Point by point response to the reviewers

We sincerely thank Dr Maussion and reviewer #2 for their constructive comments on our paper, and we have tried to take them into account as thoroughly as possible. The main point raised in the 2 reviews relates to the model product and the quality of the numerical simulation. We thus address this essential issue first, and we then provide point by point answers to the other comments of the two reviewers.

1. Description and purpose of the WRF simulation

Dr. Maussion comment. The authors rely on one single WRF simulation, but WRF is sensitive to the parametrizations and forcing data used. From the literature and my own experience I don't expect that the conclusions of the present study will be affected substantially (over-estimation of precipitation, for example, is a known feature of the model), but this limitation should be acknowledged in the discussion. I also have a few concerns about some aspects of the simulation design. I do not formally ask for new simulations, but I suggest the authors to consider the possibility of adding a small number of sensitivity studies (see specific comments below). This would help to strengthen their conclusions by also adding some recommendations for scientists wishing to conduct modelling studies in the region.

Reviewer #2 comment. - P. 6645, the simulations strongly depend on the choice of parameterization. Why did the authors choose this set of parameterizations? Authors should show how sensitive the results are to the choice of parameterization at least for the microphysical scheme. Provide some results from sensitivity studies.

Author response: Various WRF configurations have indeed been tested in the region. Several of them gave results very similar to the simulations presented in the paper, especially from the rainfall distribution point of view. We are therefore confident that the WRF rain field retained for comparison with the other types or rainfall product is fairly representative of rain fields produced by regional atmospheric simulations in the region. It would have overloaded the paper to enter into the details of these various configurations; however, in order to provide the reader with some background on this important issue, we added this paragraph in Section 2.5:

« *The over-estimation of the precipitation is a frequent bias in numerical models (e.g. Mearns et al 1995), particularly in complex orographic regions. Preliminary tests of sensitivity with various WRF parameterizations (including different cumulus schemes, cloud microphysics, planetary boundary layer and land surface options) have been done in the tropical Andes at a 27 km horizontal resolution; a clear over-estimation of precipitation was observed with all these configurations and over all the domain, including the high mountain areas. The biases found with other configurations were almost similar to those of the one selected here in terms of the precipitation spatial distribution, and with quantitative differences more pronounced in the eastern slopes of the Andes and in the Amazon region rather than in high mountain zones like the Cordillera Blanca. The configuration finally retained for this study (Table 3) has been selected because (i) it minimizes the positive precipitation bias in the tropical Andes above 3500m, and (ii) it simulates correctly the spatial distribution of the precipitation in the region, including the zones of maximum precipitation situated in the Amazon basin and in the eastern slopes of the Andes (Fig. 2), when compared with the TRMM data. At 3-km resolution, the Noah-MP option was found to decrease the precipitation over-estimation in the Cordillera Blanca and show a more realistic snow distribution when compared with previous observations.* »

We provide below some additional material for the reviewer. As mentioned, WRF was tested at a 27 km horizontal resolution with six different parameterizations, including different cumulus schemes, cloud microphysics, planetary boundary layer and land surface options, for the month of February 2013. Results of this WRF-Ensemble mean (WRF-EM) is displayed in Figure R1 below. Over almost the entire domain and particularly over the Cordillera Blanca, the standard deviation computed among the six monthly means (Fig. R1a) is clearly smaller than the bias computed with the WRF-EM minus TRMM (Fig. R1b).

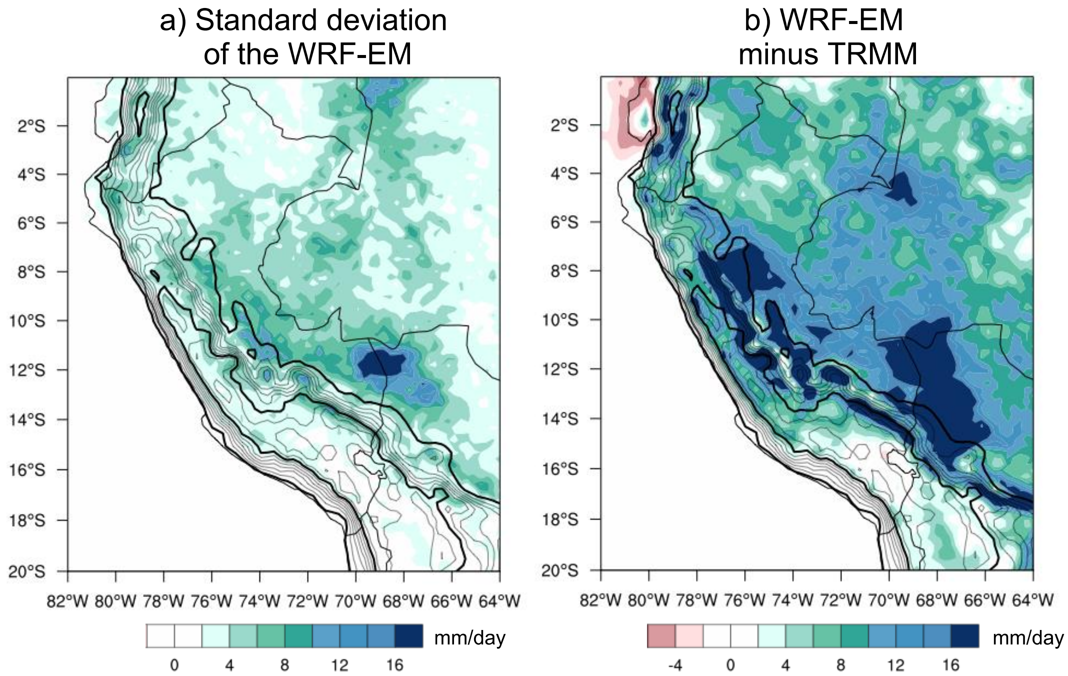

Figure R1 (not included in the manuscript): a. Standard deviation of the precipitation (mm/day) computed from the WRF-Ensemble mean (WRF-EM), six configuration of WRF-27km with different parameterization options, for the month of February 2013. b. Precipitation bias (mm/day) computed with the WRF-EM minus TRMM for the month of February 2013.

At the 3km resolution, we tested three options for the surface scheme Noah-MP during the month of February 2013. Results of this WRF3- EM are plotted in Figure R2 below, comparing monthly precipitation of WRF3-EM with in situ data. In almost all the domain, the standard deviation of the model simulations (Fig. R2a) is clearly smaller than the difference between the ground measurements and the model mean (Fig. R2b).

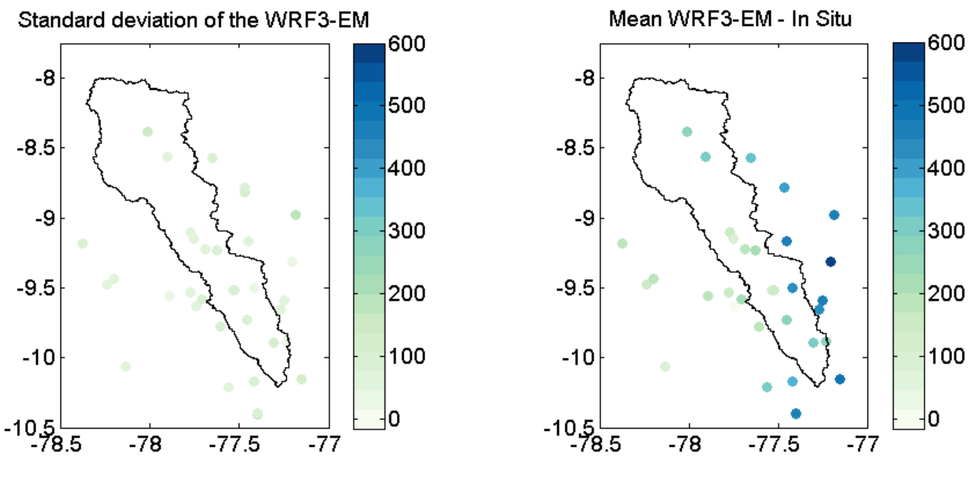

Figure R2 (not included in the manuscript): a. Standard deviation of the precipitation (mm month^{-1}) computed from the WRF3-EM (three configurations of WRF-3km with different surface scheme) for the month of February 2013. b. Precipitation bias (mm month^{-1}) computed with the WRF3-EM minus in situ data for the month of February 2013.

