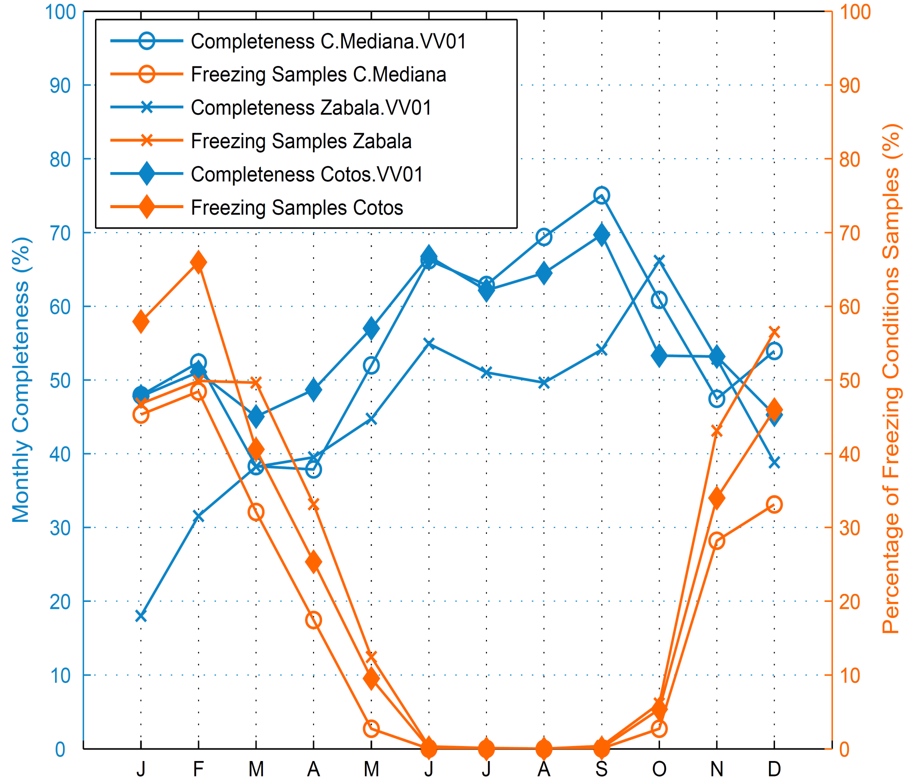


Figure 8. (a) Wind speed (Zabala.VV01) and standard deviation of wind speed (Zabala.STD) at Zabala site during a period affected by freezing rime. (b) Air temperature (Zabala.TA01) at Zabala during the same period.



593 Figure 9. Data completeness (blue) for three sites and percentage of wind speed measurements taken under
594 freezing conditions (orange).

