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Discussions

Spatio-temporal assessment of WRF, TRMM and in situ precipitation data in a tropical mountain environment (Cordillera Blanca, Peru)

L. Mourre[1], **T. Condom**[1], **C. Junquas**[1,2], **T. Lebel**[1], **J. E. Sicart**[1], **R. Figueroa**[3], and **A. Cochachin**[4]

[1]IRD/UJF-Grenoble 1/CNRS/G-INP, LTHE UMR 5564, Grenoble, France
[2]Instituto Geofísico del Perú (IGP), Lima, Peru
[3]UNASAM, Huaraz, Peru
[4]Glaciology and Water Resources Unit, National Water Authority (ANA-UGRH), Huaraz, Peru

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Correspondence to: L. Mourre (lise.mourre@ujf-grenoble.fr)

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Abstract

The estimation of precipitation over the broad range of scales of interest for climatologists, meteorologists and hydrologists is challenging in high altitudes of tropical regions, where the spatial variability of precipitation is important while in situ measurements remain scarce largely due to operational constraints. Three different types of rainfall products – ground based, satellite derived, RCM outputs – are compared here during the hydrological year 2012/13 in order to retrieve rainfall patterns at time scales ranging from sub-daily to annual over a watershed of approximately 10 000 km^2 in Peru. It is a high altitude catchment, located in the region of the Cordillera Blanca, with 41 % of its area above 4000 m a.s.l. and 340 km^2 glaciated. Daily in situ data are interpolated using a kriging with external drift (KED) algorithm; the satellite product is TRMM 3B42, which incorporates monthly gauge data; RCM outputs are obtained from WRF run with a Thompson microphysical scheme at three nested resolutions: 27, 9 and 3 km. The performances of each product are assessed from a double perspective. A local comparison with gauge data is first carried out when relevant (diurnal and seasonal cycles, statistics of rainfall occurrence); then the ability of each product to reproduce some well-known spatial features of rain fields at various time scales (from annual down to daily) is analysed.

WRF simulations largely overestimate the annual totals, especially at low spatial resolution, while reproducing correctly the diurnal cycle and locating the spots of heavy rainfall more realistically than either the ground-based KED or the TRMM products. The main weakness of the KED data is the production of annual rainfall maxima over the summit rather than on the slopes, induced by a lack of in situ data above 3800 m a.s.l. One main limitation of the TRMM product is its poor performance over ice-covered areas because ice on the ground behaves in a similar way as rain or ice drops in the atmosphere in term of scattering the microwave energy. While all three products are able to correctly represent the spatial rainfall patterns at the annual scale, it not surprisingly turns out that none of them meets the challenge of representing both

accumulated quantities of precipitation and frequency of occurrence at the short time scales (sub-daily and daily) required for glacio-hydrological studies in this region. It is concluded that new methods should be used to merge various rainfall products so as to make the most of their respective strengths.

1 Introduction: the challenge of precipitation estimation in the tropical Peruvian Andes

Located in the north-west of Peru, the Cordillera Blanca is the most glaciated tropical mountain range in the inter-tropical band. The total area covered by glaciers was 800–850 km^2 in 1930 and less than 600 km^2 at the end of the 20th century (Georges, 2004). This important melting rate of glaciers, documented in various studies (e.g., Georges, 2004; Silverio and Jaquet, 2005; Vuille et al., 2008a, 2008b; Bury et al., 2011), is found all over the Tropical Andes, threatening the long term existence of many of them, especially those of small to medium size (Rabatel et al., 2013). The whole water cycle of the region is consequently impacted. At the seasonal scale, the distribution of water discharge in rivers downstream of glaciers is changing, while at the decadal scale, the mean annual discharge is increasing, with the prospect of decreasing in the long run. Temperature and precipitation are the two major forcing variables most influencing the interannual variability and long term evolution of the water balance, acting on the mass balance of glaciers, as well as on the amount of snow available for melting and the partition between surface runoff and infiltration. A proper evaluation of these two variables thus remains an important issue for glaciologists and hydrologists alike.

The tropics are thermally characterized by an annual variation less important than the diurnal cycle (e.g., Kaser, 1999; Baraer et al., 2012). This applies to the Cordillera Blanca, where homogeneous thermal conditions are observed throughout the year (Juen et al., 2007). For instance, at Querococha, located in the southern part of the Cordillera Blanca, mean monthly temperature variation is less than 1 °C (Kaser et al., 2003).

By contrast, there is a strong seasonality of precipitation, controlled by the upper air circulation, with easterly wind transporting moisture from the Amazon plain (Aceituno, 1987) and westerly flow causing dry conditions (Garreaud et al., 2003). This results in two distinct seasons: the wet season from October to April with an average of 80 % of the annual precipitation (Vuille et al., 2008a), and the dry season from May to August. The wet season corresponds to the South American Monsoon System (SAMS) (e.g., Vera et al., 2006; Garreaud, 2009; Marengo et al., 2012), bringing humidity far to the West. The dry season is associated with the North American Monsoon System, the Intertropical Convergence Zone (ITCZ) being located as its northernmost position. The inter-annual variability of rainfall is important, in relation with the fluctuations of the sea surface temperature (SST) of the North Atlantic, and the El Niño Southern Oscillation (ENSO) (e.g., Espinoza et al., 2009; Lavado et al., 2012; Lavado and Espinoza, 2014).

The rainfall climatology is also characterized by strong spatial gradients at all temporal scales. First of all, the main annual rainfall pattern between 5 and 30° S is the contrast between the dry and cold conditions on the Pacific coast, stretching to the west slopes of the Andes, and the warm, humid and rainy conditions prevailing on the eastern slopes (Garreaud, 2009). This results in high precipitation amounts on the windward slopes of the Andes (up to 6000 mm yr^{-1}), and much smaller precipitation amounts on the leeward side, even at high altitudes (under 530 mm yr^{-1}) between 5° N and 20° S (Espinoza et al., 2009). Superimposed to this large scale spatial pattern, the influence of the topography becomes more and more pregnant when considering smaller temporal scales at which convective and orographic processes have a deep influence. Rainfall hot spots, heavy rainfall gradients over a few kilometers and flash floods (Young and Leon, 2009; Espinoza et al., 2015) are the most prominent hydro-meteorological patterns induced by the rough topography of the region.

Another issue arises from the high altitude involving that a significant amount of precipitation falls as snow over 4800 m a.s.l. This requires measuring reliably both the solid and the liquid precipitation all year around, something that is far from granted and that remains a major difficulty in mountain hydrology.

The estimation of precipitation over the broad range of scales of interest for climatologists, meteorologists and hydrologists is thus especially challenging in this region characterized by very uncommon geographical features. And yet socio-economic stakes are high as far as potentially drastic changes of the water cycle related to precipitation variability and long term changes are concerned, affecting the access to drinkable water in urban areas, the yields of agricultural projects and the operation of numerous hydroelectric power plants.

The driving question of this study is to identify and compare the precipitation data sets that can be used for properly characterizing the water balance over catchments of the region, from the sub-daily and daily temporal scales driving flooding to the decadal and multi-decadal scales related to climate change that is foreseen to especially affect the tropical regions at high altitudes (IPCC, 2013). Both the accumulated quantities of precipitation and the frequency of occurrence have to be properly estimated if one is to compute coherent water budgets over this large range of temporal scales, an accomplishment that no single precipitation data set can pretend to achieve on its own.

Each precipitation data set has its own strength and weakness. Starting with ground data, their main shortcoming – beyond their key advantage of being the only direct measurement of rainfall – is a poor sampling of the spatial variability that is especially important in mountainous regions (Scheel et al., 2011). This is compounded by the difficulty of installing and maintaining ground stations in a harsh environment, making whole areas very difficult to access (Salzmann et al., 2013; Schwarb et al., 2011). Rain gauges are thus most often available in the vicinity of villages, meaning that non habited areas are virtually not sampled, especially at high altitudes where distinguishing between liquid and solid precipitation is a major issue.

On their side, rainfall satellite products provide the global coverage that is lacking for ground data sets. However, the early satellite rainfall products elaborated in the mid-1980s were solely based on infrared data, affecting their accuracy in case of convective rainfall and, more generally, in presence of strong rainfall gradient. The most recent products now make use of various sources of information, blending infrared and microwave satellite data and often incorporating ground data, which make them more performant in spotting the patches of intense rainfall. It remains that there are still significant differences between the most commonly used satellite rainfall products, especially in the Tropics and for orographically forced rainfall (Ward et al., 2011). This means that the ability of these satellite products to fulfill user's expectations must be scrutinized on a case by case basis. Note also that satellite products are rather weak in distinguishing between liquid and solid precipitation.

