Atmos. Meas. Tech. Discuss., doi:10.5194/amt-2015-248, 2016
Manuscript under review for journal Atmos. Meas. Tech.
Published: 2 May 2016

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 conlussions that might be useful for the mountain meteorology observation community. Discussions about the representativeness of the data are shown. These are important for future users of this data base. Also some basic statistics of the available data is 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.

As done at 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

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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 this lack of reliable and long meteorological observations at mountains. Can be mentioned: 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 only representative of a very small area. This requires a higher density of stations than in lower elevations.

Meteorological observation at mountains has shown to be very challenging, not only from the technical point of view, also for humans conducting the observations. The very specific conditions of mountain environments make their ecosystems excellent indicators of climate change, whether or not the variations are due to internal climate variability or anthropogenically induced (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).

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 the 2000 masl of scientific quality and with a long term horizon in the Iberian Peninsula. Since then, other four automatic meteorological stations have been installed along with other measurement points. Now, this is fully operative mountain meteorological network (the *Red Meteorológica del Parque Natural de Peñalara,* RMPNP hereafter) (Figure 1.b).

The next sections outline some concepts taken into account during its design, installation and operation of this network. Some results and discussions about the representativeness of the data is also included. Technical and operational procedures that are described can be helpful for the mountain meteorology observing community and future mountain networks planned in this area (Rath 2012; Rath et al., 2014; Santolaria-Canales et al., 2015). This works pretends also to be a reference document for future users of the RMPNP data base users.

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 and the quality assurance program. A complete description of the sites and some discussions about the representativeness of the data is included. Next are the results obtained after more than a decade of field work that pretend to be a framework for future analysis when more data will be available. 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 sitting 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

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time, averaging time), exposure (macro-scale and micro-scale sitting 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 of 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. This is one of the most added values of mountains from a meteorological and climatological point of view, but for a meteorological network, it is the main source of errors. Difficulties start during the installation process, since it complicates logistics and reduces the options of materials and structures to be potentially used. It also affects negatively the frequency of the maintenance procedures and increases the vulnerability of the instruments to the elements, animals or vandalism acts. It also reduces the telecommunication options, something that turns crucial for this kind of unattended networks. Remote sites usually do not have power available for powering the electronic systems or for heating the sensors. Remoteness has the highest impact on the final cost of these kind of networks.

ii. Extreme environmental conditions. Low temperatures 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 its representativeness. 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, can affect temperature measurements, due to reflection when using regular solar radiation shields, and giving higher readings than real. Snow and rime are also a difficult problem to overcome since they can affect the observations when deposing 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

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down towers, 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 mountains 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 masl to 2079 masl. Since highest point of the area is 2414 masl, this makes an average of one site per 260 m of altitude. Density of stations is higher at higher altitudes.

iii. Sitting 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 save 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. Also sustainability of the network need 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 reporting. 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 mostly 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 this 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. This is the process that decides 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 in order to detect outliers and very clear malfunctions. The purpose of this phase is to trigger alarms for maintenance and to filter out suspicious data that will be reported online to general public in graph form or to special

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users that require an almost online information. Climatological site specific thresholds are used and internal consistency checks are performed in this phase. A second level validation process is performed once a year and can be repeated indefinitely when more information and know-how is acquired. Spatial coherence checks using information from neighboring stations and data from other networks or reanalysis are made once every three months. Also long term drift tests are programmed when time series are long enough. After this phases are concluded, data is individually tagged with the following codes: V: valid data, D: not valid data, C: corrected data and T: temporal not validated data. Once data is validated, it is ready for exchanging with scientific groups and other users of this data base.

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 (Table III) 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, general 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 the 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). Also a manual observatory of temperature and precipitation has been established at 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 specific applications. Also, some discussions about the representativeness of temperature, wind and precipitation data is shown and some comments on the rest of the variables are briefly discussed.

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 is tried to be as much representative as possible, 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 a height of 2079 and 1691 masl 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 suffer 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 online 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.

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. At the beginning this was 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 stored trough the years (Table III). The solution was found using PosgreSQL data base environment, this brought new possibilities that saved 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.

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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 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 with Zabala and C.Mediana temperature data sets for the period 2000-2014. As reference station a less than 10 km distant temperature observatory belonging to the Spanish Meteorological Agency has been used. Puerto de Navacerrada (1893 masl) observatory uses professional staff and follows standardized observation methods. Since this observatory is operated by independent staff from RMPNP and uses a completely different method of measurement, 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 ground level to rising 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. The difference between maximum and minimum temperature is a good estimator of the mean daily temperature amplitude and the differences between adjacent sites can be considered as a mean lapse rate. This figure shows how the temperature amplitude decreases with height, as expected due to a lower influence of the soil, with bottom valley sites showing higher amplitude. This decoupling is producing some episodes of temperature inversion, specially during the first hours of the day.

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 inviting for a more sophisticated method. Whether or not these errors are acceptable for future users of this data base depends on the application since there are other more sophisticated methods to do this (Henn et al., 2013).

3.2 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 as long 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 looses 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 loose functionality. Since this is a winter phenomena, 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 height and for all seasons. Also number of wind measurements taken under freezing conditions is 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 showing the percentage of valid data and gaps produced either by a 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 Gudarrama 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).

3.3 Representativeness of Precipiation Time Series

Regarding precipitation, this magnitude 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 an 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 need special attention

Figure 13 .b shows a scatter plot of days with precipitation below 1 mm (orange) and days with snow (light blue) and rain (dark blue) precipitation over 1 mm and mean daily relative humidity and mean air temperature observed at Cotos using a manual rain-gauge and data from the nearby automatic station. It is clear how precipitation occurs normally with mean daily relative humidity values higher than 80%. This fact makes measurement of relative humidity relevant for precipitation data validation (Figure 13.c). This fact has been used to build a precipitation validation algorithm. Higher refinements of this algorithm are expected to be done in the future discriminating between seasons and hour, since relative humidity follows a clear daily cycle.

Some precipitation events with low mean relative humidity have been found related with 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.

Finally, in an attempt to evaluate the impact of using non-heated tipping-bucket rain gauges for measuring precipitation at Guadarrama a comparison between manual and automatic methods used at Cotos has been performed. Figure 14 shows the relationship found between the monthly differences between the two methods and the number of hours per month with saturating conditions (relative humidity over 80%), and near freezing temperatures (air temperature under 5ºC), as an estimator of potential snow conditions. A significant linear relationship between the automatic sensor underestimation and the number of hours potentially having snow precipitation have been found. This relationship could be used to estimate the amount of underestimated precipitation at other close locations that use the same rain-gauge or in the validation process.