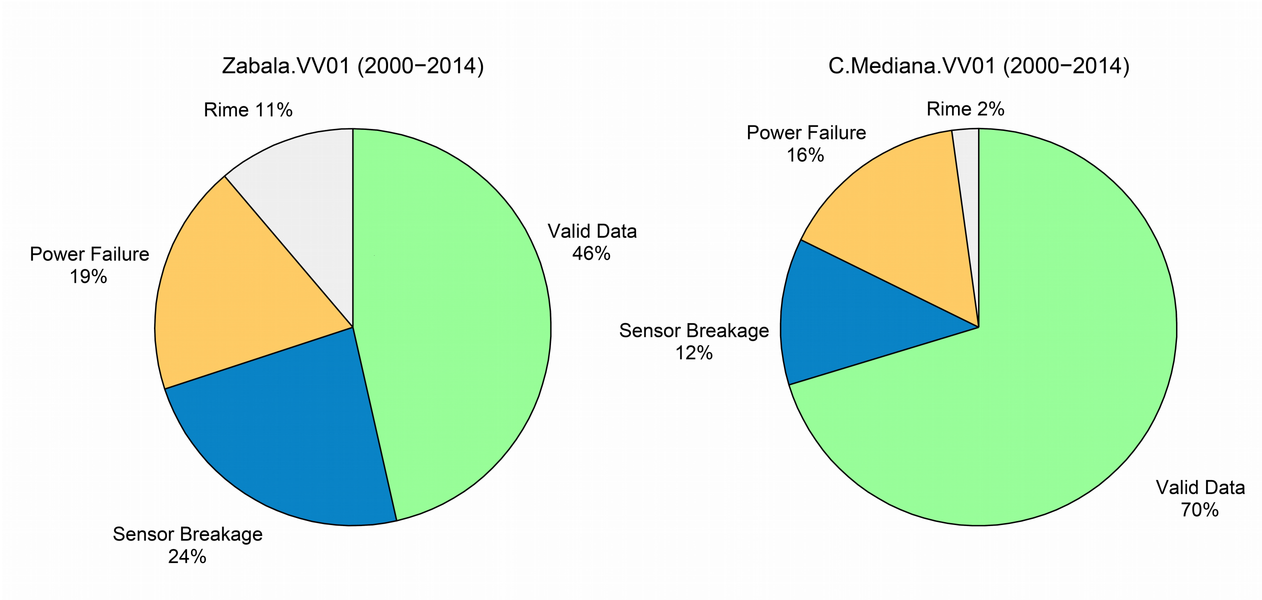


Figure 10. Percentage of factors that lead to wind speed data loss (rime, power failure and sensor breakage) and total valid data at Zabala and Cabeza Mediana sites.

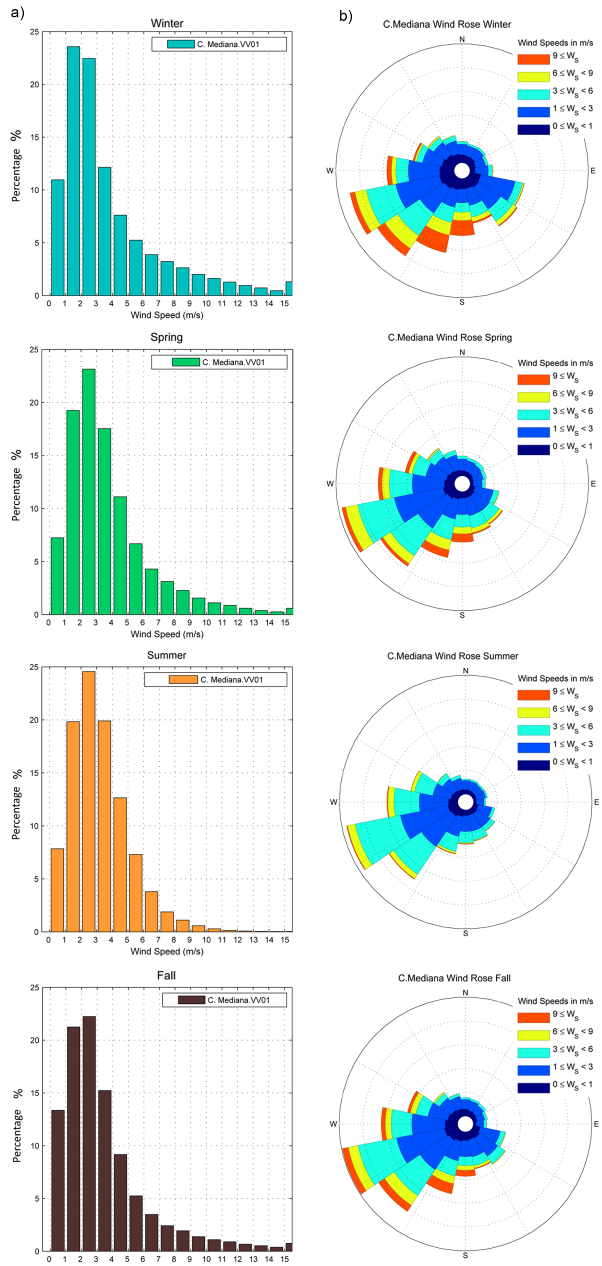


Figure 11. (a) Seasonal wind speed distribution at Cabeza Mediana for the period 2000-2014. (b) Seasonal wind rose at Cabeza Mediana for the period 2000-2014.