In the perspective of quantifying the spatial and temporal variability of water budgets over catchments, another possibility for providing the required rainfall component is to use the precipitation produced by climate models. This presents two main advantages: (i) the physical coherency of the various elements of the water budgets computed by these models and (ii) the possibility of studying the evolution of the water budgets in the future in a context of global warming. Note, however, that global climate models usually fail to simulate properly the regional processes and their spatial variability, especially for precipitation in mountainous area, a default particularly critical in the Andes due to their complex topography (Giovannettone and Barros, 2009). To remedy these limitations, downscaling approaches based on the nesting of regional climate models (RCM) into global models is frequently used. The performance of nested regional models depends on the study area, the spatial resolution and the parameterization used (Box and Bromwich, 2004), which means that their added value, as compared to the other sources of rainfall information, should also be considered on a case by case basis.

2 Study area and data

2.1 Study area

Draining an area of 11 930 km^2 located between 8 and 10° S and 79 and 77° W, the Rio Santa runs northward, between the Cordillera Negra to the West and the Cordillera Blanca to the East (Mark and Seltzer, 2003), before making its way to the

Pacific. 41 % of the catchment area is above 4000 m a.s.l., including the highest point of the cordillera, Huascaran, peaking at 6768 m a.s.l. (Fig. 1). The upper Rio Santa catchment, with an outlet at Condorcerro, drains an area of about 10 000 km^2, and will be our main study area.

Some modeling projections based on the mean of meteorological variables from four GCM grid points predict the disappearance of ice cover for 2080 in some sub-watershed of the Rio Santa (Juen et al., 2007), which would have a significant impact on the flow regime of the river, since glaciers meltwater regulates its annual flow. At the Condorcerro outlet of the upper Rio Santa watershed (Fig. 1), glaciers meltwater currently provides 10–20 % of the annual rate, and up to 40 % in the dry season (Kaser et al., 2003; Mark and Seltzer, 2003; Baraer et al., 2012; Condom et al., 2012). In order to improve the accuracy of such case studies, it would be important to take into account the spatial variability of precipitation, through finer grid mesh, or more dense rain gauges networks.

The studied area is a rectangle of 84 000 km^2, centered on the Rio Santa (Fig. 1). It can be divided into four hydrological sub-regions from the North–East to the South–West. The Rio Marañon catchment is located on the Amazon side; where the highest yearly precipitated amount was measured in situ during the hydrological year 2012–2013 (> 1100 mm yr^{-1}). The second sub-region is the West side of the Cordillera Blanca, draining to the Pacific. Stations in this area are located inside the Rio Santa catchment. In situ measured precipitation amounts in the Cordillera Blanca area range from 478 to 1000 mm yr^{-1} (Table 1). The third region is the Cordillera Negra, which is much drier (from 44 to 434 mm yr^{-1}) and lower in altitude (Table 1). This zone includes all stations located west of the Rio Santa riverbed, up from 3625 m a.s.l. to an altitude of 1000 m a.s.l. Finally, the dry area near the Pacific Ocean, named Costa, is defined as the land area whose altitude ranges from 0 to 1000 m a.s.l. The topography data shown in Fig. 1 is from STRM (90 m resolution).

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2.2 In situ data

It was not an easy task to gather data from a sufficiently large number of stations in order to properly cover our study area. First of all, there was the need to obtain some background climatological information; 10 stations operated by the *Servicio Nacional de Meteorología e Hidrología de Perú* (SENAMHI) since 1965 (Table 1) allow computing monthly and yearly long term averages. However, their specific location and loose spatial sampling prevent from estimating correctly the long term average rainfall either over the Rio Santa Catchment or over the whole study area. Data from an additional set of 8 SENAMHI stations cover the period August 2012 to July 2013 at a daily resolution. We also had access to 3 stations from the *Unidad de Glaciología y Recursos Hídricos* (UGRH) from the *Autoridad Nacional de Agua* (ANA). These stations are of a tipping bucket type; they have the double advantage of being located at higher altitudes and of providing data at sub-daily time steps. As compared to previous studies in this region the key new information used comes from a database of 16 meteorological stations with hourly data located in the Ancash region of Peru. They were installed in the framework of a project (*Centro de Información e Investigación Ambiental de Desarrollo Regional Sostenible* – CIIADERS), operated by the *Universidad Nacional Santiago Antúnez de Mayolo* (UNASAM) of Huaraz. These stations provide essential information for understanding the spatial (increased sampling density) and temporal (hourly resolution) distribution of precipitation within our study area.

Unfortunately the CIIADERS network has been in operation since 2012 only, limiting this study to one hydrological year (August 2012 to July 2013). The average pluviometric index of this one-year study period, which corresponds to a reduced centered anomaly and enable to distinguish a dry or a wet year, is close to 0 (0.0774), meaning that the annual precipitation is close to the mean precipitation for a 51 years study (1965–2014) over 10 stations among the 37 studied (Table 1). Note also that

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stations with more than 25 % of missing data during that year have been removed, leaving only 32 stations available to compute our ground based rainfall grids.

A weakness of this 32-station network is the lack of data for the dry Cordillera Negra and the high altitudes areas of the Cordillera Blanca (only 3 stations located above 3800 m a.s.l.). This shortcoming was partly overcome by using accumulation data provided by UGRH for the Artesonraju and Yanamarey glaciers at near 5000 m a.s.l., which are net accumulations during one year, including solid precipitation and melting over the period. Related to snow, it is important to keep in mind that the rainy season occurs during summertime in this area and that consequently few solid precipitations are observed under 4600 m a.s.l. (Condom et al., 2011).

2.3 Gridded precipitation from in situ data

A major problem when comparing precipitation data sets from different sources relates to their different spatial resolutions. Satellite and RCM data are provided as gridded products, while rain gauges provide point data. A spatial interpolation procedure is thus required to get each product on the same grid. There is a considerable amount of literature on selecting an appropriate interpolation method for computing rain grids from point data. This is an especially tricky problem in regions of rough topography.

Several studies showed that Kriging with External Drift (KED), using altitude as an external variable, provides good results over complex terrains (e.g. Masson and Frei, 2014; Tobin et al., 2011; Ochoa et al., 2014).

Block kriging with altitude as an external drift was thus chosen here as our reference interpolation method. While accounting for the strong influence of topography on the structure of rain fields is crucial in mountainous regions, another issue arises from the type of variogram to be used and whether it is allowed to vary from day to day. Related to this topic, different concepts of spatio-temporal kriging have been tested in previous studies (Amani and Lebel, 1997; Vischel et al., 2011; Gräler at al., 2012). Mean (KED-M) variogram assume a constant variogram for all days constructed by averaging all daily variograms. Daily evolving (KED-DE) variograms assumes the hypothesis of

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a relationship between precipitation amounts of day D and $D-1$ and information from the previous days is considered with a weight chosen by the user. KED-M and KED-DE were thus considered here as two possible alternatives. A third method was also tested, consisting in a kriging interpolation without external drift but with a daily evolving variogram (K-DE). We choose the best method among those three (KED-M, KED-DE, K-DE) (see Sect. 3.1) to compute daily gridded precipitation at 27, 9 and 3 km spatial resolutions, thus matching the resolution of the satellite and RCM products that will be presented below in Sects. 2.4 and 2.5.

2.4 TRMM product

Tropical Rainfall Measuring Mission (TRMM) Multi-Satellite Precipitation Analysis (TMPA) products are available since 1998. This study makes use of the TRMM3B42 version 7 product, which provides precipitation data at a 3 h time step from a combination of remote sensing observations (microwave imager, precipitation radar, visible and infrared scanner) and monthly in situ observations (Huffman et al., 2007; Huffman and Bolvin, 2012). This product will simply be referred to as TRMM in the rest of the study. The TRMM dataset covers a region between 50° S and 50° N, with a spatial resolution of 0.25° (approximately 27 km). This product can be used for hydrological application in regions with scare in situ data. A study from Andres et al. (2014) in southern Peru found better to use daily rain gauges interpolated fields rather than TRMM products, considering outflow outputs. However, in hydrological studies, it could be rather difficult to separate the influence of the hydrological model calibration procedure in relation to the influence of input data. Even though the TRMM mission was focused on the monitoring of tropical rainfall, it suffers from a number of drawbacks, the main being its poor time sampling reduced to one or two passage per day depending on the area considered. This causes a significant loss of information for short duration storms (Roca et al., 2010; Condom et al., 2011; Ward et al., 2011). The effect of these time sampling errors are reduced when aggregating in time (Scheel et al., 2011; Mantas et al., 2014), but TRMM products still show significant biases

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in monthly values in the tropical Andes (Condom et al., 2011) as well as on solid precipitation (Maussion et al., 2014).