In order to show if this effect is relevant for the rest of the sites, the mean zero isotherm has been calculated using temperature and height of the sites. Figure 15 shows how during winter, partly fall and spring months most of the sites, except Ontalva and Alameda, have average freezing temperatures. The precipitation underestimation is potentially occurring at most of the observatories and that observations should be used with precaution during winter, spring and fall.

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 is feasible but there are important factors that affect representativeness, including data completion, which are strong 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 has 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 masl on the bottom of the valley to 2079 masl 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 execute almost online and useful for online 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.

Temperature and relative humidity automatic measurements have shown to be very robust. Even though there have not been found indications of serious interferences, some aspects might need further investigation probably 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.

Radiation measurements have shown to be very robust and useful for data validation. Nevertheless not a practical solution has been found in order to guarantee that the sensor is not blocked totally or partially by snow or ice. Probably the use of four component radiometers might help to identify icing conditions.

Non-heated tipping bucket rain gauges do not record precipitation under 5ºC. 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.

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.

Aknowledgements

This network would have never exist without the funding and support of the Peñalara Natural Park authorities. Also field work would have never be done without the extraordinary help of its staff who actively took part of some the observations used here and helped on the maintenance and surveillance of the network through all these years.

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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 (masl)	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
003	Refugio Zabala	40º50'20''N 3º57'1'' W (Rascafría, Madrid)	X: 419300 Y: 4521330 Z: 2079	2008	PA01	Atmospheric pressure 1.75m (hPa)	NovaLynx
				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
004	Cotos	40º49'31''N 3º40''' W (Rascafría, Madrid)	X: 418955 Y: 4519800 Z: 1857	2008	PA01	Atmospheric pressure 2m (hPa)	NovaLynx
				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

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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.

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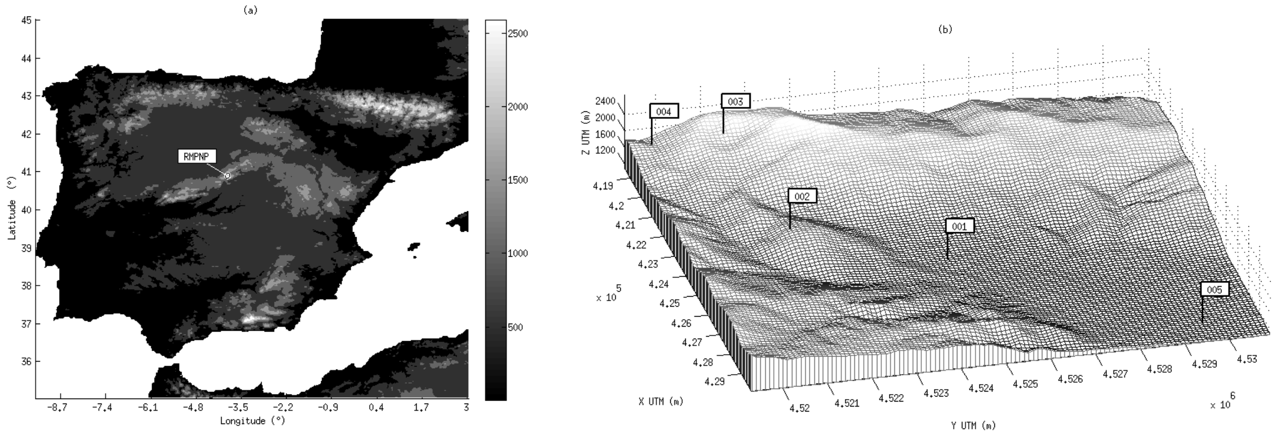
Table III. Annual average of data completeness of the stations based on availability of air temperature observations (Blue for completeness>=75%, orange for completeness <75%, and white for not fully operative). Collection method are Local that stands for in-situ downloading of data, GSM for analog GSM 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



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

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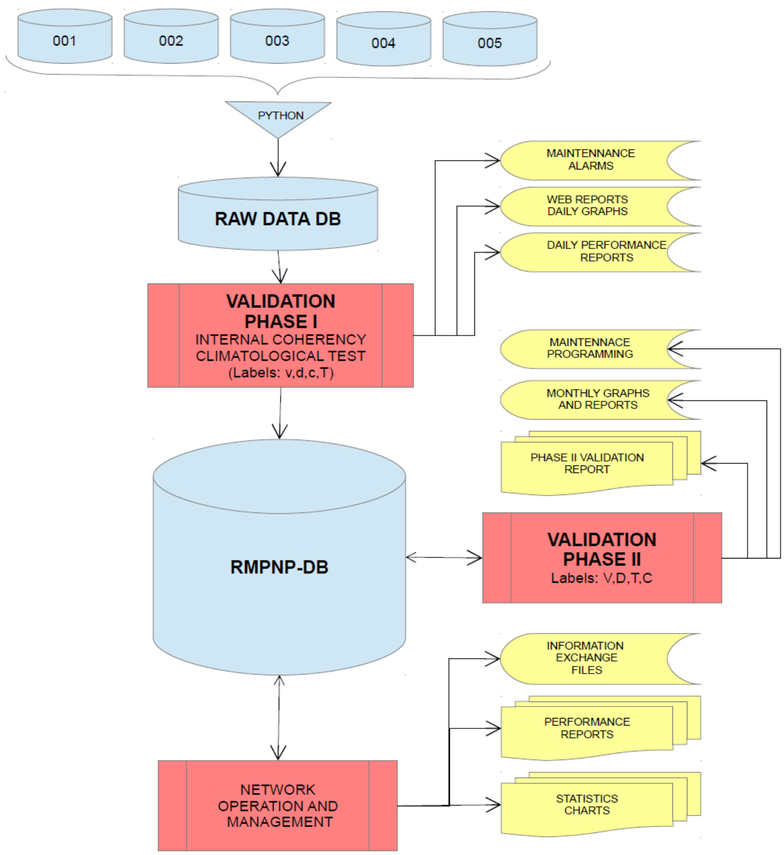