Response to referee #1 (F. Maussion) on "Spatio-temporal assessment of WRF, TRMM and in situ precipitation data in a tropical mountain environment (Cordillera Blanca, Peru)" by L. Mourre et al.

1. General discussion on the quality of the chosen products

A first general comment on the quality of the chosen products is that we do not pretend that they are the best possible candidates for representing their respective family. We only think that in each case they are reasonable choices, so that their main characteristics can be considered as typical of the family to which they belong.

Our second comment is that the goal of the paper is to assess the main differences between these products so as to draw the attention of the reader on their possible bias and shortcomings, keeping in mind that we claim that no rainfall product in this region can be considered as a reference at all scales. Thus it would be very difficult to state which product is the best within a given family.

Third, we must recognize that it is indeed a natural request to provide the reader with some information on the spread of the characteristics of the products belonging to the same family, in order to be able to judge whether the differences between the typical products of each family are significantly larger than the differences between products of the same family.

And finally the remarks and questions of the two reviewers are extremely relevant and we hope to provide here the answers they deserve.

1.1 Critical evaluation of the kriging products.

Reviewer comment: *The algorithm relies on the calibration of a statistical interpolation model, with the addition of the topography as a further predictor. As acknowledged by the authors, this does not work very well since the precipitation maxima are found at the mountain tops. The authors however do not discuss another (to my opinion, more important) short-coming of this method: the direction of the air flow. It is well known that the leeward and windward sides of orographic barriers have opposed precipitation patterns. The shortcomings of KED are best shown in Fig. 05: the north-eastern part of the domain (towards the Amazon Basin) should be much wetter, as shown by TRMM and WRF. Here the effect of topography is overestimated by the KED model.*

This might not be too problematic within the Rio Santa basin thanks to the reasonable number of stations on each side of the basin. Outside of the basin the KED results should be interpreted with great caution. I would argue that the omission of the air flow directions is the major reason why the daily-evolving variogram performs best for the cross-validation (Table 5): it contains indirect information about the air flow through the current precipitation patterns that day (K-DE works also better than KED-M for the daily values).

Author response: As the reviewer points out, the north-eastern part of the domain (towards the Amazon Basin) is much dryer in KED outputs compared to what it is in WRF and TRMM. This underestimation is primarily due to the lack of sampling in this area which does not allow catching the rainfall effect of the moisture influx from the Amazon Basin. Our belief is that no statistical method could really make up for this lack of measurements. KED is an efficient interpolator when a simple external drift – as the altitude – can be found. But when it comes to incorporating in the interpolation such a changing and complex variable as the air flow, we cannot rely on a simple linear method. This is why physical models are a necessary complement of ground measurements, especially in those regions of great spatial variability associated with a complex topography.

The fact that rainfall is significantly underestimated in the Amazon Basin is not a major concern for us, since the focus of the paper is on the Santa catchment. However we added a comment in the new version in order to acknowledge this problem (in Section 2.1 of the new version).

It is a reasonable assumption that DE (daily evolving) variogram contains information about the spatial structure of precipitation related to the air flow direction, explaining why this type of variogram gives better results; but in fact it is a more general statistical matter that DE variograms are more tied up to the observed structure of the daily rain field than an average variogram.

> Reviewer comment: *Furthermore, when comparing the KED products to the other products at the station locations (Figs. 3, 4, 7) the authors should not use the full-model products but the cross-validation ones. For example, the frequency diagrams at Corongo should not rely on the observations at Corongo for the calibration. Maybe the authors did this already it is not clear from the text. This might well mitigate the good results of KED in these analyses.*

Author response: This is absolutely right and in the new version we use the ground cross-validation products rather than the ground full-interpolation products thus removing the methodological bias associated with the latter.

While the results are very similar for the 27-km resolution, a change in the upper part of the distribution is observed at the 3-km resolution (Figure 4; Figure 3 in the previous version of the paper), resulting in a slight decrease in performance with respect to the HSS index in figure 5 (figure 4 in the previous version of the paper), and also concerning the precipitation above 5 mm d^{-1} in figure 3 (figure 4 in the new version). This shows that the empirical distribution of the ground rainfall products is indeed very sensitive to the network sampling. When there are no observations within a grid mesh, the smoothing out produced by the interpolation process tends to minimize the occurrence of strong rainfall while overestimating the occurrence of rainfall (187 days in the cross-validation product against 153 days for the full sample product).

On the other hand as for the ground full-interpolation products, the WRF and KED products remain significantly different with a likely strong overestimation of heavy daily rainfall by WRF.