2.5 WRF simulation

In this study we use the regional climate model Weather Research and Forecasting (WRF) version 3.4.1 (Skamarock et al., 2008), that had only few application in the tropical Andes (Murthi et al., 2011; Ochoa et al., 2014; Sanabria et al., 2014). The WRF is a nonhydrostatic RCM and uses a terrain-following vertical coordinate (sigma). The limited domain simulations are forced by boundary condition every 6 h by the National Center for Environmental Prediction (NCEP) Final Analyses (FNL) Global Forecast System (GFS) with 1° of latitude and longitude horizontal resolution. Elevation dataset is from the USGS GTOPO30. A large tropical Andes domain was first delimited for simulations at a 27 km resolution (WRF27). Two sub-domains were then used for carrying out simulations at a 9 km (WRF9) and a 3 km (WRF3) resolution respectively, both being centered in the Santa river basin (Tables 2, 3). WRF9 (WRF3) simulations are forced by the WRF27 (WRF9) simulations using a one-way nesting technique.

Figure 1a shows the boxes corresponding to each simulation domain, and Table 2 lists the resolutions and coordinates of each configuration. Table 3 lists the parameterizations used in the simulations. We use the Thompson microphysical scheme (Thompson et al., 2008), and the Grell–Devenyi ensemble scheme for the cumulus parameterization. We also use a topographic correction for surface winds, previously tested in a complex orography terrain of the Iberian Peninsula (Jimenez and Dudhia, 2012). The Noah-MP (Multi-physics) land surface model is used for the representation of land–atmosphere interaction processes (Niu et al., 2011; Yang et al., 2011). Noah-MP is an extended version of the Noah land surface model with enhanced Multi-Physics option to address critical shortcomings in Noah for long-term soil state spin-up and snow modeling. In particular, this version of the Noah model has shown improvements in the representation of surface energy fluxes, snow cover and snow albedo treatment. The partitioning precipitation into rainfall and snowfall

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was set to option 2 (opt_snf = 2) using the Biosphere–Atmosphere Transfer Scheme which assumes all precipitation as snowfall when the air temperature is lower than the freezing point plus 2.2 K, and rainfall otherwise.

3 Methods and criteria used for comparing the rainfall products

A total of seven gridded rainfall products are compared here, as described in Table 4. These products differ from one another on two accounts: (i) the type of information used (ground data, satellite data, climate model), (ii) the spatial resolution, ranging from 27 km corresponding to the size of the TRMM satellite product grid mesh, down to 3 km, the finest resolution at which the WRF climate model was run. These seven gridded products are available at the daily scale which is the corner scale for the comparison carried out in this paper. While TRMM products and WRF simulations are inherently gridded, in situ data need to be interpolated in order to build grids at the three spatial resolutions: 27, 9 and 3 km.

3.1 Computation of daily precipitation grids from in situ data

As presented in Sect. 2.3, three different models of KED were compared in order to choose the best unbiased estimator among those three. This determination is based on a "leave-one-out" cross validation procedure (Li and Heap, 2008). The procedure is applied individually to each of the three KED methods tested. It consists in leaving aside one measurement point at a time, and estimating the value at that point from the remaining 31 stations. The procedure is applied successively to each of the 32 measurement stations, allowing for computing the bias (Eq. 1), the root mean square

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(RMSE) score (Eq. 2) and the correlation coefficient, as follows:

$$\text{bias} = \sum_{i=1}^{n} \sum_{d=1}^{m} (\hat{P}_{i,d} - P_{i,d}) \quad (1)$$

$$\text{RMSE} = \sum_{d=1}^{m} \sqrt{\frac{1}{n} \sum\nolimits_{i=1}^{n} (\hat{P}_{i,d} - P_{i,d})^2} \quad (2)$$

Where $\hat{P}_{i,d}$ is the daily precipitation estimated at point i for day d, using all the other gauges, $P_{i,d}$ is the corresponding measured daily rainfall, n is the number of stations (32 when no missing data on day d) and m the number of days studied.

Table 5 reports the results of the cross validation for the three different spatio-temporal kriging methods applied to in situ daily precipitation data. Correlation for daily evolving variogram is the highest, in daily as in yearly values, with a weight given to previous day data of 10 %. The use of altitude in KED-DE, compared to the single use of spatial coordinates (in K-DE), improves the performance of the interpolation, and more significantly for annual amounts (Table 5). The best technique, KED-DE, was selected to create gridded daily precipitation amounts in the area of the Rio Santa watershed. These three products will be referred to in the following as KED27, KED9 and KED3, for the 27, 9 and 3 km spatial resolutions respectively (Table 4, Fig. 2). Daily RMSE value is large (3.41 mm d^{-1}), compared to the mean daily precipitation over all stations (1.85 mm d^{-1}), and errors are reduced with aggregation on a yearly basis (RMSE of 271 mm yr^{-1} for an average in situ amount of 572 mm y^{-1} for the 32 stations, and correlation coefficient of 0.78). In yearly values, kriging products will then be the basis of our comparison to TRMM data and WRF outputs. Despite some bias in the estimation of annual and daily rainfall, it is assumed that the most important spatial pattern is captured by KED-DE. In the following the simple KED terminology is used to refer to KED-DE products.

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3.2 Comparing the daily and annual precipitation products

Daily precipitation is defined as the accumulation of rainfall between 00:00:00 LT (Local Time) and 23:59:00 LT. An important point is that all gridded products suffer from weakness and thus, the aim of the comparison is to analyze differences between products.

The daily products are compared from three different standpoints: the statistical distribution of non-zero rainfall, the grid annual values and the seasonal cycle.

The frequency of daily precipitation at one location (one station or the grid mesh corresponding) was studied through the cumulative distribution function of the non-zero precipitation (Sambou, 2004):

$$f(x) = -\log_{10}(1 - F(x)) \tag{3}$$

Where $F(x)$ is the cumulative frequency of the daily precipitation amount above $1\,\mathrm{mm\,d^{-1}}$ and x is the daily precipitation ($\mathrm{mm\,d^{-1}}$).

To assess the statistical performance of the 3 km resolution products against punctual in situ data at a daily time scale, the contingency table for rainfall/no rainfall was built (Table 6). The bias score (BIAS – ratio of the number of rainy days simulated $(A+B)$ over the number of rainy days observed $(A+C)$), false alarm rate (FAR – ratio of the number of rainy days incorrectly simulated (B) over the total number of rainy days simulated $(A+B)$), probability of false detection (POFD – ratio of the number of rainy days incorrectly simulated (B) over the number of days without rain in the observations $(B+D)$) and the frequently used Heidke Skill Score (HSS) (Eqs. 4–6) were calculated.

$$\mathrm{HSS} = \frac{S - S_{\mathrm{ref}}}{1 - S_{\mathrm{ref}}} \tag{4}$$

$$S = \frac{A + D}{N} \tag{5}$$

$$S_{\mathrm{ref}} = \frac{(A+B)(A+C) + (B+D)(C+D)}{N^2} \tag{6}$$

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Where N is the size of the statistical population, and A, B, C and D values are explained in Table 6.

A perfect product would have a BIAS of 1, a FAR of 0, a POFD of 0 and a HSS of 1.

Annual grids were computed by temporal aggregation of the daily grids. In the aim to study the water balance in a purpose of hydrological applications, each product was evaluated in terms of volume of water precipitated over the area of the upper Rio Santa watershed, corresponding to the watershed limited by the outlet at Condorcerro (Fig. 1).

Finally, to evaluate the seasonal cycle of precipitation in one site, we used the temporal standard score S_t (Eq. 7).

$$S_t = \frac{\overline{P_j}^{10} - \langle P_j \rangle}{\sigma_j} \tag{7}$$

Where $\overline{P_j}^{10}$ is the running means of daily precipitation amounts over 10 days in one location, $\langle P_j \rangle$ and σ_j are the temporal average and standard deviation of the daily precipitation respectively.

3.3 Assessing the quality of the WRF3 hourly precipitation grids

To facilitate the comparison among all stations, the hourly precipitation amounts were normalized by dividing them by the mean of hourly values during the year. Few studies deal with hourly rainfall amounts from WRF modeling. In this study, we compared the timing of the precipitation peak from hourly rain gauge data and from WRF3 simulation outputs. Studying hourly data allowed us to see if short time processes governing precipitation in the Rio Santa valley are well represented in WRF3, considering there in situ hourly measurement as the reference.

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4 Results

4.1 Frequency and intensities of daily precipitation amounts

In this section, we first analyze the statistics of daily precipitation, temporal scale for which all the 8 products are available (Table 4), and presented them for the Corongo location (no. 2 in Table 1). This station, located in the northern part of the Rio Santa watershed was selected because it is representative of the 16 stations located inside the Rio Santa catchment in terms of precipitation areal averaging effect, except when comparing the differences between the three different spatial resolution products of WRF. In a second part, we studied daily precipitation occurrences based on the contingency table indices (see Sect. 3.2, Table 6) for all stations located in the Sierra area.