577 Figure 2. Flow chart of RMPNP data management and QAQC system.

578

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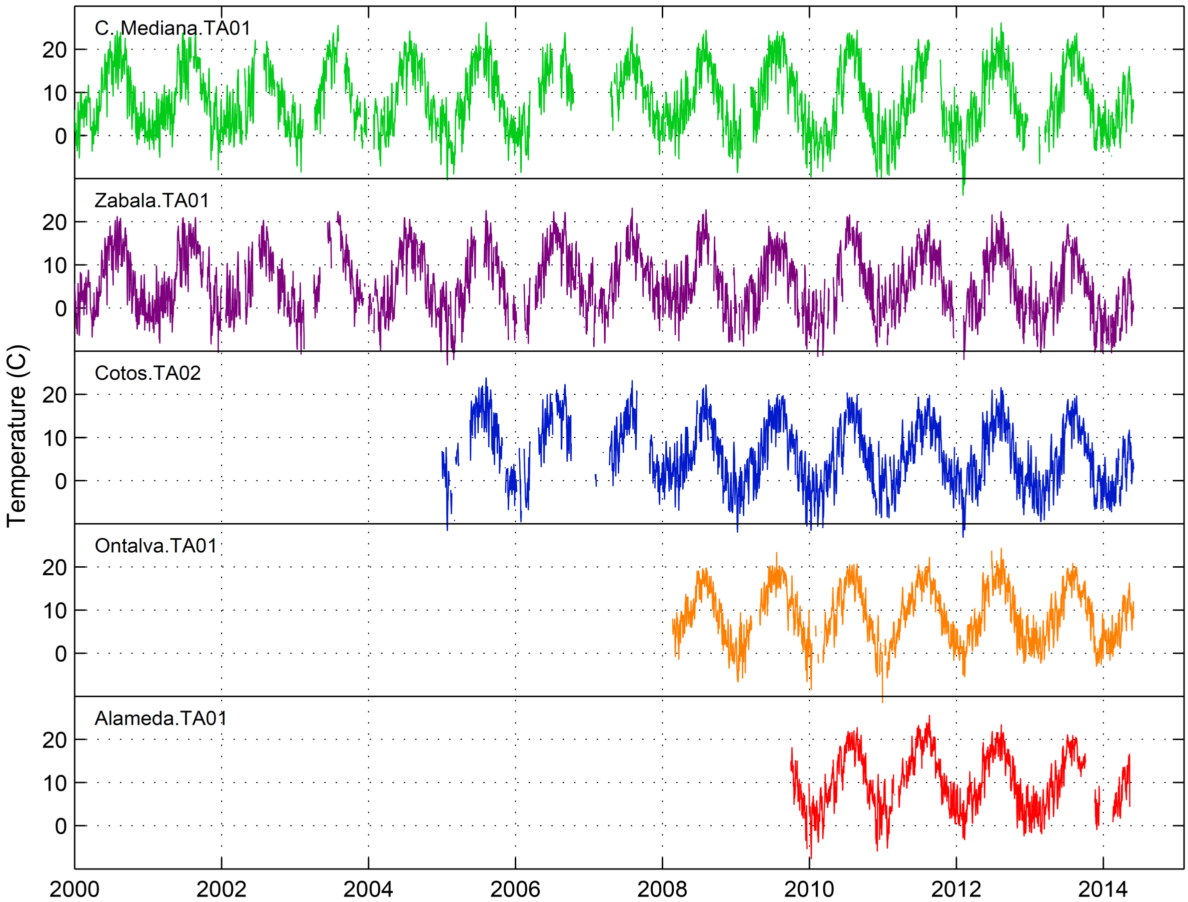

579 Figure 3. Time series of air temperature at the sites from 2000 to 2014.

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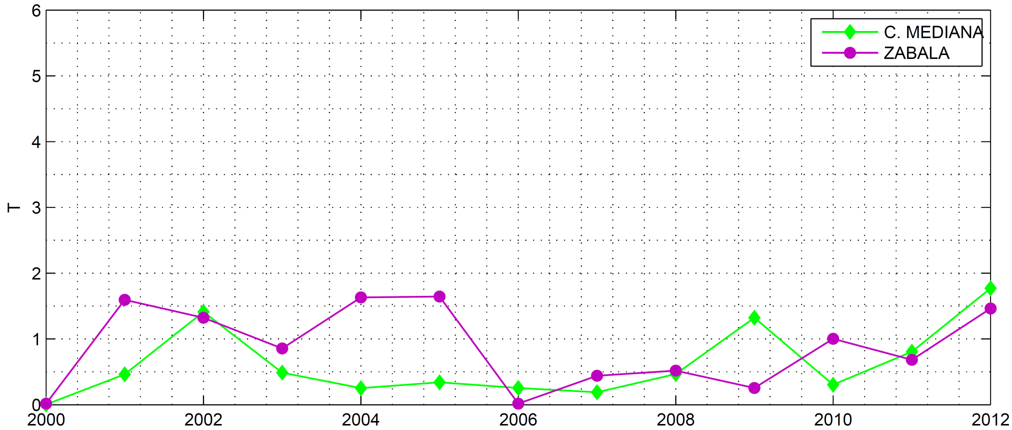

581 Figure 4. Values of T of an Alexandersson test for annual mean temperature observed at Cabeza Mediana and
582 Zabala using Puerto de Navacerrada AEMET observatory as a reference station. The critical T value for 5%
583 confidence level and 14 samples is 6.

584

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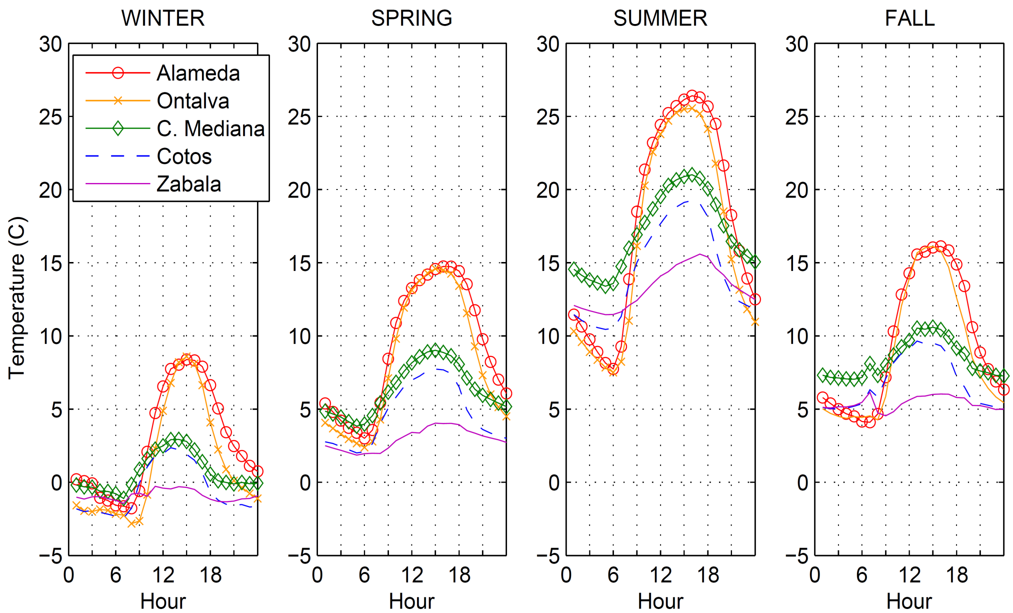