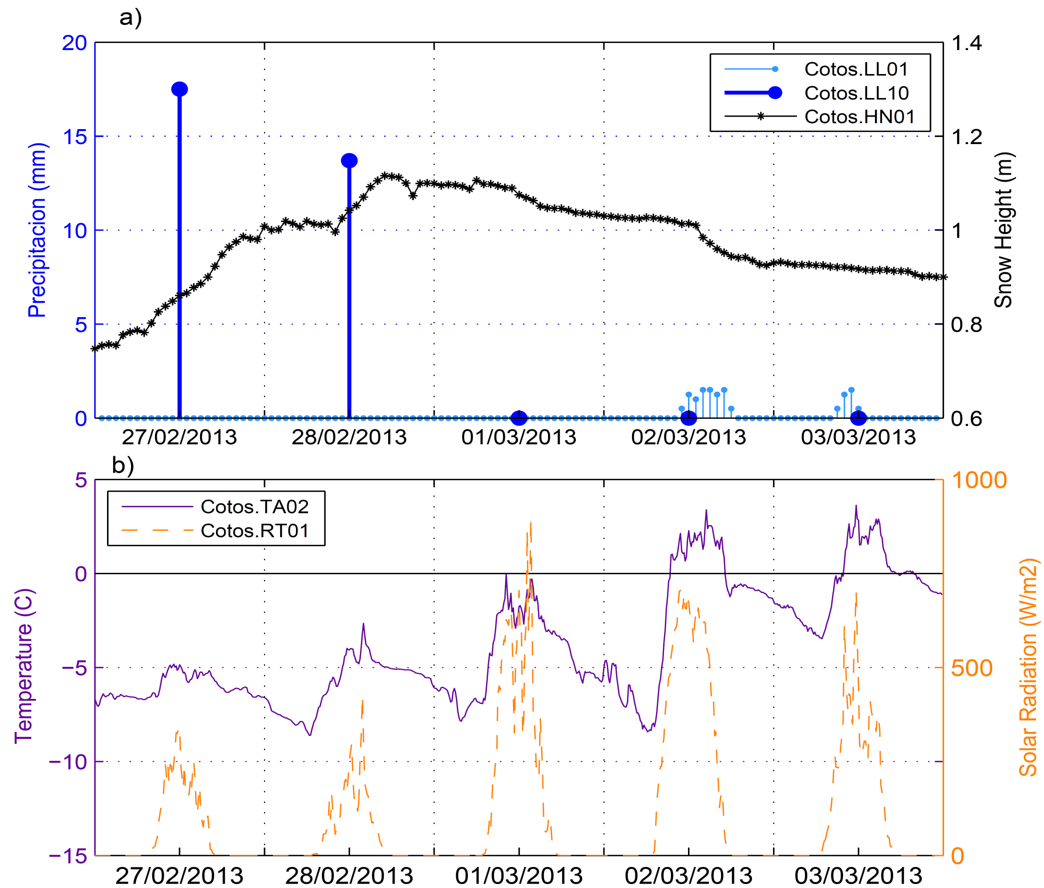


Figure 12.(a) Precipitation observed using both a manual (Cotos.LL10) and a non-heated tipping bucket (Cotos.LL01) rain gauge, and the snow height in Cotos site for the same period. (b) Air temperature (Cotos.TA02) and solar radiation (Cotos.RT01) observed at Cotos site.