Figure 3 shows the cumulative frequency of daily precipitation above 1 $mm\,d^{-1}$ for the Corongo location comparing (i) the three spatial resolutions of WRF (Fig. 3a), (ii) the three spatial resolution of KED (Fig. 3b), (iii) comparing TRMM, WRF and KED products at 27 km (Fig. 3c), (iv) comparing WRF and KED products at 3 km spatial resolution vs. in situ punctual data (Fig. 3d). The number in the box of each graph represents the number of days with precipitation over 1 $mm\,d^{-1}$ ($n_{p>1}$) for each product. WRF precipitation areal averaging effect is the only one that is not similar at all stations inside the Rio Santa watershed, and this complex problem, beyond the scope of this study and probably related to the internal thermodynamic of the model, will not be addressed here. Regarding KED data, the three spatial resolutions have few differences that can also be seen in the number of $n_{p>1}$ (Fig. 3b). Concerning the 27 km spatial resolution, KED27 and TRMM are more similar to each other compared to WRF27 (Fig. 3c), despite an underestimation of $n_{p>1}$ for TRMM (108 days) compared to KED27 (186 days). WRF3, as WRF27 (Fig. 3c and d) do not correctly reports daily precipitation amounts, with stronger values compared to the other datasets. In this comparison, KED3 seems to underestimate daily precipitation amounts and overestimate $n_{p>1}$ in light of in situ data, but this can be related to a resolution effect between 3 km resolution grid and punctual measurement.

Noting that WRF products are unrealistic in term of daily precipitated quantities we will now evaluate its performances in term of occurrence, a notion that is essential in glacio-hydrological studies. This can be seen in the results of the contingency table and is studied comparing KED3 and WRF3 with in situ data for different daily precipitation threshold in Fig. 4. The results are shown for the Sierra region, but are similar for the Cordillera Negra and Marañon area. Only the Costa area shows different results, caused by very low precipitation annual rate inducing a large number of FAR in gridded products.

WRF3 largely overestimate the number of strong daily precipitation, which can be linked with the overestimation of the product (Fig. 3d). The FAR, POFD and HSS show that there is an important improvement considering only precipitation above 1 mm d^{-1} in KED3 and that the number of daily precipitation between 0 and 1 mm d^{-1} is largely overestimated by this product (Fig. 4b–d). POFD can be seen as an inter-comparison indicator as it does not depend on the number of predicted events. Above 1 mm d^{-1}, KED3 is then a better estimator of precipitation occurrence compared to WRF3. However, we faced the same spatial resolution problem as above, when comparing 3 km mesh grid and in situ data for low precipitation amounts. HSS indicates that daily precipitation in KED3 is in better accordance to in situ data than WRF3, with few rainy days well predicted in WRF3. Although we noted a spatial resolution effect for daily precipitation quantities under 1 mm d^{-1}, KED3 appears as a good estimate of precipitation in terms of daily average quantities and occurrences and will be considered later as a basis of comparison between different gridded products.

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4.2 Annual amount and seasonal cycle

4.2.1 Annual cumulated precipitation amounts during the hydrological year 2012–2013

The estimations of the annual precipitation over the Upper Rio Santa catchment (about 10 000 km^2) for the 27 km resolution products, range from 450 $mm\,yr^{-1}$ for TRMM to 2080 $mm\,yr^{-1}$ for WRF27 (and 810 $mm\,yr^{-1}$ for KED27) (Table 4). Thus, even at this large integrative scale, the 27 km products display large discrepancies. KED annual rainfall is 30 % smaller at the 3 km resolution (580 $mm\,yr^{-1}$), compared to the 27 km resolution, while the diminution is of 40 % for WRF (1250 vs. 2080 $mm\,yr^{-1}$). Figure 5 shows those annual precipitation amounts for all different products used in this study. Even though the KED3 estimate is certainly not devoid of bias, it is clear that WRF overestimates rainfall, probably due to errors in the NCEP-FNL forcing at the lateral boundaries of the simulation domain. WRF products, compared to KED, shows more spatial variability in precipitation amounts in both 3 and 9 km resolutions, with stronger altitudinal gradient. TRMM and KED27 are closer along the Rio Santa valley, as they both incorporate rain gauges data. However, on the Marañon watershed side, TRMM integrates the tropospheric flows from the Amazonian lowlands, compared to KED27 which ground observations are under sampled over this area. Although coarse resolution products (TRMM and WRF27) do not provide acceptable rainfall grids for hydrological applications in complex topography area because of their lack of representation of the finer spatial pattern, they are not totally useless at this annual scale. They correctly represent the longitudinal precipitation gradient between the humid and rainy condition of the Amazon plain, the orographic influence of the Cordillera Blanca and the dry and cold Pacific coast conditions (Fig. 5f and h). Those products may thus be used as indicators of spatial precipitation pattern for the study of long term trends in precipitation (that are costly to generate with WRF3, and not available with KED, because half of the gauge network was installed only in 2012).

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4.2.2 Orographic influence on annual amount at 9 and 3 km spatial resolution

Field data are too remote, with no measurement at high altitude to provide information on the altitudinal gradient of precipitation. On a longitudinal transect near the Huascaran peak, we observed important differences in annual precipitation amount and spatial pattern between KED products and WRF outputs (Fig. 6b and c). At very high altitude, we compared precipitation to accumulation data measured at 5100 m a.s.l. on the Artesonraju glacier (station no. 5 from Table 1). We can observe in Fig. 6c that KED3 and KED9 products suffer from one major impediment: in regions of low gauge density, the spatial pattern will be solely driven by the altitude, not taking into account the effect of local slopes and orientation. As a consequence daily rainfall maxima produced by KED are located over the summits, whereas it is well known that these maxima are rather located on the slopes, as correctly simulated by WRF3 (Fig. 6b). The only area with less precipitation in WRF3 compared to WRF9 is the upper zone of the Cordillera Blanca mountain range, near the highest peaks (Fig. 6b). In WRF3, the altitudinal variation is greater than in WRF9 with summit reaching 5000 m a.s.l., the spatial resolution is finer, and in this configuration, the orographic processes on the windward slopes of the Andes is more pronounced and correctly represented at the 3 km spatial resolution.

Over 4800 m a.s.l., an important amount of precipitation falls as snow. No direct in situ observations of the precipitation phase are done at such altitudes, but we can use the altitude of the 0 °C isotherm to evaluate WRF solid precipitation outputs. WRF9 snow output amounts are in hatched bar while WRF3 snow outputs amounts are in dark gray in Fig. 6b. The freezing line is found on average within $\sim 4800 \pm 300$ m a.s.l. for tropical region between $\sim 20^{\circ}$ N and 20° S (Harris et al., 2000; Bradley et al., 2009). Gurgiser et al. (2013) documented a snow line altitude between 4720 and 4885 m a.s.l. for the Shallap glacier (no. 17 in Table 1) during the years 2007–2008, so liquid precipitation can be found around 4800 m a.s.l. In WRF3 outputs, about a third of the precipitation amount remain liquid for mesh grids around 5000 m a.s.l. This could have a negative

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impact on the surface energy balance of glaciers. But we have to keep in mind that it corresponds to precipitation averaged for 3 km grid cells that could include lower area in this zone of strong altitudinal gradients.

4.2.3 Seasonal changes along the Rio Santa valley

The annual cycle is presented in detail for cells corresponding to three stations located along the Rio Santa valley: Corongo (station no. 2), Shilla (station no. 12) and Shancayan (station no. 16) (Fig. 1, Table 1), as these three stations are representative of others located in the Sierra area. Day 1 in Fig. 7 corresponds to the beginning of the hydrological year, the 1 August 2012. The upper panels (Fig. 7 a–c) correspond to 27 km spatial resolution of TRMM products, KED27 products and WRF27 outputs. During the dry period, between day 1 and 50, and 300 to 350, TRMM largely overestimates precipitation amount for Shilla (Fig. 7b). The percentage of ice-covered area in the mesh corresponding to Shilla station is up to 10 %, while it is less than 0.5 % for the meshes of Corongo and Shancayan. Error in dry season for Shilla can be seen as a poor consideration of ice covered surface in TRMM algorithm, as ice on the ground scatter energy in a similar way as precipitation drops in the atmosphere (Maussion et al., 2011). Temporal trends of KED27 and WRF27 are similar, with occasional shifts of few days in heavy rainfall events (for example between day 200 and 230 for Corongo station, Fig. 7a).