585 Figure 5. Mean hourly temperature for every site and season. Differences between maximum and minimum
586 temperatures represent the mean seasonal temperature amplitude.

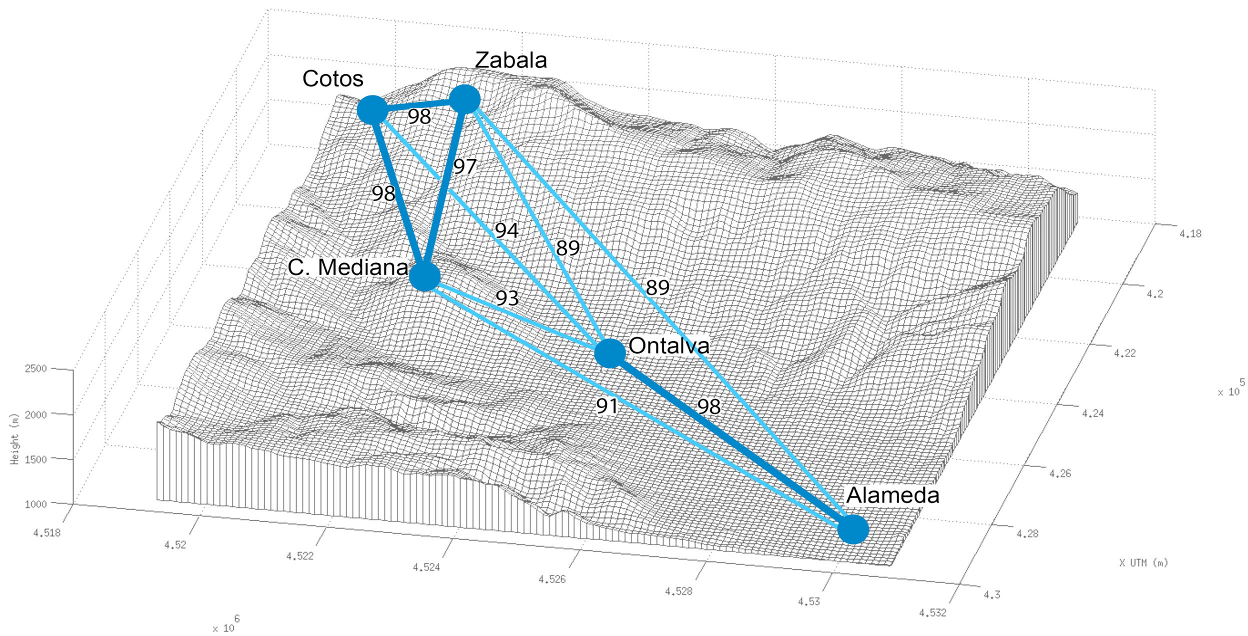

Figure 6. Correlation coefficients of air temperature 10 minutes time series between all the sites of the network. Width of the lines is proportional to the Pearson correlation factor value.

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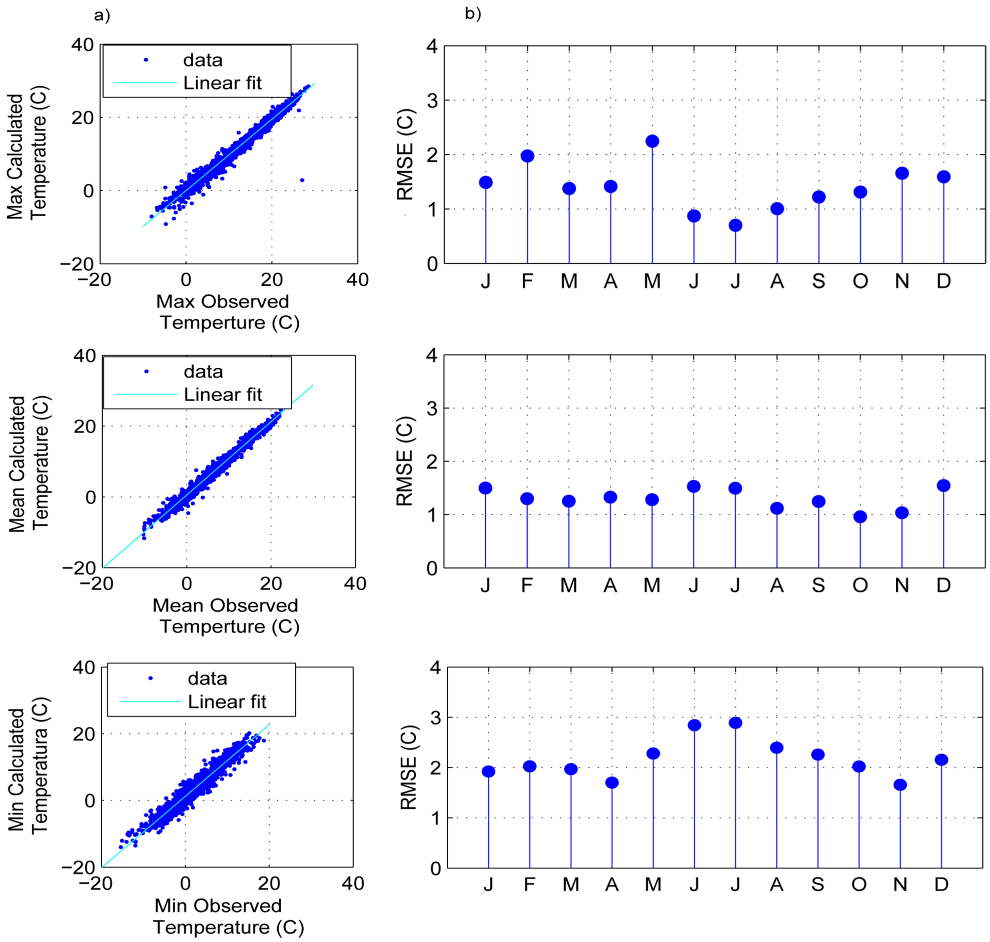

Figure 7. (a) Scatter plot of observed and calculated time series of daily maximum (up), average (center) and minimum (bottom) temperatures at Cotos site (b) Monthly RMSE of the calculated maximum (up), average (center) and minimum (bottom) temperatures.