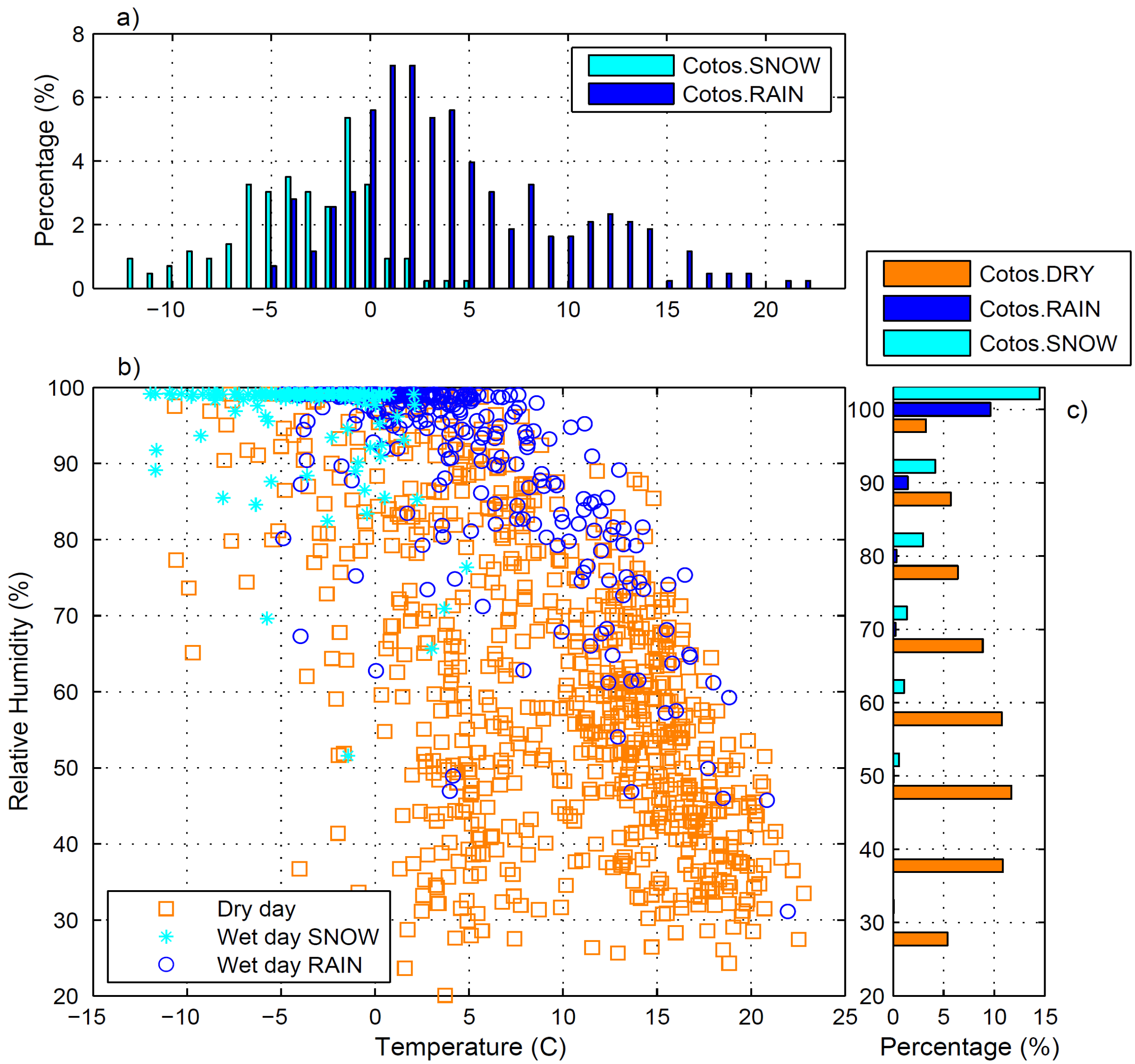


Figure 13. (a) Bar plot of rain (Cotos.RAIN) and snow (Cotos.SNOW) observed using a manual rain gauge at Cotos for different values of daily mean air temperature. (b) Scatter plot of daily relative humidity against daily temperature for days with precipitation under 1 mm (squares), days with snow precipitation above than 1 mm (asterisks) and days with rain precipitation above 1 mm (circles) at Cotos. (c) Bar plot of percentage of days with precipitation under 1mm (Cotos.DRY), days with snow precipitation (Cotos.SNOW) and days with rain precipitation (Cotos.RAIN) above 1 mm and mean daily relative humidity.