Concerning the finer spatial resolution (Fig. 7d–f), KED3 and in situ data have strong similarities for the 3 stations and that confirms the use of the 3 km spatial resolution to compare gridded data with in situ punctual data. Regarding WRF3, intensities of precipitation peaks are false in the heart of the rainy season, but the temporal distribution remains close to that of rain gauges precipitation.

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4.3 Diurnal cycle of precipitation along the Rio Santa valley

Half of the rain gauges available over the region of study are daily-reading stations; the network of recording rain gauges is consequently too sparse and too unevenly distributed to permit the computation of relevant rainfall grids at sub-daily scale. WRF3 thus remains the only product able to account for the diurnal cycle of precipitation by providing hourly rainfall grids (even though TRMM3B42 is available at a 3 hourly time step, the fact that the satellite overpasses the studied area only once or twice daily makes it difficult to trust its accuracy for sub-daily time scales). This is important since the diurnal cycle in a glaciological context controls the precipitation phase and consequently the surface albedo (one strength of WRF is that it produces liquid as well as solid precipitation).

In situ data at Corongo (station no. 2), Shilla (station no. 12) and Shancayan (station no. 16), display a clear precipitation peak in the late afternoon, between 16:00:00 and 19:00:00 LT (Fig. 8). This diurnal cycle is visible in the WRF3 simulations, even though somewhat less pronounced (more rainfall around noon), and with a slight lag at Shilla and Shancayan. Looking at the diurnal cycle of precipitation at a regional scale (Fig. 9), it is noteworthy that the peak hour of precipitation occurs later in the bottom of the Rio Santa valley (dark green for altitudes below 4000 m a.s.l., around 19:00:00 LT) than in the surrounding mountains (light green color, around 17:00:00 LT). A lack of hourly information at high altitude prevent from validating these hourly-scale characteristics with observations, but they correspond to well documented orographic processes (valley and mountain breezes) (Biasutti et al., 2012; Barros, 2013). In the afternoon, moisture is transported to the peaks by anabatic winds. At the beginning of the night, moisture downs into the valley with katabatic winds. In a physical climate model like WRF, the representation of thermal and orographic circulations theoretically benefits from a finer resolution, and mountain-valleys breezes seem to be accurately estimated for the 3 km resolution runs.

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5 Summary and conclusions

Over the past 40 years the warming climate of the Tropical Andes has led to a significant melting of the glaciers, impacting the hydrological cycle to an extent that remains to be assessed, both for present and for future times. One obstacle in doing so is our limited ability to evaluate properly the precipitation falling over high altitude catchments if only because of the difficulties for installing and maintaining sufficiently dense in situ networks. In addition, the rough topography generates strong spatial gradients that are very challenging to sample. In such a context, remote sensing and modeling look as attractive means for complementing the information provided by in situ measurements. With this in mind, this paper has presented a comparison of rainfall products based on three different sources of information: krigged rain gauge measurements, TRMM3B42 satellite product and WRF-RCM outputs. The TRMM3B42 product having a resolution of 27 km; the same resolution was thus used for the computation of coarse rainfall grids from gauge measurements and for WRF simulations (WRF27). Then gauge rainfall grids and WRF simulation were also produced at the finer resolutions of 9 km (WRF9) and 3 km (WRF3). This makes a total of seven gridded precipitation products that were computed and inter-compared over the region of the Rio Santa in Peru, a highly glaciated catchment and the second largest river flowing from the Tropical Andes to the Pacific.

Each process leading to the computation of gridded rainfall products has its own weaknesses: interpolation errors for the rain gauge products, indirect measurement of rainfall for the satellite products, sub-mesh parametrisation for the RCM outputs. Therefore none of them can be taken as an undisputable reference, whether be in term of quantities or in terms of occurrence. This is why the performances of each product were assessed from a double perspective. A comparison with measured on site data was carried out when relevant (diurnal and seasonal cycle, statistics of rainfall occurrence), while the ability of each product to reproduce some well-known spatial

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features of precipitation fields at various time scales (from annual down to daily) was analysed when no obvious quantitative reference could be used.

Note that WRF27 simulations are totally unrealistic in terms of annual quantities. WRF9 and WRF3 simulations are better in this respect but still largely overestimate the annual total, with WR9 being in addition unable to catch properly the details of the spatial pattern, that are well restituted by WRF3. This shortcoming of WRF9 has two reasons: (i) at this 9 km resolution, non-hydrostatic effects are significant and since convection is partially solved in the model more realistic precipitation quantities are produced, (ii) however this resolution is still too coarse to reproduce correctly the orographic influence, because a number of key features are smoothed out (for instance, grid meshes reaching altitudes above 5000 m a.s.l. are found in the WRF3 topography, which is not the case in the WRF9 topography).

TRMM, with its coarse spatial resolution of 27 km, performs poorly over ice covered surfaces, because ice on the ground behaves in a similar way as rain or ice drops in the atmosphere in term of scattering the microwave energy. Using TRMM in glaciated mountain ranges should thus be avoided, especially at small time scales where spatial error compensation does not occur, as it might do when averaging annual totals over large areas. On the other hand, TRMM might provide some useful information over the low lands in the Amazonian side of the Andes as already mentioned by Lavado et al. (2009).

Coarse resolution products (TRMM and WRF27), however, correctly represent the large spatial gradient between the humid Amazonian lowlands and the dry Pacific coast and their long term precipitation series can thus be used to study the interannual variability of the spatial patterns at large regional scale and possible long term trends linked to climate change.

Comparing the diurnal cycle of the hourly WRF3 simulations with observations in meshes containing one recording rain gauge leads to the conclusion that this diurnal cycle is fairly realistic. Of course the default of the large overestimation of precipitation by WRF3 prevents from using directly the WRF3 grids as inputs to hydrological models.

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The challenge is thus to combine the hourly temporal distribution of precipitation in WRF3 with more accurate precipitated amounts. In this respect, one path to explore is to use the WRF3 diurnal cycle for disaggregating the KED daily grids.

A more general conclusion is that the topography and the associated rainfall gradients are too steep in this region for rainfall products at the spatial resolution of either 9 or 27 km to provide good rainfall estimates and good rainfall spatial patterns for glacio-hydrological purposes. Moreover, due to a poor sampling at high altitudes, kriging with external drift does not take into account local slope and orientation effects as the spatial pattern is solely driven by altitude. In summary, combining the daily rain gauge measurements with the spatial patterns generated by WRF3 appears as promising way for building daily rain fields. There are several techniques to do so, one being to use the WRF3 rain field, instead of the topography, as the external drift when interpolating the in situ measurements with a KED technique.

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Table 1. Information on in situ rainfall stations. For the Situation, CB = Cordillera Blanca, CN = Cordillera Negra, M = Marañon, C = Costa. [NS] indicate stations used for the study along the Rio Santa valley. [H] indicate stations used for the transect along the Huascaran peak. * indicate stations used to calculate the precipitation index (data from 1965) (Sect. 2.2). Precipitation (mm yr^{-1}) during the hydrological year 2012/13 is indicated at each rain gauge station for in situ data (Obs), TRMM and WRF (WRF27, WRF9 and WRF3). Accu indicates that it is the value for glacier accumulation over the year.

UNASAM no.	Lon	Lat	Alt. [m]	Situation	Obs	TRMM	WRF27	WRF9	WRF3
2 [NS]	−77.9	−8.6	3172	CB	542	407	2173	1517	1225
6	−77.2	−8.9	2786	M	577	671	3377	1090	1716
7	−77.8	−9.1	2350	CB	478	307	4219	997	796
9	−78.4	−9.2	125	C	31	107	121	214	341
10	−77.4	−9.2	3770	M	1162	271	2758	2421	2821
11 [H]	−77.7	−9.2	2500	CB	598	1596	4219	1000	849
12 [NS]	−77.6	−9.2	3040	CB	738	1596	2758	1073	1145
14	−78.2	−9.5	133	C	14	158	121	182	338
15	−77.5	−9.3	3480	M	1028	558	2558	3472	3948
16 [NS]	−77.5	−9.5	3091	CB	666	434	4625	1663	1025
18	−77.4	−9.5	3850	CB	–	1674	4625	3168	2513
28	−78.1	−10.1	18	C	8	78	49	102	250
29	−77.1	−10.1	3405	CB	624	381	1861	1664	3069
32	−77.4	−10.4	3268	CN	307	523	2203	1990	2860
SENAMHI no.	Lon	Lat	Alt. [m]	Situation	Obs	TRMM	WRF27	WRF9	WRF3
1	−78.0	−8.4	3160	CB	972	343	2502	1498	1373
3 *	−77.6	−8.6	3375	M	959	437	2173	1651	1483
4 [H]	−77.5	−8.8	3605	M	1030	530	2758	2248	2160
8	−77.7	−9.1	2527	CB	744	307	4219	1000	719
13	−78.2	−9.4	216	C	28	158	121	219	396
16	−77.5	−9.5	3079	CB	634	434	4625	1663	1025
19 *	−77.8	−9.5	2285	CN	251	233	1320	797	761
20	−77.9	−9.5	1260	CN	91	234	710	502	528
21 *	−77.7	−9.6	3625	CN	668	434	4348	1800	1169
22 *	−77.7	−9.6	3325	CN	–	434	4348	1524	1310
23 *	−77.2	−10.1	3137	M	687	790	2402	2456	3289
25 *	−77.4	−9.7	3444	CB	756	790	4348	1942	1541
26 *	−77.6	−9.8	3440	CN	–	358	4348	1705	973
27 *	−77.2	−9.9	4400	CB	–	645	3413	2684	3922
29 *	−77.2	−10.1	3382	CB	620	381	1861	1678	3069
30	−77.4	−10.2	3200	CN	–	329	1861	837	1867
31	−77.5	−9.6	1221	CN	44	192	499	454	662
32 *	−77.4	−10.4	3230	CN	383	271	1861	1255	1586
UGRH no.	Lon	Lat	Alt. [m]	Situation	Obs	TRMM	WRF27	WRF9	WRF3
5 [H]	−77.6	−9.0	5100	CB	Accu: 1006	545	4188	3010	2922
17	−77.4	−9.5	4281	CB	–	1674	3215	2691	2479
24	−77.3	−9.6	4955	CB	Accu: 1000	790	3215	2809	3894