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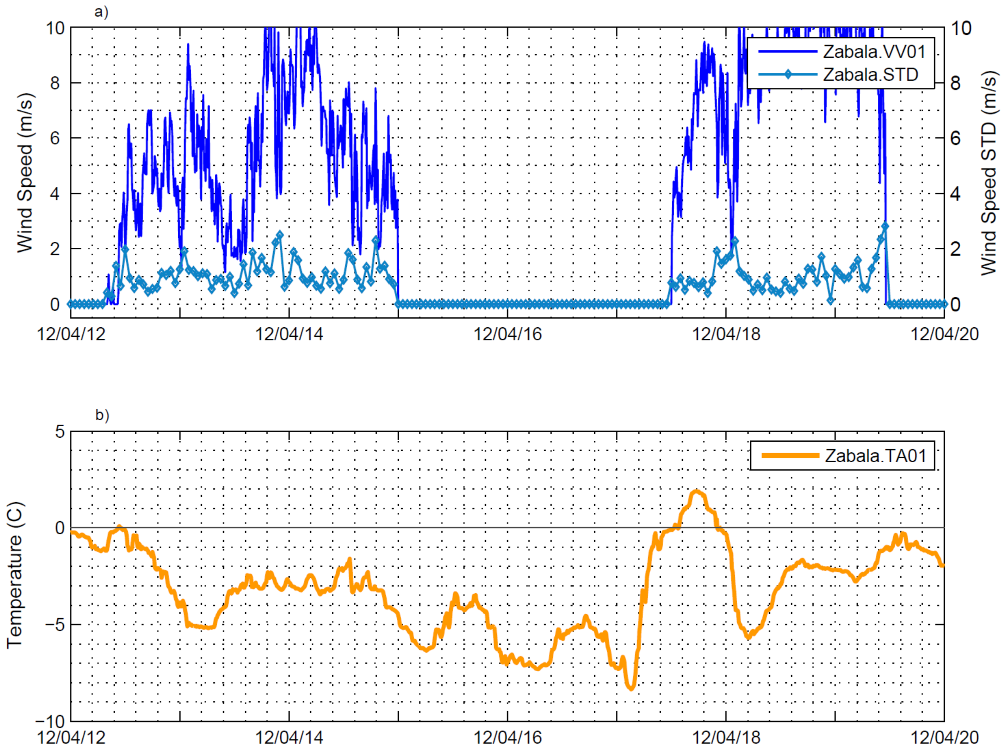
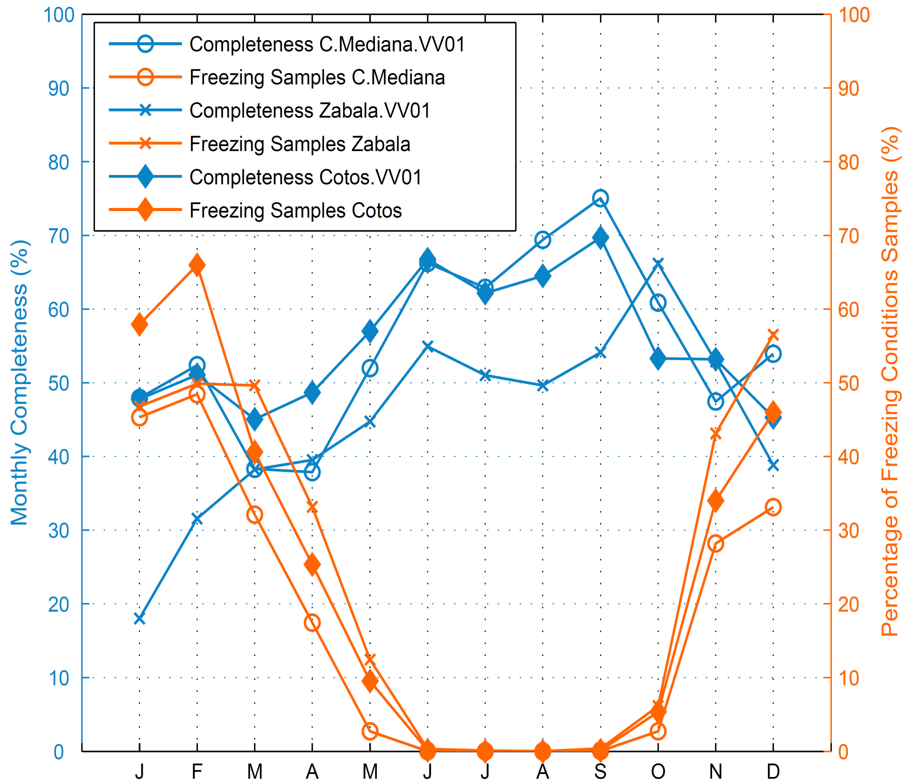
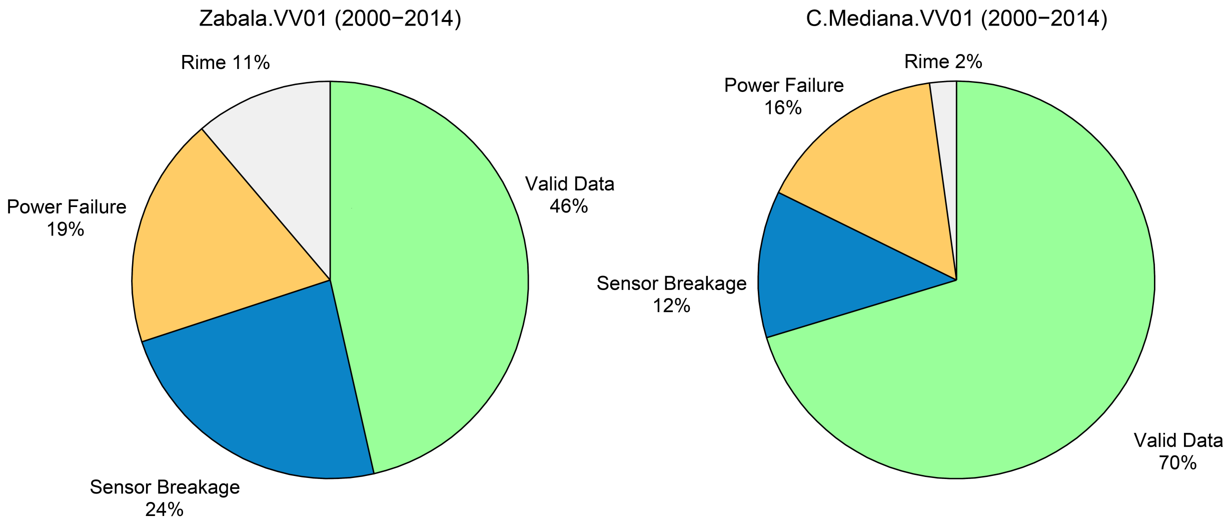