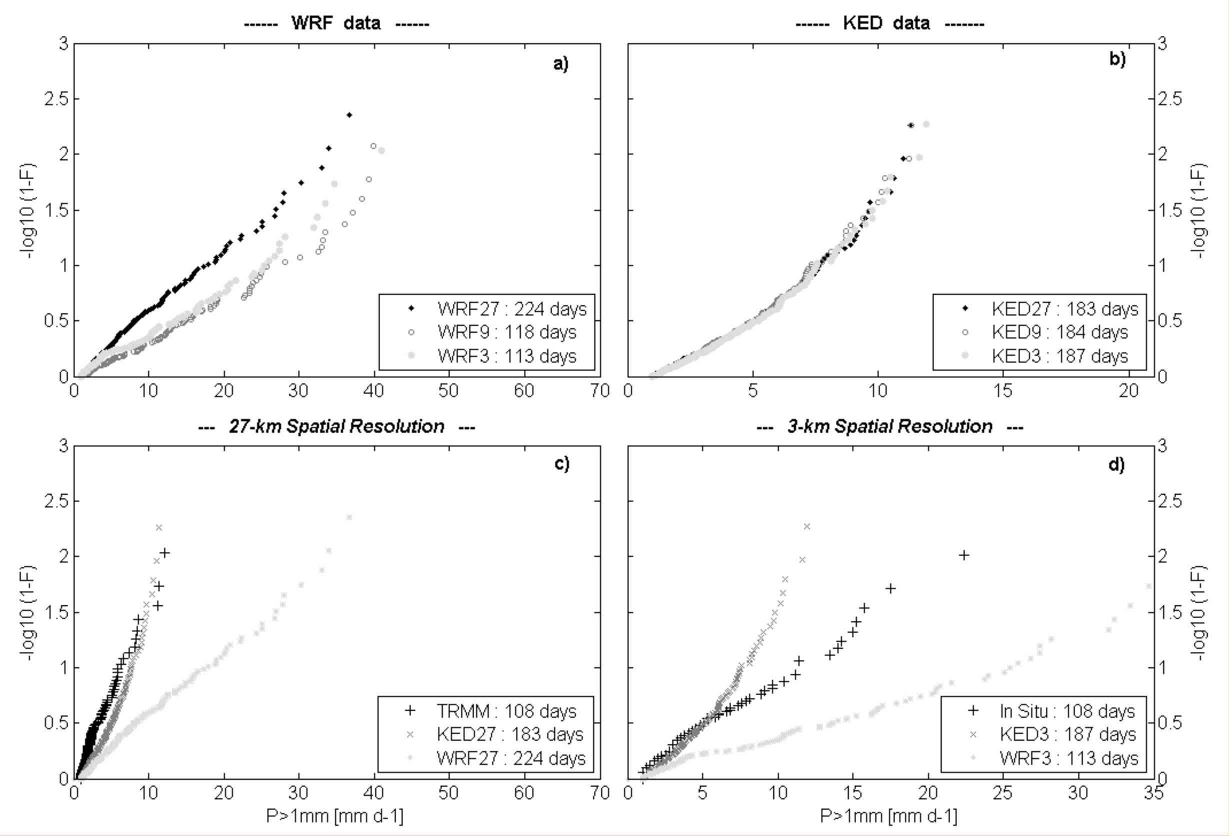

Figure 4 (Figure 3 in the previous version): Frequency diagram of Corongo (station n°2) of daily precipitation data > 1 mm d^{-1} for WRF outputs (a) and KED products (b) at three different spatial resolutions, and for all products at 27 km (c) and 3 km spatial resolution (d). Numbers in the bottom right corner indicates the number of days with precipitation > 1 mm d^{-1} for each dataset.

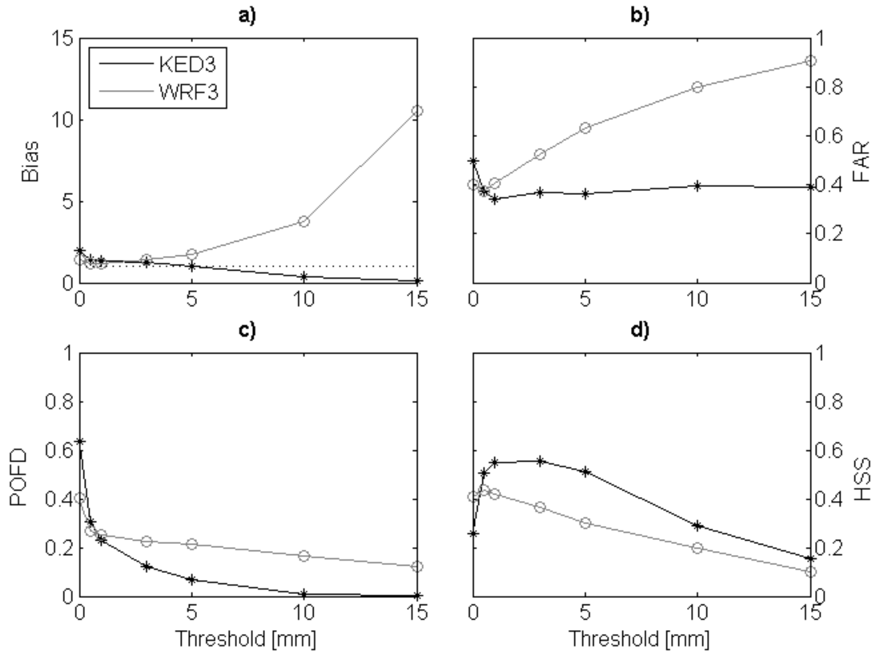

Figure 5 (Figure 4 in the previous version): Daily precipitation indices: BIAS (a), False Alarm Rate (b), Probability Of False Detection (c) and Heidke Skill Score (d). Calculated for KED3 (black) and WRF3 (gray) against rain gauges precipitation data located in the Sierra area. Scores have been evaluated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

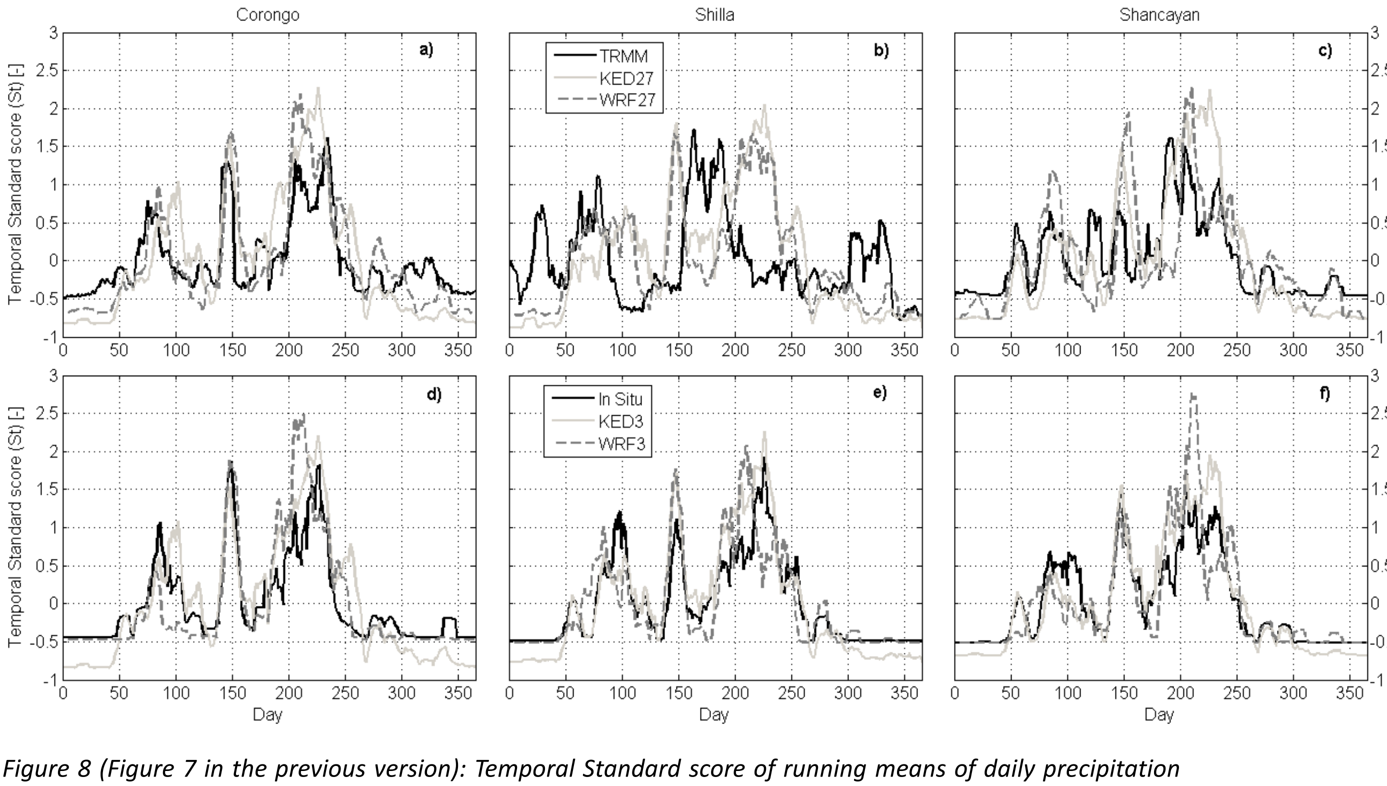

Figure 8 (Figure 7 in the previous version): Temporal Standard score of running means of daily precipitation amounts over 10 days for three stations along the Rio Santa valley, for 27 km (a-b-c) and 3 km (d-e-f) spatial resolutions. Gray line is for KED, dotted line for WRF, and dark line either for TRMM (upper panels) or in situ (lower panels). Day 1 corresponds to the 1st of August 2012.