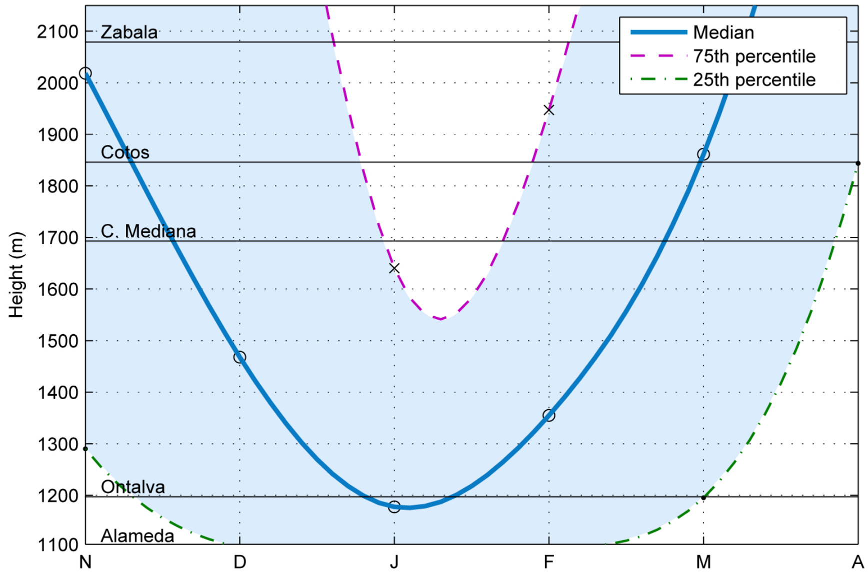


Figure 14. Median, 75th percentile and 25th percentile of elevations of the zero isotherm for winter months calculated out of the temperatures observed at all sites.