Table 2. Characteristics of the WRF simulations at the three different spatial scales.

	Simulation 1 WRF27	Simulation 2 WRF9	Simulation 3 WRF3
Horizontal resolution (km)	27	9	3
Domain	Tropical Andes	Rio Santa region	Rio Santa watershed
Domain center coordinates	8°30′ S, 72° W	9°1′4″ S, 77°37′53″ W	9°11′25″ S, 77°43′7″ W
Configuration	Regional simulation	One-way nesting	One-way nesting
Forcing	NCEP_FNL	WRF27	WRF9
Vertical resolution	27 sigma levels	27 sigma levels	27 sigma levels
Run time-step (s)	150	50	6
Outputs time resolution (h)	6	3	1

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Table 3. List of the physical parameterizations used in the WRF simulations.

	Parameterizations	References
Clouds microphysics	New Thompson Scheme	Thompson et al. (2008)
Radiation	Longwave: Rapid Radiative Transfer Model (RRTM)	Mlawer et al. (1997)
	Shortwave: Dudhia Scheme	Dudhia (1989)
Cumulus parametrization	Grell–Devenyi ensemble Scheme	Grell and Devenyi (2002)
Planetary boundary layer	Yonsei University Scheme	Hong et al. (2006)
	Wind topographic correction (option 1)	Jimenez and Dudhia (2012)
Land surface	Noah-MP (multi-physics) Partitioning precipitation option 2	Niu et al. (2011); Yang et al. (2011)
Surface layer	MM5 similarity	Paulson (1970)

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Table 4. Precipitation data used in this study, with their spatial and temporal resolution, and the accumulated amount precipitated over the Upper Rio Santa watershed during the hydrological year 2012/13. WRF and KED (corresponding to kriging data with external drift – daily evolving variogram) are at 3 different spatial resolutions (27, 9 and 3 km). TRMM is the TRMM3B42 product.

Product	Spatial resolution	Temporal resolution used in this study			Annual precipitation over the watershed [m]
		Hourly	Daily	Yearly	
In situ	Punctual	x	x		–
KED27	27 km × 27 km		x	x	0.81
KED9	9 km × 9 km		x	x	0.64
KED3	3 km × 3 km		x	x	0.58
WRF27	27 km × 27 km		x	x	2.08
WRF9	9 km × 9 km		x	x	1.19
WRF3	3 km × 3 km	x	x	x	1.25
TRMM	27 × 27 km		x	x	0.45

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Table 5. Indices from the cross-validation results with in situ precipitation data for the different interpolation methods, in daily and yearly values. Spatio-temporal block kriging with altitude as an external drift (KED) is applied with mean (KED-M) and daily evolving (KED-DE) variogram. Kriging without external drift was also applied with the daily evolving variogram method (K-DE).

	Daily Values			Yearly Values		
Indices	RMSE	Bias	Correlation Coefficient	RMSE	Bias	Correlation Coefficient
KED-M	4.57	0.08	0.57	284.74	48.19	0.75
KED-DE	3.41	−0.04	0.61	270.96	−34.40	0.78
K-DE	3.64	0.01	0.54	391.82	−56.14	0.42

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Table 6. Contingency table used to assess the statistical performances of the 3 km resolution products against punctual in situ data at a daily time scale.

		In situ	
	P_j	Yes	No
3 km grid	Yes	*A*	*B*
Product	No	*C*	*D*

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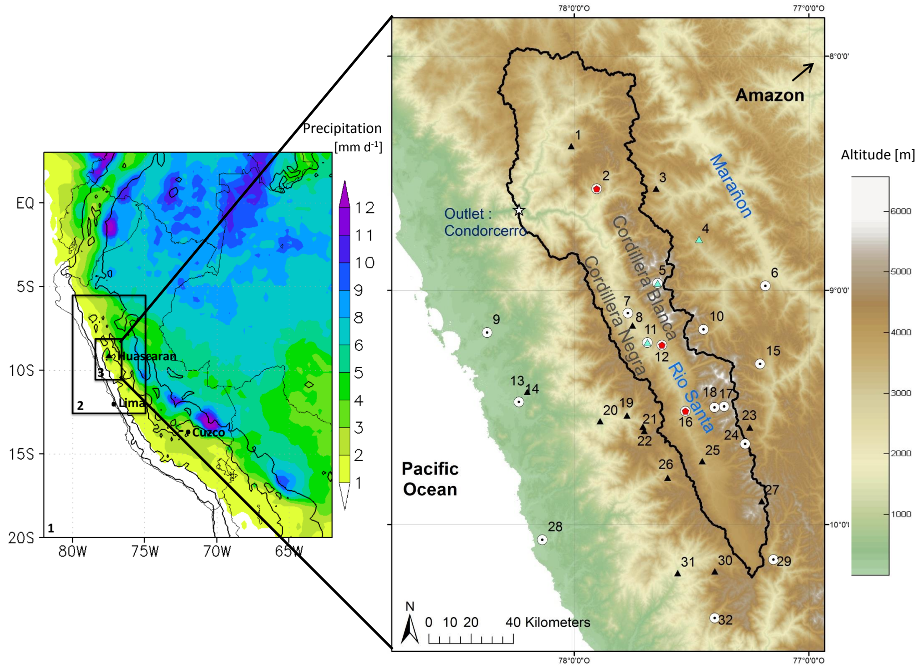

Figure 1. Left: mean daily precipitation TRMM for the hydrological year 2012/13 and boxes of WRF simulations [1] 27 km × 27 km; [2] 9 km × 9 km; [3] 3 km × 3 km). Topography contours are displayed at 500 and 3500 m. Right: location of the upper Santa watershed (the star marks outlet: Condorcerro). White dots indicate station with hourly precipitation data (UNASAM, UGRH). Black triangles indicate stations with daily precipitation values (Senamhi). Red dots indicate the 3 stations used for the study along the Rio Santa valley. Blue triangles indicate stations used for the study of the transect along the Huascaran peak. Numbers of each station correspond to their reference in Table 1. Topography is from SRTM (http://srtm.csi.cgiar.org/).

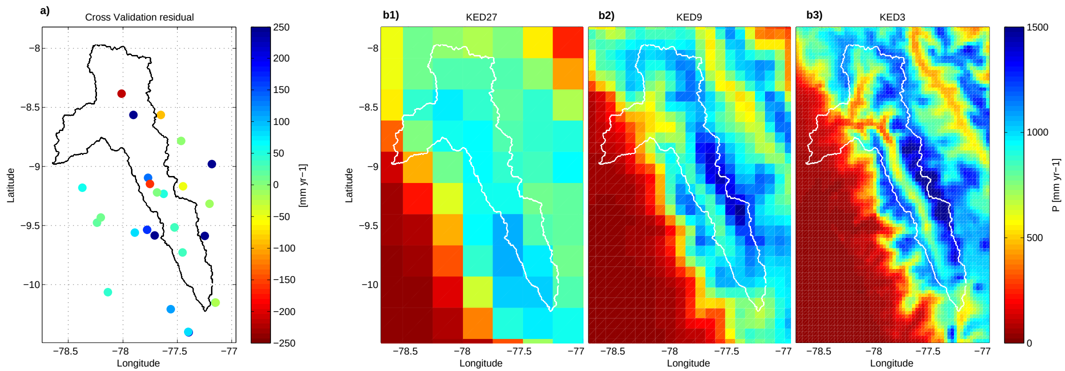

Figure 2. (a) Cross validation residuals with in situ yearly precipitation amount. **(b)** Annual precipitation amount from KED interpolations at 27 **(b1)**, 9 **(b2)** and 3 km **(b3)** spatial resolutions. Delimitation of the Rio Santa watershed is indicated in black **(a)** or white **(b)**.