593 Figure 8. (a) Wind speed (Zabala.VV01) and standard deviation of wind speed (Zabala.STD) at Zabala site
594 during a period affected by freezing rime. (b) Air temperature (Zabala.TA01) at Zabala during the same period.



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



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

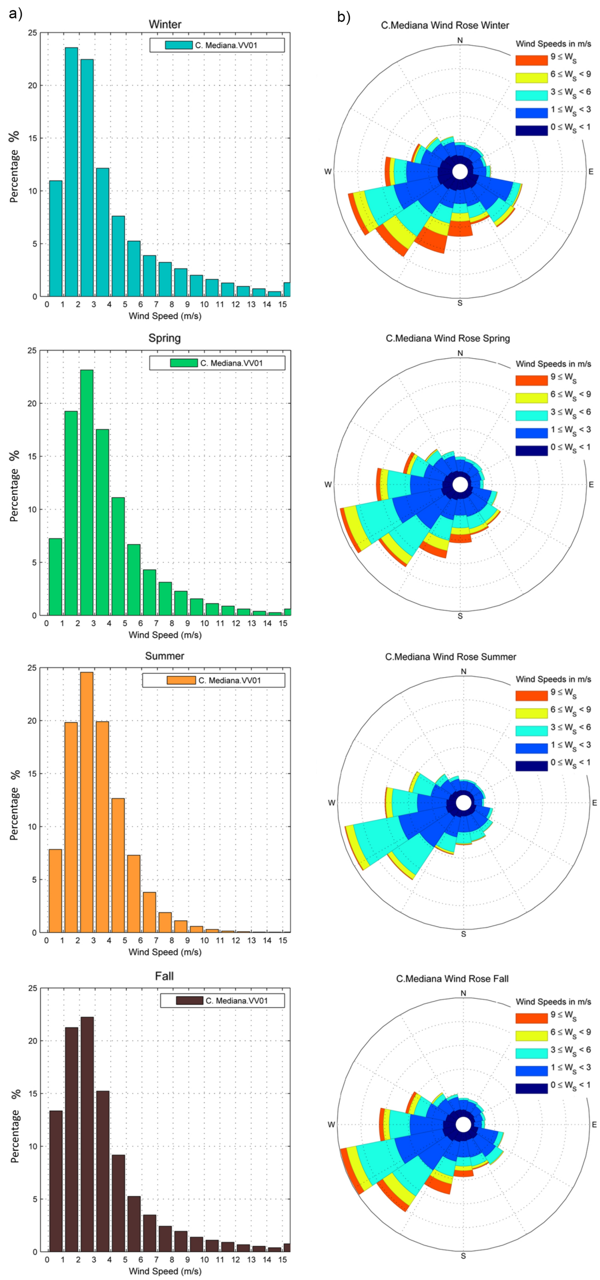


Figure 11. (a) Seasonal wind speed distribution at Cabeza Mediana for the period 2000-2014. (b) Seasonal wind rose at Cabeza Mediana for the period 2000-2014.

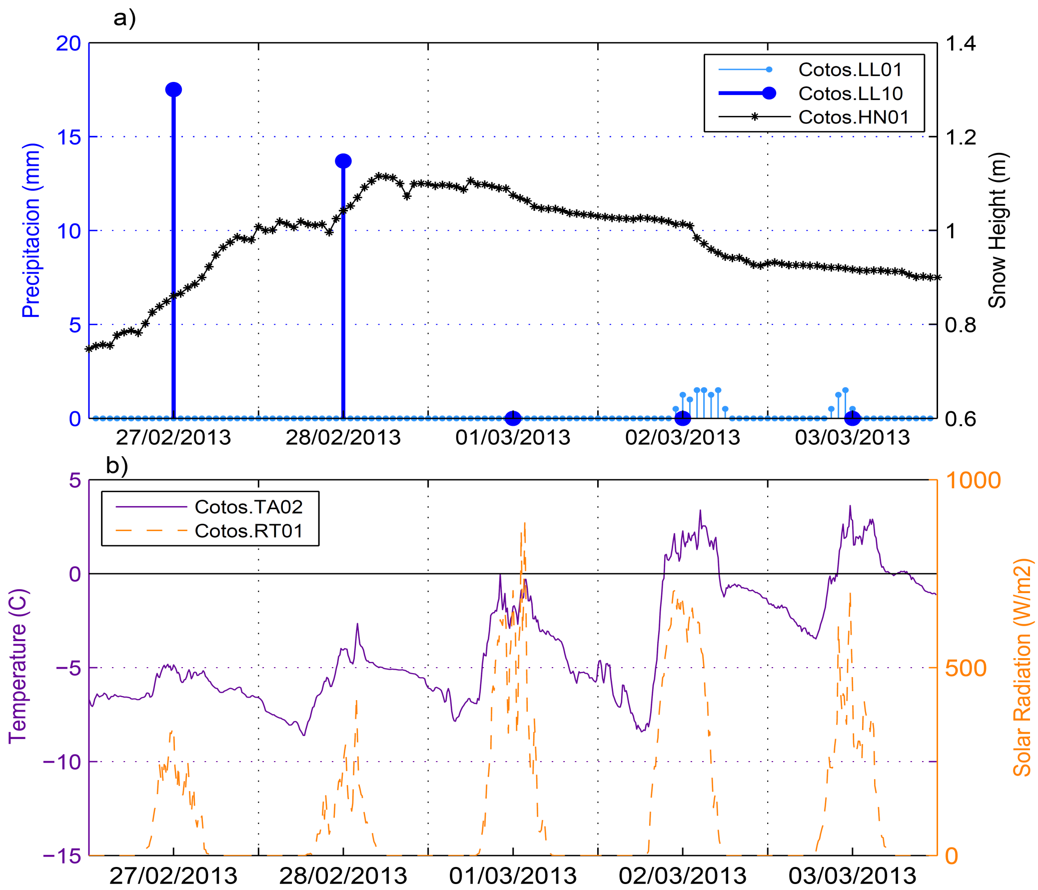


Figure 12.(a) Precipitation observed using both a manual (Cotos.LL10) and a non-heated tipping bucket (Cotos.LL01) rain gauge, and the snow height in Cotos site for the same period. (b) Air temperature (Cotos.TA02) and solar radiation (Cotos.RT01) observed at Cotos site.