Shorten the text to focus on the essentials:

Reviewer comment. The manuscript could attract more readers with a clearer and more concise writing. There are some repetitions throughout the manuscript, the introduction material is sometimes only indirectly related to the study.

Author response: Following the advice of the reviewer several modifications were made in order to avoid repetitions and to better focus the paper (abstract, introduction, comparison of the ground products, conclusion).

2. Specific comments

Reviewer comment. Abstract: It is a matter of taste but I suggest to avoid using paragraphs and to shorten it. I suggest to remove certain details ("largely due to operational constraints", "glacial area", "Thompson microphysical scheme", . . .) and to avoid repetitions ("– ground based, satellite derived, RCM outputs –" repeated afterwards anywhere, "here", etc.).

Author response: As proposed, certain details had been removed in the new version of the paper.

Reviewer comment. P6639 you write: "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". You should be more careful here because you actually don't (and can't) address all these scales (data availability, computational cost of WRF, etc.). I would welcome a more concrete formulation of the study's objectives.

Author response: A more specific formulation is used in the revised version:

"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 sub-daily to yearly temporal scales."

Reviewer comment. P6639 "the precipitation produced by climate models" → I suggest to use a more precise formulation ("climate models" cover a wide range of models). I would also refrain to use the term "RCM" for your WRF simulation: a one year long simulation data forced by analysis data cannot be termed a "climate simulation". Some studies prefer "Mesoscale Atmospheric Model" (MAM), or simply "Numerical Weather Prediction model" (which is, after all, what WRF was designed to be).

Author response: Agreed: a one year study is obviously not a climate simulation; "RCM model" was replaced by "WRF model", throughout the paper.

Reviewer comment. P6645, WRF simulation: More information is needed here:

• Rationale for the choice of the first domain boundaries. Domains 2 and 3 are close to the western boundary of domain 1, which is usually not a good thing for the consistency of the boundary conditions (the influence of the large-scale driving data is much larger at the boundaries).

Author response: Domain 1 includes all the tropical Andes, as it was designed to be part of a project including the entire region. The western boundary conditions were verified and the critical zone is not included in the domain 2.

• *Reviewer comment. For future studies, consider using reanalysis products instead of FNL analysis data to avoid time-consistency problems, as discussed by Maussion et al. (2014).*

Author response: We thank the reviewer for the suggestion. The FNL analysis were used for practical reasons, as they are more easily and rapidly available than other WRF forcing data. However a sensitivity test was performed with ERA-Interim reanalysis as forcing data, and the over-estimation precipitation bias was found to be stronger in the Cordillera Blanca region than with the FNL analysis.

• <u>Reviewer comment.</u> *Did you use a spin-up for your simulation?*

<u>Author response:</u> Yes. The simulation starts at the beginning of April 2012, but in order to perform the comparison on a 1-year hydrologic year corresponding to the period where in-situ data are available, the 4 first months were finally not used and considered as a spin-up period. This information has been added in Section 2.5 of the new version.

<u>Reviewer comment.</u> *Did you consider using some kind of nudging during the simulation time? I suspect that the good temporal performance of WRF (Fig. 7) can be attributed to the small simulation domains and to the fact that the nested domains are all close to the boundaries.*

<u>Author response:</u> Nudging was not used in our WRF simulation. The model is forced at the boundary every 6 hours. Domain 2 is close to domain 1 at the western boundary. However, the moisture flux mainly comes from the Amazon Basin, on the eastern side of the Andes (Garreaud, 2009) and the seasonal variability of precipitation is more strongly associated with regional processes from the East than from the West (except in case of a strong ENSO year).

• <u>Reviewer comment.</u> *From Table 3 it seems that you have used a cumulus parametrization for all three domains. If this is the case you should justify it. There are arguments against using cumulus parametrizations for spatial scales well below the resolutions they have been designed for (so called "gray-scales", see e.g. Arakawa (2004) or the introduction by Grell and Freitas (2014) for more references).*

<u>Author response:</u> In theory, current cumulus parameterizations (CP) were developed for grid scales from 32 to 48 km (Arakawa, 2004), and have shown to work well also for a 12-km grid resolution (Wang and Seaman, 1997). Below a 5-km resolution, the influence of CP is not clear yet, and sensitivity tests should be performed for each configuration and region of study. However, in real cases, using a CP at high resolution is useful in complex orography regions so as to improve the air column stability of the model. In addition, Gililand and Rowe (2007) have shown that it is not always appropriate to assume that model simulations using small grid spacing (< 5 km) will not need a CP. While in an idealized case with a 3-km grid scale configuration they found that a CP is not needed, in a real-case study they demonstrated that a CP is needed in order to accurately represent the small sub-grid scale processes that occur with isolated, discrete convective cells. In their example, at 3 km WRF without CP was not able to resolve all the precipitation, in a region where precipitation comes from cumulus formation.

In the tropical Andes, the most common precipitation bias of regional climate models is an overestimation in the higher mountains. Grell and Freitas (2014) show that the no-CP WRF parameterization at 5-km horizontal resolution better reproduces precipitation in the monsoon areas of South America when compared with TRMM. However, in the tropical Andes it is clear in their Figure 11 that this no-CP configuration also shows the strongest overestimation bias, when compared with activated cumulus parametrization configurations. However, more sensitive simulations should be pursued in order to confirm the use of a CP or not in Cordillera Blanca at 3-km.

These precisions were added in the text (Section 2.5).

<u>Reviewer comment. P6652, L12 "</u>*WRF overestimates rainfall, probably due to errors in the NCEP-FNL forcing": the discussion about this "overestimation" is not new. From all possible reasons, the "wrong boundary conditions" would not be my first choice. In the absence of more detailed information (further forcing data experiments? Other WRF parametrizations experiments? Underestimation of rain gauges?), I suggest to remove this sentence.*

<u>Author response:</u> We agree with the reviewer that the overestimations of rainfall in WRF cannot be attributed only to the large scale boundary forcing, and that a larger spectrum of runs would be required to deal properly with this question. As this is not on the scope of our study, the sentence was removed.

Reviewer comment. Conclusions about TRMM: I wonder if these are not an over-interpretation. Most of these conclusions are general and not directly related to the material presented in the paper.

Author response: While we did not carry out a detailed study on the TRMM product used here, the effect of ice scattering on the ground on the quality of the TRMM product for high altitude regions has been documented in previous studies (see e.g. Yin et al., 2004, the Tibetan Plateau). Considering that some studies directly use TRMM data as inputs to an hydrological model (Lavado et al., 2009; Andres et al., 2014), we believe that those remarks are relevant to our paper, which aims at providing some overall perspective on the rainfall products that can be used for forcing hydrological models in this region.

3. Technical Corrections

All the modifications related to the technical comments made by the reviewer were included in the revised version of the paper. Some of these modifications are more specifically commented below.