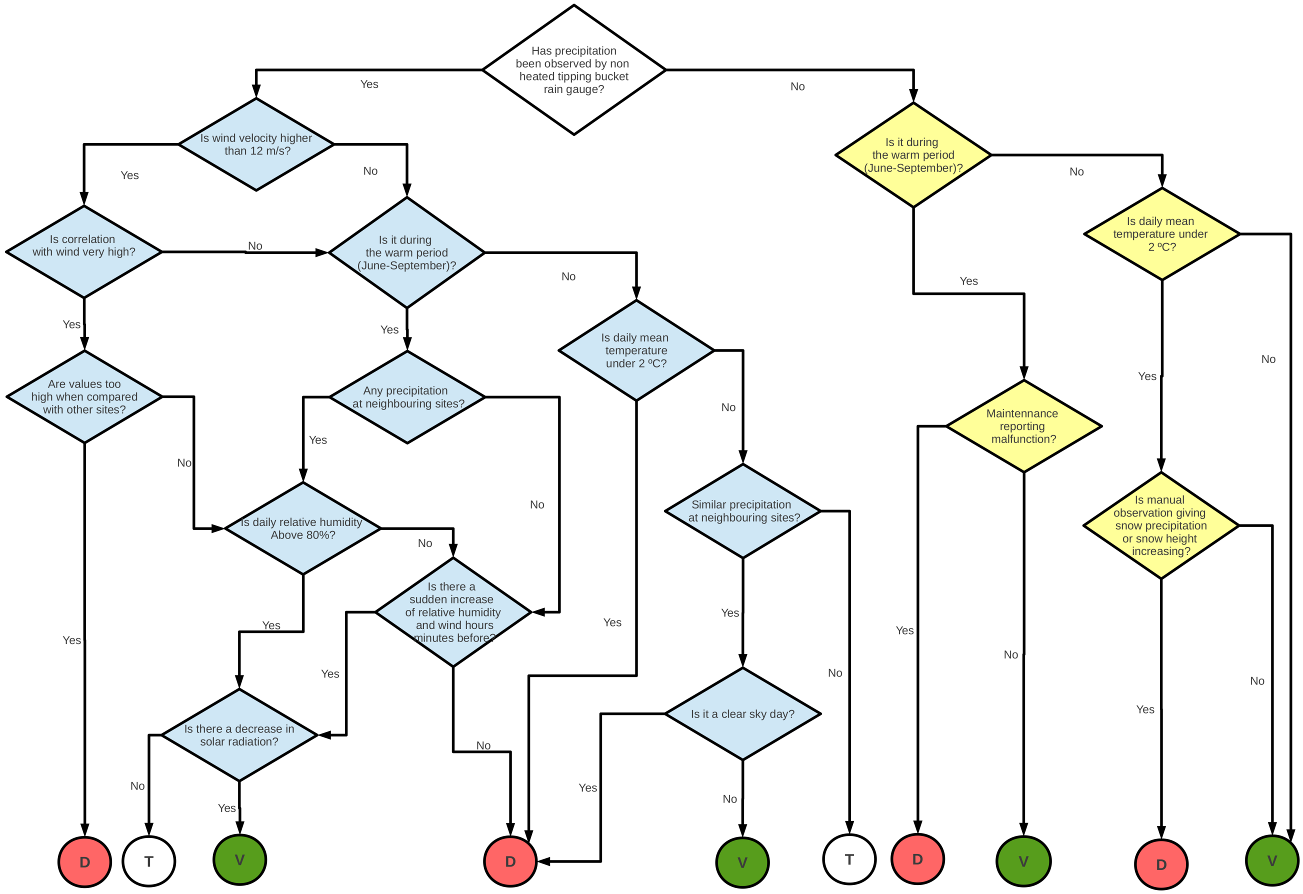


Figure 15. Guidelines for precipitation validation. “V” means data with a high probability of being valid. “D” means data with a high probability of not being valid. “T” means data with an incoherent behavior with other variables (internal consistency) or other sites (spatial consistency) and which deserve further research.

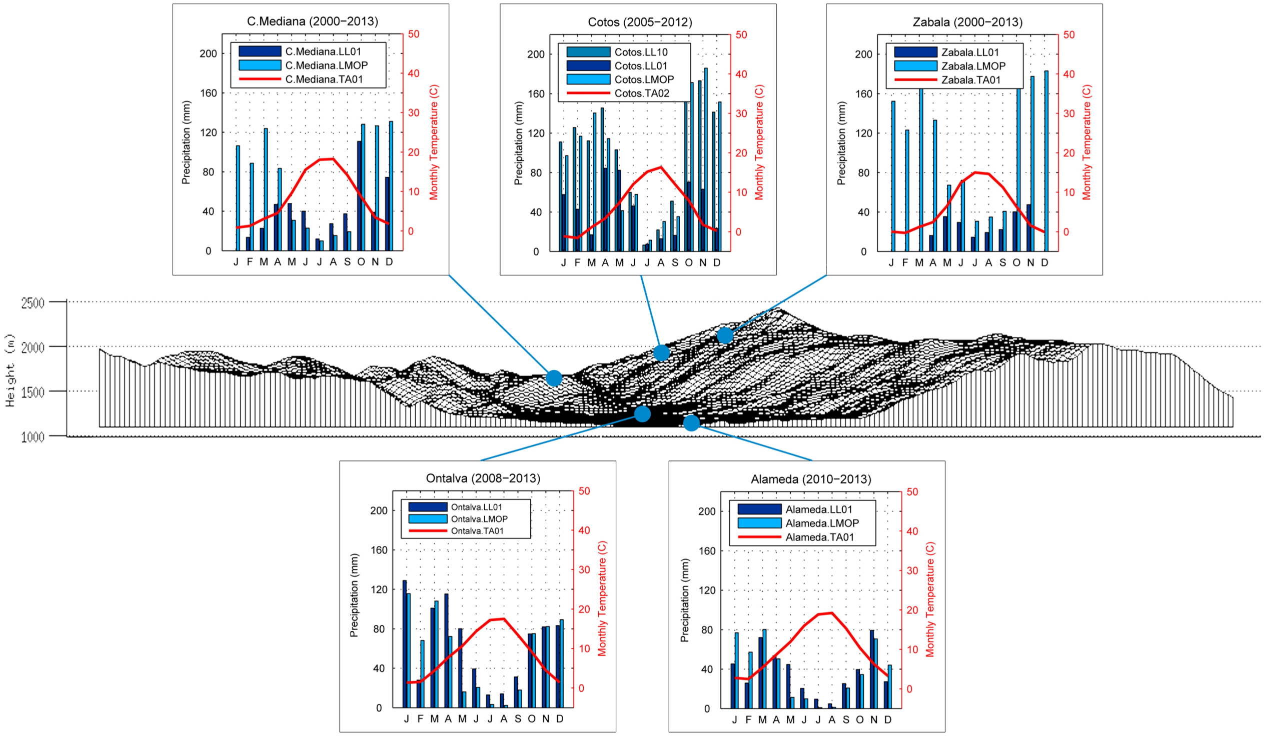


Figure 16. Mean monthly temperature (TA01, TA02) and precipitation observed (LL01, LL10) and modeled (LMOP) at all sites.