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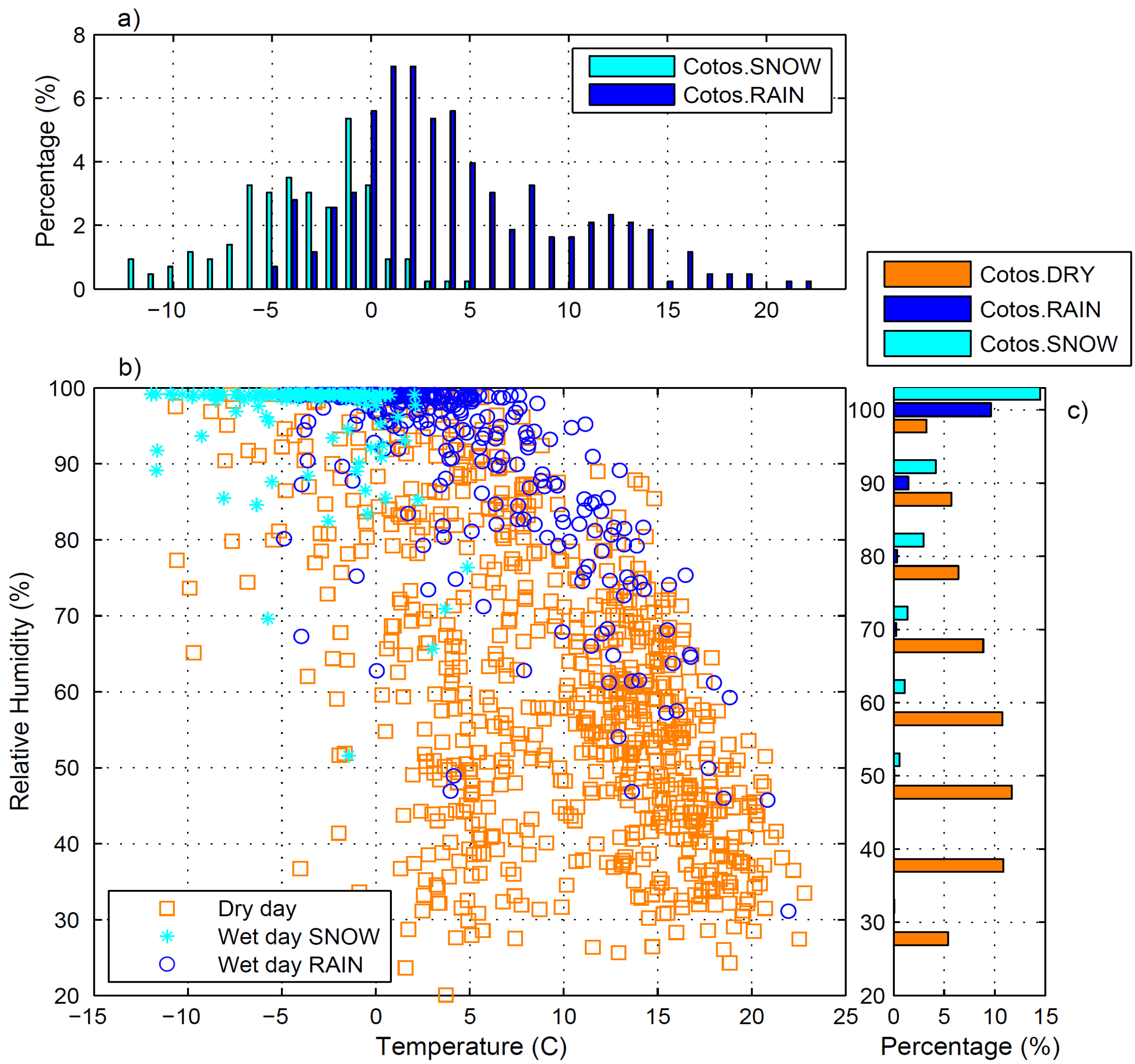

Figure 13. (a) Bar plot of rain (Cotos.RAIN) and snow (Cotos.SNOW) observed using a manual rain gauge at Cotos for different values of daily mean air temperature. (b) Scatter plot of daily relative humidity against daily temperature for days with precipitation under 1 mm (squares), days with snow precipitation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

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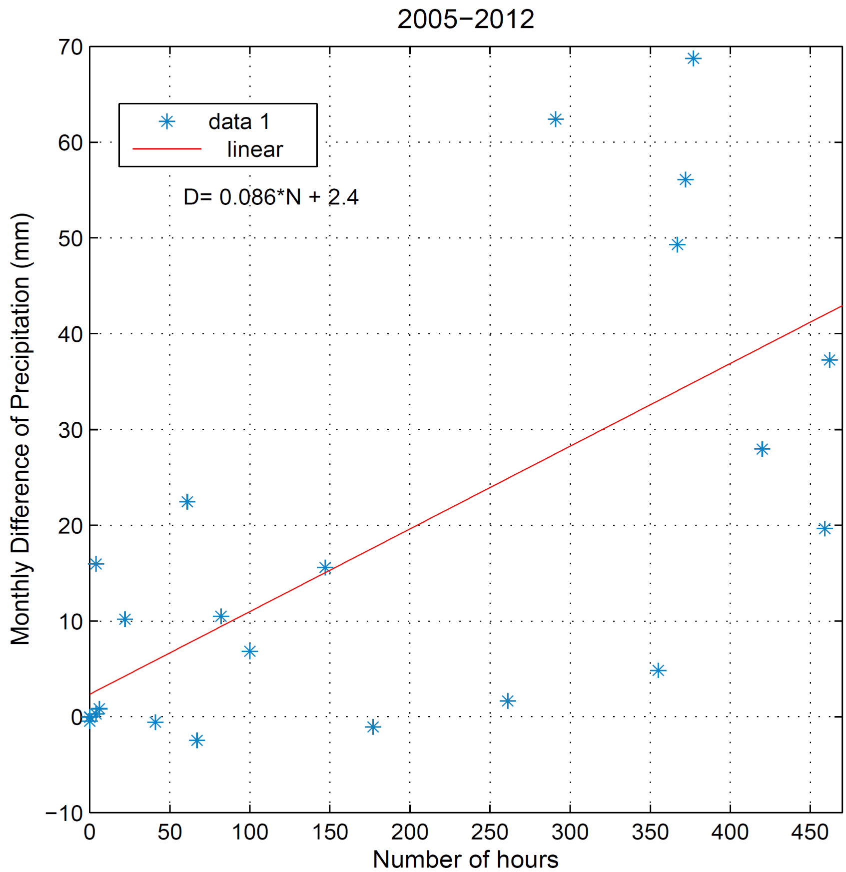