Reviewer comment. ***P6642*** *"one hydrological year (August 2012 to July 2013)". Unless there are good reasons to call this "hydrological year" I would suggest to simply call it "year" (most HESS readers would expect an hydrological year to span Oct. to Sep.).*

Author response: In this region, the driest months are June – August with rainfall sometimes reappearing in August. We thus think that it is appropriate to specify that our period of study roughly corresponds to a hydrological year

Reviewer comment. ***P6643*** *"summertime"→ austral summer. Are temperatures really higher during austral summer in the region?*

Author response: Although variations of the seasonal temperatures are less than 1°C in the region (Juen et al., 2007), temperatures are slightly higher during austral summer and can modify the 0°C isotherm line altitude (considering a lapse rate from other studies (Juen et al., 2007; Carey et al., 2012; Schauwecker et al., 2014) the displacement is between 125 to 155 meters).

Reviewer comment. ***P6642****, "In-situ data" The authors gathered an impressive number of stations for the region. I think that some readers will be interested to know what is the "availability" of these data. If they are available, state where they can be downloaded. If they are not publicly available, say it too (this will spare some searching time for the curious reader).*

Author response: The SENAMHI data were available thanks to our collaboration with this institute and particularly with Waldo Lavado. They are not freely available.

The UGRH data were also available thanks to our collaboration with this institute and are not freely available.

The UNASAM will normally soon be available at http://www.ciiaders.com/.

Reviewer comment. ***P6646, L10*** *"daily scale which is the corner scale for the comparison carried out in this paper": you also provide an analysis of diurnal cycles.*

Author response: The daily time scale is the only one for which all datasets are available and at which we can compare all the different sources of precipitation data. The diurnal cycle analysis is only carried out on the in situ data and the WRF3 outputs. That is why we considered that the daily time scale is the corner scale of our study.

Reviewer comment. ***P6650, L18*** *"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.": I don't understand this sentence.*

Author response: The point we wanted to make is that the differences between the WRF27/WRF9 distributions and the WRF3 distribution vary in nature from one station to another, which raises some questions on the model behavior. However, since this point is not illustrated in our paper (distributions are shown for one station only in Fig.4 –Fig. 3 in the previous version of the paper) and since it would require additional space to comment it while it is not central to the paper, we chose to remove this comment.

> Reviewer comment. ***P6652, L5*** *there are approx 13 grid points of 27km resolution in the catchment. Random sampling errors are very likely: how did you compute the area-averaged precipitation for the catchment? Did you use sub-pixel masks, or did you consider the center coordinates of the grid points?*

Author response: This is a very relevant comment that allowed improving the quality of our computations. Initially two watershed masks (at 27 and at 9-km spatial resolution) were considered. In the revised version proposed here, a new watershed mask was computed at a resolution of 90 meters in order to reduce the sampling errors in the mountainous areas. This 90-meters resolution mask was used to re-calculate the water precipitated over the catchment for all the products (each 90m*90m pixel is given the value of the coarser pixel to which it belongs). This modifies the results, as can be seen from the new Table 4.

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 hydrological year 2012/2013. 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	27×27 km²		x	x	0.83
KED9	9×9 km²		x	x	1.01
KED3	3×3 km²		x	x	0.95
WRF27	27×27 km²		x	x	2.91
WRF9	9×9 km²		x	x	1.95
WRF3	3×3 km²	x	x	x	1.97
TRMM	27×27 km²		x	x	0.57

> Reviewer comment. ***P6654, L1*** *"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.":in the "real world", yes, but not in the "WRF world". There is no subgrid topography in WRF and it is a common misinterpretation: the grid cell height in the one "true" height in WRF and the solid precipitation estimations of WRF are based on this altitude only.*

Author response: The reviewer is right, WRF has no subgrid parameterization and the altitude of the grid cell is the true one for the selected resolution. However, when using WRF precipitation as inputs for glacio-hydrological modeling with a finer spatial resolution for the topography, not taking the precipitation gradient within the original WRF pixel will have some impacts on the quality of the simulation. Nevertheless, we removed this sentence that could be misunderstood in this context.

*<u>Reviewer comment.</u> **P6654, L16** "as ice on the ground scatter energy in a similar way as precipitation drops in the atmosphere (Maussion et al., 2011)": Let's try to avoid reference chains. Maussion et al. (2011) (wrongly) attributed this sentence to Yin et al. (2008) who in fact referred to their earlier study (Yin et al. 2004).*

<u>Author response:</u> We give this citation back to Yin et al. (2004).

***Fig. 8**: specify which time is used (LT?). Station observations: the hours of day where precipitation is not observed at all seem unlikely (e.g. from 4H to 9H at Shancayan). Any explanation?*

<u>Author response:</u> Local Time (LT) is used in this figure. Most of the UNASAM stations measure little rainfall during the second part of the night. However the scale of figure 8 (figure 9 in the new version of the paper) was misleading. The threshold of detection with the tipping bucket gauge used is 0.254 mm. As can be seen from the additional figure R3 presented below several isolated tipping occurrences can be recorded in the early morning, but it is very rare to observe more than 2 tippings during one hour for this part of the day and few days recorded rainfall during those hours.

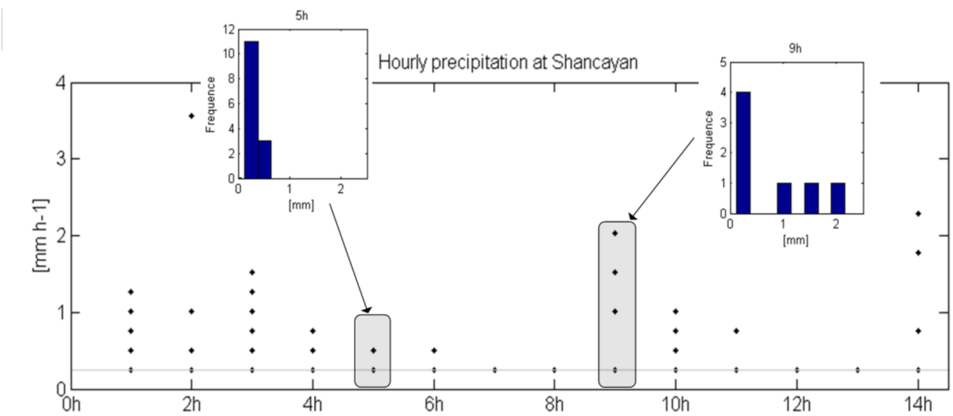

Figure R3 (not included in the manuscript): Values of hourly precipitation at Shancayan between 0h and 14h for the hydrological year 2012/2013 (1st August 2012 to 31st July 2013). The gray line corresponds to the threshold detection of the tipping bucket gauge. Note that each black point is representative of several measurements.

*<u>Reviewer comment.</u> **P6657** "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": I don't understand this sentence.*

<u>Author response:</u> Applying WRF in Portugal at 9 and 27 km spatial resolution, Soares et al. (2012) concluded that the non-hydrostatic effects of WRF where relevant for resolution of 10 km or higher, and that at this resolution convection is partially solved. However, this sentence, which is based on a single source, was removed.

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Response to referee #2 on "Spatio-temporal assessment of WRF, TRMM and in situ precipitation data in a tropical mountain environment (Cordillera Blanca, Peru)" by L. Mourre et al.

1. Quality of the rain fields

Reviewer comment. - P. 6639, lines 15-25: provide more detail about QC and information about the average distance between rain gauges (this can also be addressed in sec. 2.2);

Author response: We added information concerning the quality control of data in the section 2.2: "The SENAMHI data are routinely quality controlled, using standard procedures in use in the Met services worldwide. For the UGRH and UNASAM data, we had to carry out our own quality check leading to remove errant values, for instance by comparing precipitation amounts reported by stations located in the same area. "

The average minimal distance between rain gauges is 24 km.