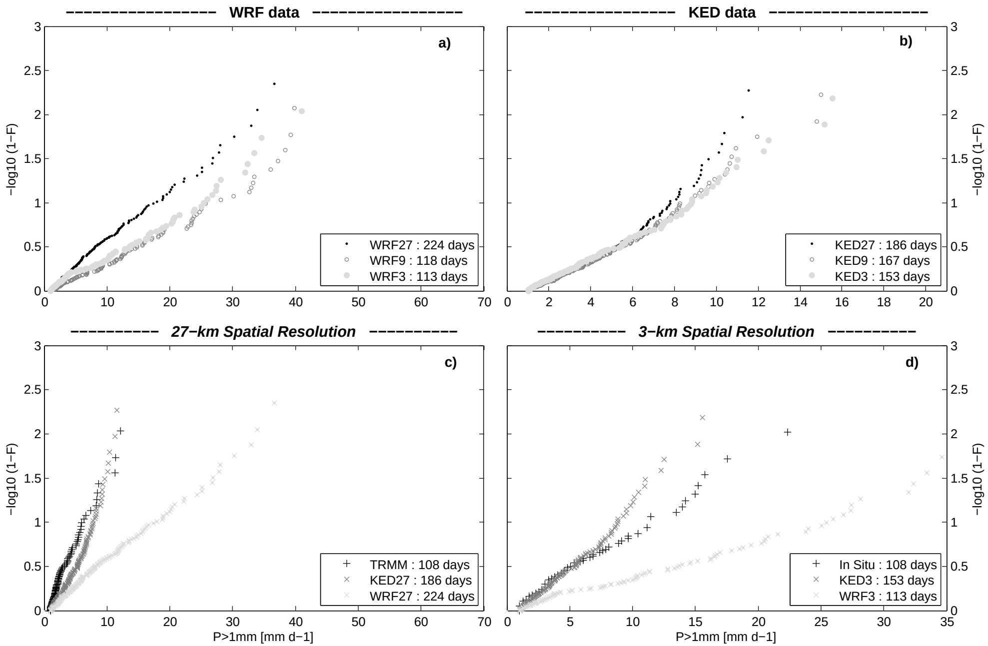

Figure 3. Frequency diagram of Corongo (station n°2) of daily precipitation data > 1 mm d^{-1} for WRF outputs **(a)** and KED products **(b)** at three different spatial resolutions, and for all products at 27 km **(c)** and 3 km spatial resolution **(d)**. Numbers in the bottom right corner indicates the number of days with precipitation > 1 mm d^{-1} for each dataset.

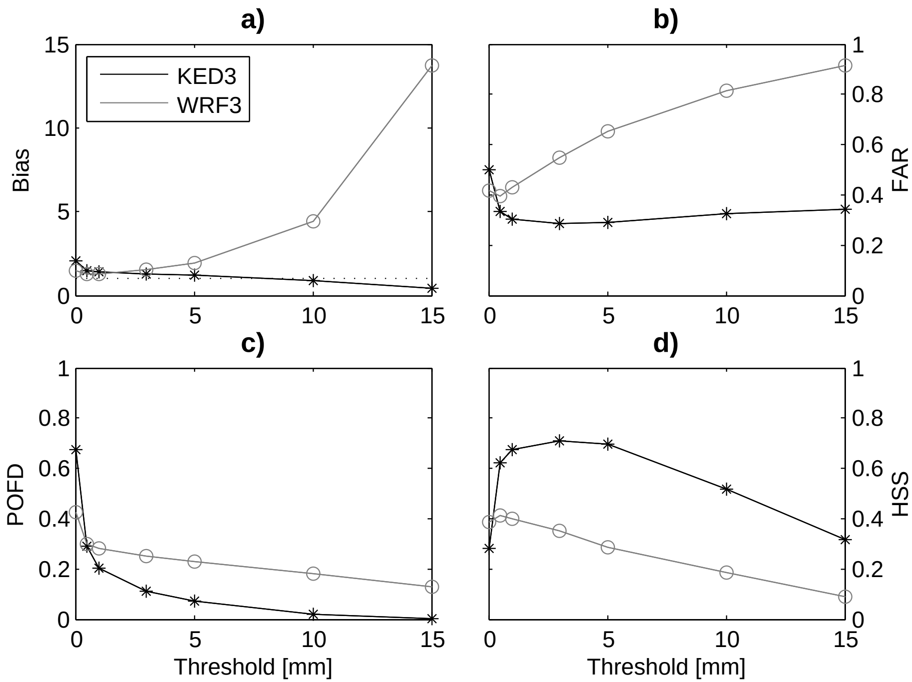

Figure 4. Daily precipitation indices: BIAS **(a)**, False Alarm Rate **(b)**, Probability Of False Detection **(c)** and Heidke Skill Score **(d)**. Calculated for KED3 (black) and WRF3 (gray) against rain gauges precipitation data located in the Sierra area. Scores have been evaluated for several daily precipitation thresholds: 0.1, 0.5, 1, 3, 5, 10 and 15 mm.

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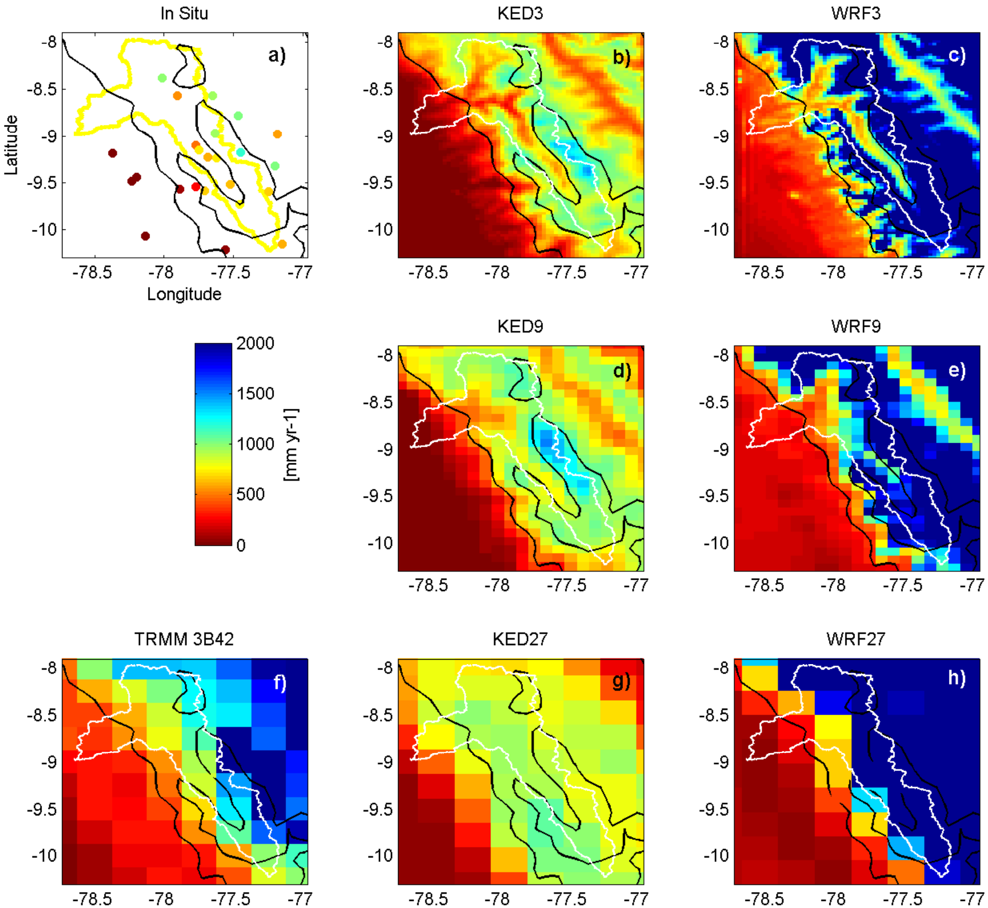

Figure 5. Annual precipitation amounts for all products. Altitudinal contours of WRF9 are drawn every 2000 m. Delimitation of the Rio Santa watershed is in black **(a)** or white.