614 Figure 14. Relationship found between the monthly precipitation differences between a manual and a non-heated
615 tipping bucket rain gauge and the number of hours per month with relative humidity over 80% and air
616 temperature below 5ºC (snow precipitation conditions).

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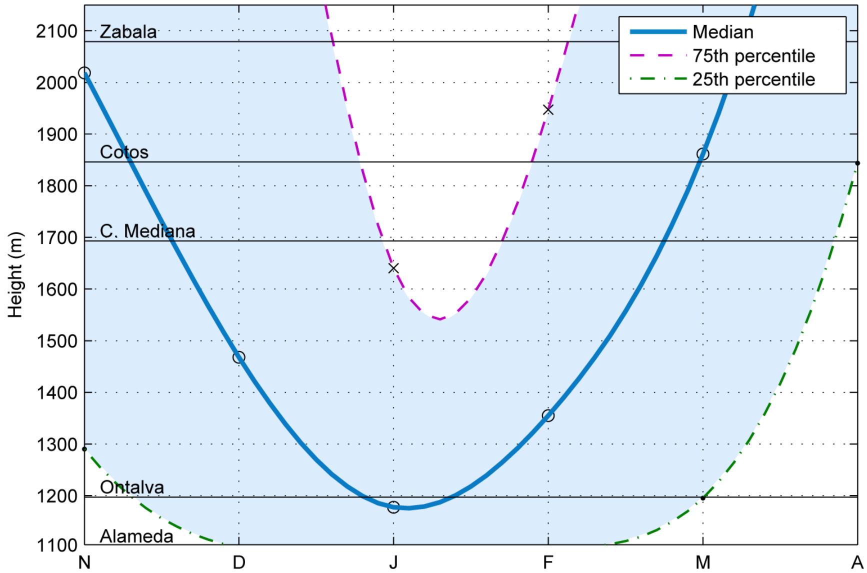

617 Figure 15. Median, 75th percentile and 25th percentile of elevations of the zero isotherm for winter months
618 calculated out of the temperatures observed at all sites.

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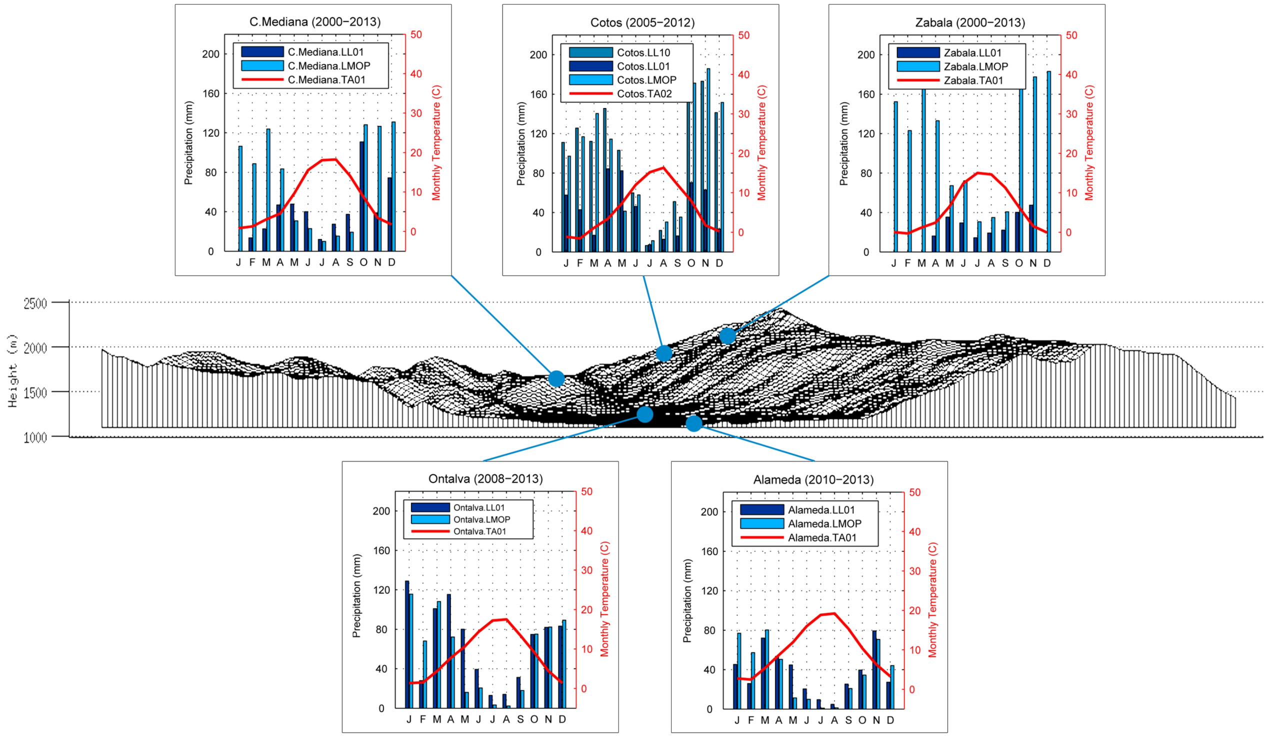

620 Figure 16. Mean monthly temperature (TA01, TA02) and precipitation observed (LL01, LL10) and modeled
621 (LMOP) at all sites.