Reviewer comment. - P. 6641, lines 13-14: What would be the desired distances between rain gauges in order to account for spatial variability in Peru?

Author response: This is a very relevant question, difficult to answer quantitatively. The spatial variability depends on the temporal scale at which data are analyzed. Annual precipitation amounts are spatially smoothed and required less rain gauges in order to account for the yearly spatial precipitation pattern. The rain gauges network has to be adapted to the temporal resolution studied. For daily precipitation, we generally consider that the distance between stations has to be less than 50 km. In this context, the southern part of the Upper Santa watershed is well sampled while we have to regard with caution results in the northern part.

Reviewer comment. - P. 6642, What QC is applied to the data? What is the error bar?

Author response: Considering the QC, see above answer to commentary of P. 6639, l. 15-25. In a conventional manner, it can be considered that errors are 5 to 10 % precipitation measurement. The WMO project of precipitation measurement inter comparison (Sevruk et al., 2009) concluded with the value of 3 % for liquid precipitation and up to 80 % for solid precipitation. Gauge in the Rio Santa mainly measure liquid precipitation.

2. Specific comments

Reviewer comment. - P. 6638, line 3: change to "westerly flow causing dry conditions due to the cold Humboldt current";

Author response: We changed the sentence

Reviewer comment. - P. 6638, lines 10-12: explain how SST and ENSO affect rainfall;

Author response: Studying 155 meteorological stations in Peru between 1965 and 2007, Lavado and Espinoza (2014) concluded that precipitation anomalies are significant only during strong ENSO events, when the Southern Oscillation Index is greater than 10 in absolute value.

In the Introduction, we added:

"According to Lavado and Espinoza (2014), the Rio Santa catchment belongs to an area where positive precipitation anomalies are observed during strong Niño as well as during strong Niña events."

Reviewer comment. - P. 6638, lines 15-20 windward and leeward depends on the flow, which can be easterly or westerly, I assume that authors mean easterly flow when they use windward or leeward, but it is not really clear throughout the paper

Author response: For more clarity, we indicated that the term "windward" was considered during easterly flow (section 1) in the new version.

<u>Reviewer comment.</u> - *P. 6639, lines 3-4 clarify what are the common features and what are the socio-economic stakes in Peru*
<u>Author response:</u> The "uncommon geographical features" refer to what has been described in the preceding lines in the introduction:

- P. 6637, l. 7-8: "*the Cordillera Blanca is the most glaciated tropical mountain range in the inter-tropical band.*"
- P. 6638, l. 1 : "*there is a strong seasonality of precipitation*"
- P. 6638, l. 13-14: "*The rainfall climatology is also characterized by strong spatial gradients at all temporal scales.*"
- P. 6638, l. 26 : "*Another issue arises from the high altitude*"

The socio-economic stakes in Peru are "*the access to drinkable water in urban areas, the yields of agricultural projects and the operation of numerous hydroelectric power plants*" (P. 6639, l. 6-7) (Carey et al., 2014). As this is not the main subject of the study, we chose not to detail more those topics.

<u>Reviewer comment.</u> - *P. 6639, lines 25 since TRMM only passes 1-2 per day, the daily data are basically surface observations.*
<u>Author response:</u> TRMM3B42 also includes data from GMS (Geostationary Operational Environmental Satellite), GOES-E and GOES-W (Geostationary Satellite Server), Meteosat-7, Meteosat-5 and NOAA-12 (Huffman et al., 2007). The in situ data are included only at a monthly time step. TRMM3B42 data are then not basically surface observation but are derived from a complex algorithm.

<u>Reviewer comment.</u> - *P. 6641, line2: indicate Huascaran in Fig. 1 (so that it is visible)*
<u>Author response:</u> We plotted Huascaran in figure 1.

<u>Reviewer comment.</u> - *P. 6641, lines 15ff: What is the study area, the watersheds or rectangular boxes? Need to be indicated somewhere. Also is 2012-2013 a good representation for rainfall in Peru, it needs to be somehow put into relation to other years.*
<u>Author response:</u> The studied area is the one that was presented in figure 1b. In order to add precision, we now devote the entire figure 1 (in the new version of the paper) to the study area. Boxes of WRF simulations are then shown in a separate figure (figure 2 in the new version of the paper). We also added two sentences in the text in section 2.1:
"The larger studied area is a rectangle of 84 000 km² (Fig. 1)."
"While we will be looking at the entire 84 000 km² region, our analysis is focused on the precipitation falling over the Upper Santa watershed, because this is our region of interest from a hydrological standpoint and because it is where we have the best ground network coverage."
The year 2012-2013 is compared to other years through the pluviometric index (see next commentary).

<u>Reviewer comment.</u> - *P. 6642, line 24: explain pluviometric index*
<u>Author response:</u> The pluviometric index was calculated with the following equation:

$$I_p = \frac{1}{N}\sum_{i=1}^{N}\frac{P_i^j - \overline{P_J}}{\sigma_j}$$

Where P_i^j is the annual precipitation for year i at location j, $\overline{P_J}$ and σ_j are the inter-annual mean and standard deviation for annual precipitation at location j in mm yr^{-1}. N is the number of stations. The results for the period 1965-2013 are shown in the figure below (additional material not included in the paper).

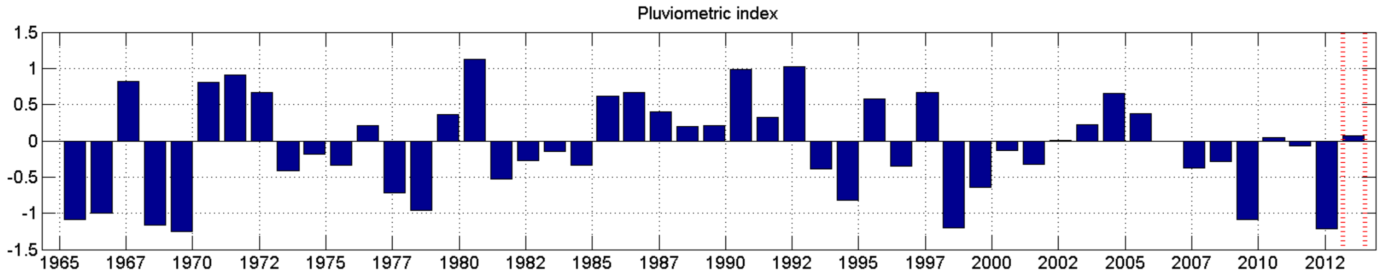

Figure R3: Pluviometric index for 10 long term SENAMHI stations. The vertical red bars delimit the studied year.

We also looked at the 2012/2013 year in a synoptic context with the MEI, PDO and AMO index. Considering the figures R3 and R4, we conclude that 2012/2013 can be qualified as a "standard" year during the period 1950-2013.