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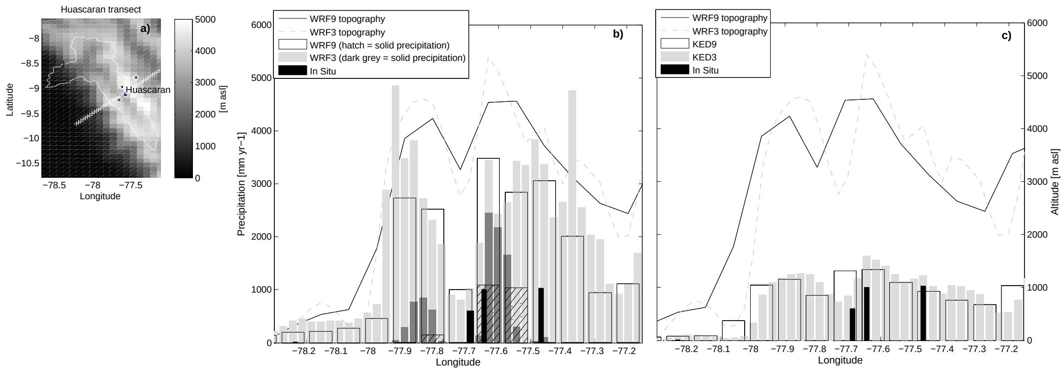

Figure 6. Annual precipitation along a longitudinal transect (white squares in **a**). Black bars in **(b, c)** corresponds to measured precipitation or accumulation. Elevation at 9 km spatial resolutions is in dark, at 3 km in dotted gray line. WRF9 liquid (empty bar) and solid (hatched bar) precipitation, and WRF3 liquid (light gray) and solid (dark gray) precipitation are plotted in **(b)**. KED9 precipitation (empty bars) and KED3 precipitation (light gray) are plotted in **(c)**.

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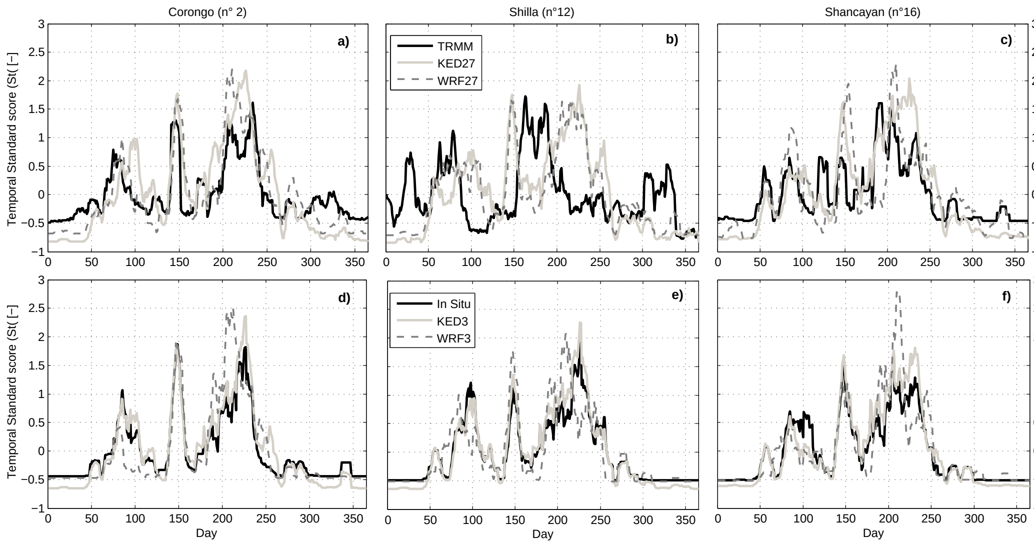

Figure 7. Temporal Standard score of running means of daily precipitation amounts aver 10 days for three stations along the Rio Santa valley, for 27 km **(a–c)** and 3 km **(d–f)** spatial resolutions. Gray line is for KED, dotted line for WRF, and dark line either for TRMM (upper panels) or in situ (lower panels). Day 1 corresponds to the 1 August 2012.

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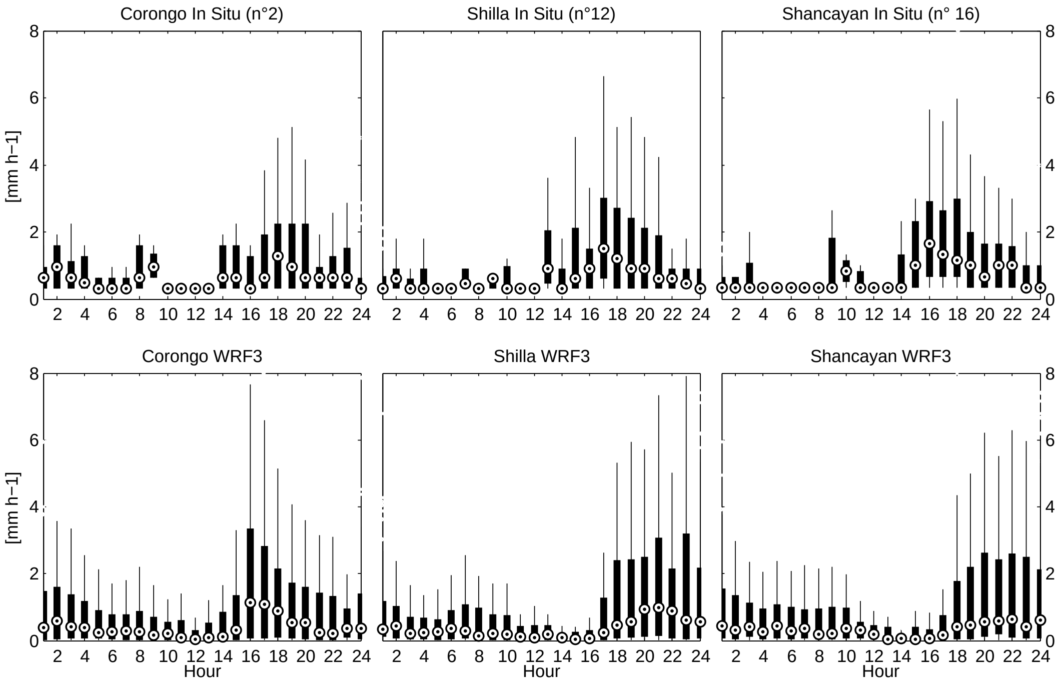

Figure 8. Box plot of hourly precipitation amounts normalized by the mean of hourly data during one year (August 2012/July 2013) for three rain gauges along the Rio Santa valley (Corongo, Shilla and Shancayan). In situ data are plotted in the upper panel, while WRF3 outputs are plotted in the lower panels.

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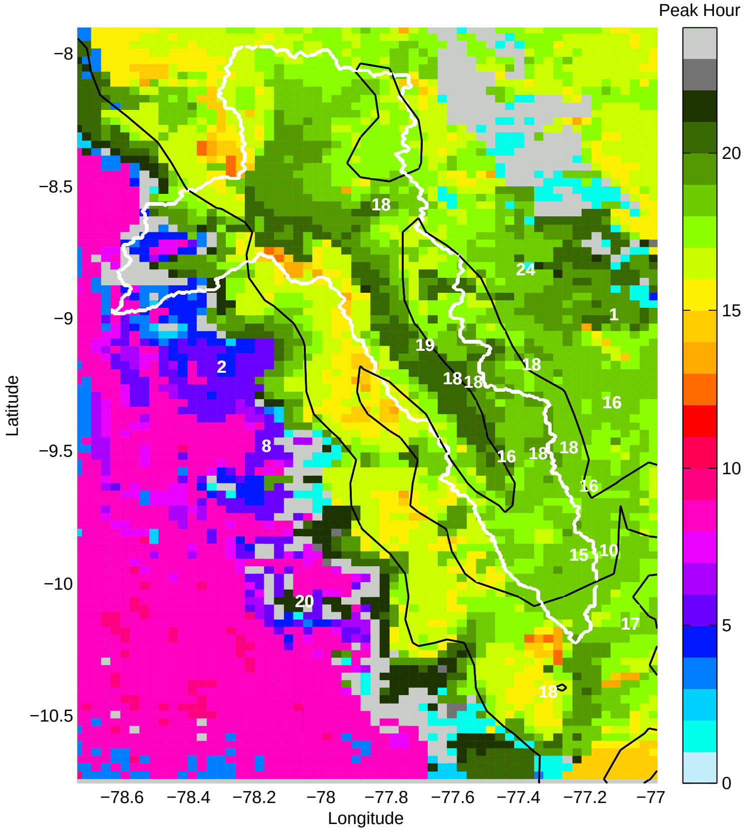

Figure 9. Peak hour of precipitation in WRF3. White numbers correspond to peak hour for the in situ data. The altitude of WRF9 is drawn every 2000 m (black lines). Delimitation of the Rio Santa watershed is in white.

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