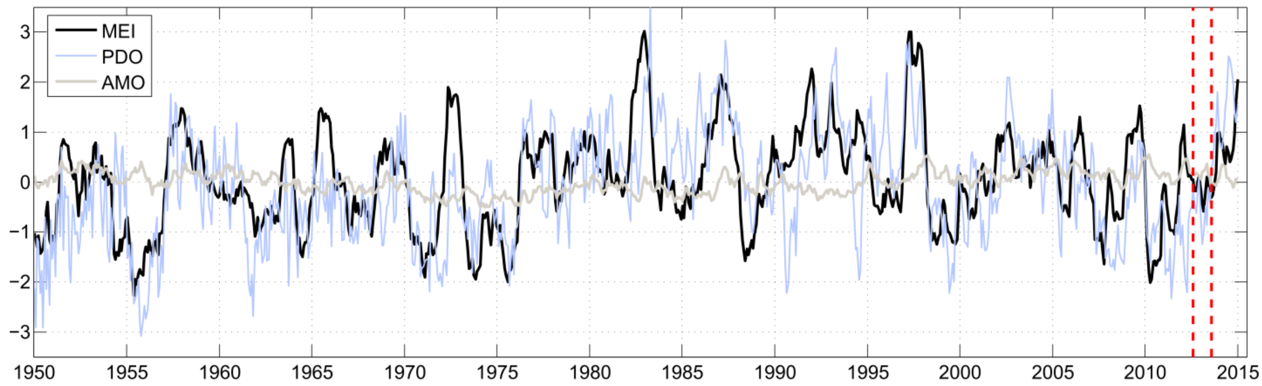

Figure R4: Variations of monthly index of MEI, PDO and AMO. Data are from the NOAA. The vertical red bars delimit the studied year.

<u>Reviewer comment.</u> - *P. 6644, lines 18-22: clarify and be more specific*

<u>Author response:</u> *"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."*

As this sentence is confused and does not provide essential information in order to understand the text, we will remove it.

<u>Reviewer comment.</u> - *P. 6648, lines 14-21, Table 6; clarify and explain what A, B, C, D are*

<u>Author response:</u> We explained in the legend of Table 6 what are A, B, C and D:

"Contingency table used to assess the statistical performances of the 3-km resolution products against punctual in situ data at a daily time scale. The B value corresponds for example to a day with no precipitation in the in situ measured data and precipitation > threshold mm d^{-1} in the 3 km grid product."

<u>Reviewer comment.</u> - *Section 3.3: The performance of rain gauge vs model strongly depends on the weather type. If the rainfall is more convective (or has embedded convection, which is very likely in orographic rain) than we would expect the model maybe to outperform the observations, in particular when the observations are coarse. Maybe WRF3 does not overestimate rainfall but the rain gauges underestimate rainfall, which is typically the case in orographic rain. Justify your argument that KED3 is better than WRF3.*

<u>Author response:</u> There is no conclusion in this section 3.3 saying that KED3 is better than WRF3.

Moreover, the goal of the paper is to assess the main differences between products, based on the idea that no rainfall product in this region can be considered as a reference at all scales. In this context, we don't understand this remark.

Reviewer comment. - *P. 6652, lines 11-14 - Quantify why WRF overestimates rainfall and show that it is related to NCEP-FL if you claim this.*
Author response: As pointed out by the reviewer #1, the overestimation of rainfall in WRF cannot be attributed only to the large scale boundary forcing (NCEP-FNL) and a larger spectrum of runs would be required to deal properly with this question. As this is not on the scope of our study, the sentence was removed.

Reviewer comment. - *P. 6652, line 15: TRMM product includes in-situ observations therefore it is not surprising that TRMM and KED27 are almost identical, please state this in the text*
Author response: We wrote in the text (P. 6652, l. 15-16):
« TRMM and KED27 are closer along the Rio Santa valley, as they both incorporate rain gauges data. ».

Reviewer comment.- *P. 6652, line 16: Where is the Maranon watershed?*
Author response: We outlined the Marañon watershed in figure 1b (figure 1 in the new version of the paper).

Reviewer comment. - *P. 6655, lines 24-27: Show that WRF is capable of retrieving mountain circulations. I personally doubt it. The better representation of the 3 km run is solely due to resolving the terrain, i.e., better vertical velocity and adiabatic cooling both creating more clouds and precipitation.*
Author response: Previous studies have found that at high spatial resolution of WRF is able to reproduce the main atmospheric circulation features in complex mountain regions (e.g., Jimenez et al, 2013), and in particular the upslope and downslope flows in zones of large valleys (e.g. Weckwerth et al, 2014). However, we agree with the reviewer and it is not clear yet if such mechanisms occur in the Santa basin and if WRF is reproducing it or not.

Reviewer comment. *Fig. 1left: enlarge figure; what are all these lines and which ones are 500 and 3500m?*
Author response: In new Figure 2 a bold isoline of topography is displayed every 500m. Other thin lines are national borders.

Reviewer comment. *Fig. 1right: outline all watersheds and domains that are discussed in the paper (also watershed in 1b looks different than in 2a?)*
Author response: In new Figure 1, the Marañon watershed was also plotted, and to clarify the figures, we plotted in all figures the Upper Santa watershed, with an outlet at Condorcerro.

Reviewer comment. *Fig. 2 outline the coast and water sheds*
Author response: We marked the 0 meter line, indicated the Ocean and the Upper Santa watershed.

Reviewer comment. *Fig 3: light gray is hard to see*
Author response: We increased the marker sizes for more visibility.

Reviewer comment. *Fig. 5 what exactly are the yellow, black and white lines? Which ones are the altitude lines and what altitude is it?*
Author response: We modified all Upper Santa watershed contours into gray and indicated in the first plot the altitude of the iso-altitudes lines (0, 2000 and 4000 meters asl).

Reviewer comment. *Fig. 6a: enlarge; Fig. 6b-c: dashed line is impossible to see and light gray is hard to see as well; change "is in dark" to solid black line, in caption mention the black bars*

Author response: We modified the dashed line of WRF3 topography.

Reviewer comment. *Table 1: remove table and put rainfall information in scatter plot and provide a statistics about the differences.*

Author response: We added rainfall information in a scatter plot in figure 1, but we choose not to remove table 1 to keep those synthetized information about the elevations and locations of all stations.

Reviewer comment. *Table 6: don't understand it and maybe can be put in the main text*

Author response: We explained the legend for more clarity (see above answer to commentary P. 6648, lines 14-21, Table 6).

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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], 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}

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

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 (kriging interpolation), satellite derived (TRMM3B42), atmospheric model RCM outputs (WRF) – are compared here during the for one hydrological year 2012/2013 in order to retrieve rainfall patterns at time scales ranging from sub-daily to annual over a watershed of approximately 10 000 km² in Peru. It is a high altitude catchment, located in the region of the Cordillera Blanca, with 41% of its area above 4 000 m a.s.l. and 340 km² 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. An ensemble of three different spatial resolutions is considered for the comparison (27, 9 and 3 km), as long as a range of time scales (annual totals, daily rainfall patterns, diurnal cycle).

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 kriged products is the production of annual rainfall maxima over the

summit rather than on the slopes, mainly due to a induced by a lack of in situ data above 3 800 m a.s.l.. This study also confirms that oOne 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 The Cordillera Blanca glaciers are melting at an unprecedented high rate (e.g., Georges, 2004; Silverio and Jaquet, 2005; Vuille et al., 2008a, 2008b; Bury et al., 2011), impacting the whole water cycle of the region. 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 is consequently a key issue for properly predicting the future of the glaciers and of the associated water resources.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 due to the Humboldt current (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). According to Lavado and Espinoza (2014), the Rio Santa catchment belongs to an area where positive precipitation anomalies are observed during strong Niño as well as during strong Niña events.

The rainfall climatology is also characterized by strong spatial gradients at all temporal scales. First of all, the main annual rainfall pattern between 5°S 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 6 000 mm yr^{-1}), and much smaller precipitation amounts on the leeward side, even at high altitudes in easterly flows situation (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 4 800 meters 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 yearly temporal scales. ~~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 km² 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 4 000 m a.s.l., including the highest point of the cordillera, Huascaran, peaking at 6 768 m a.s.l. (Fig. 1). The upper Rio Santa catchment, with an outlet at Condorcerro, drains an area of about 10 000 km², 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. For a sub-watershed of the upper Rio Santa watershed (4 700 km², 8 % glaciated), ~~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 larger studied area is a rectangle of 84 000 km², 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 (> 1 100 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 mm yr^{-1} to 1 000 mm yr^{-1} (Table 1 and Fig. 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 and Fig. 1). This zone includes all stations located west of the Rio Santa riverbed, up from 3 625 m a.s.l. to an altitude of 1 000 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 1 000 m a.s.l.. The topography data shown in Fig. 1 is from STRM (90 meter resolution). While we will be looking at the entire 84 000 km² region, our analysis is focused on the precipitation falling over the upper Santa watershed, because this is our region of interest from a hydrological standpoint and because it is where we have the best ground network coverage.

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 document 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 upper 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. The SENAMHI data are routinely quality controlled, using standard procedures in use in the Met services worldwide. For the UGRH and UNASAM data, we had to carry out our own quality check, for instance by comparing precipitation amounts reported by stations located in the same area, leading to remove errant values.

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 of the ~~for a 51 years study (~~1965-2014~~)~~ period as calculated from ~~over~~ 10 long term stations among our total of ~~the~~ 37 ~~studied (Table 1)~~. Note also that 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 (Table 1 and Fig. 1).

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 5 000 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 austral summer~~time~~ when temperature is slightly higher ~~in this area~~ and that consequently few solid precipitations are observed under 4 600 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~~sampling. Satellite and ~~RCM~~ atmospheric model 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 - note however that other types of kriging interpolators were tested, but a cross validation evaluation showed KED to be the most efficient of all in our case.. 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 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~~.~~ (10% is used in this study). ~~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)~~ This is the method that was finally chosen to compute daily gridded precipitation at 27 km, 9 km and 3 km spatial resolutions, thus matching the resolution of the satellite and ~~RCM~~ WRF model products that will be presented below in Sect. 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~~our~~ 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) (Table 3~~4~~). 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 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 high resolution simulations from 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~~ model and uses a terrain-following vertical coordinate (sigma). The limited domain simulations are forced by boundary condition every 6 h~~ours~~ 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 (Table 2, Table 3). WRF9 (WRF3) simulations are forced by the WRF27 (WRF9) simulations using a one-way nesting technique. The simulations begin on April 2012, the four first months being used as a spin-up period for producing one year of data to be compared to the KED and TRMM products.

Figure 2~~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 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.

The over-estimation of precipitation is a frequent bias in numerical models (e.g. Mearns et al 1995), particularly in complex orographic regions. Preliminary tests of sensitivity with various WRF parameterizations (including different cumulus schemes, cloud microphysics, planetary boundary layer and land surface options) have been done in the tropical Andes at a 27 km horizontal resolution; a clear over-estimation of precipitation was observed with all these configurations and over all the domain, including the high mountain areas. The biases found with other configurations were almost similar to those of the configuration selected here in terms of the precipitation spatial distribution, and with quantitative differences more pronounced in the eastern slopes of the Andes and in the Amazon region rather than in high mountain zones like the Cordillera Blanca. The configuration finally retained for this study (Table 2) has been selected because (i) it minimizes the positive precipitation bias in the tropical Andes above 3500 m a.s.l., and (ii) it simulates correctly the spatial distribution of the precipitation in the region, including the zones of maximum precipitation situated in the Amazon basin and in the eastern slopes of the Andes (Fig. 2), when compared with the TRMM2B31 data. At 3 km resolution, the Noah-MP option was found to decrease the precipitation over-estimation in the Cordillera Blanca and show a more realistic snow distribution when compared with previous observations.

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~~ atmospheric 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~~The performance of the KED outputs is determined 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 (RMSE) score (Eq. (2)) and the correlation coefficient, as follows:

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

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

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~~ I~~i~~n the following, the gridded daily precipitation product at 27, 9 and 3 km spatial resolutions will respectively be referred to as KED27, KED9 and KED3~~, for the 27, 9 and 3 km spatial resolutions respectively~~ (see Table 4 and~~,~~ Fig. ~~2~~3). 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.~~

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):

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

Where *F(x)* is the cumulative frequency of the daily precipitation amount above 1 mm d^{-1} and *x* is the daily precipitation (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 56). 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) (Eq. (4 -), (5), (6) and (7)) were calculated.

$$HSS = \frac{S - S_{ref}}{1 - S_{ref}} \qquad (4)$$

$$S = \frac{A + D}{N} \qquad (5)$$

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

Where N is the size of the statistical population, and A, B, C and D values are explained in Table 56.

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)).

$$S_t = \frac{\overline{P}_j^{10} - < P_j >}{\sigma_j} \qquad (7)$$

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

It is important to mention that when comparing the performances at one location of the KED daily products with those of the TRMM and WRF, use is made of the cross-validation products, so that the local information is not taken into account, which would artificially advantage the ground product with respect to the satellite and model products.

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.

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 (n° 2 in Table 1 and Fig. 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 upper 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 5~~6~~) for all stations located in the Sierra area.

Figure 4~~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. ~~3~~4a); (ii) the three spatial resolution of KED (Fig. 4~~3~~b); (iii) comparing TRMM, WRF and KED products at 27 km (Fig. 4~~3~~c); (iv) comparing WRF and KED products at 3 km spatial resolution ~~versus~~ vs. in situ punctual data (Fig. 4~~3~~d). 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. 4~~3~~b). Concerning the 27 km spatial resolution, KED27 and TRMM are more similar to each other compared to WRF27 (Fig. 4~~3~~c), despite an underestimation of $n_{p>1}$ for TRMM (108 days) compared to KED27 (183~~6~~ days). WRF3, as WRF27 (Fig. 4~~3~~c 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. 5~~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 with 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. 4~~3~~d). 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. ~~4~~5b~~c~~-d). POFD can be seen as an inter-comparison indicator as it does n~~'~~ot 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.

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 Uupper Rio Santa catchment (about 10 000 km²) for the 27 km resolution products, range from 57450 mm yr^{-1} for TRMM to 2 910080 mm yr^{-1} for WRF27 (and 8310 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 1530% smaller larger at the 3 km resolution (95580 mm yr^{-1}), compared to the 27 km resolution, while the diminution is of 340% for WRF (1 250 mm yr^{-1} versus 2 91080 mm yr^{-1}). Figure 65 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 km 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, not catching the rainfall effect of the moisture influx from the Amazon basin. 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. 6~~5~~f 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).

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. 76b and c). At very high altitude, we compared precipitation to accumulation data measured at 5 100 m a.s.l. on the Artesonraju glacier (station n°5 from Table 1 and Fig. 1). We can observe in Fig. 7~~6~~c 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. 7~~6~~b). 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. 7~~6~~b). In WRF3, the altitudinal variation is greater than in WRF9 with summit reaching 5 000 m a.s.l., the spatial resolution is finer, and in this configuration, the orographic processes on the ~~windward~~ eastern slopes of the Andes is more pronounced and correctly represented at the 3 km spatial resolution.

Over 4 800 meters 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 ~4 800 ± 300 m a.s.l. for tropical region between ~20°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 (n° 17 in Table 1) during the years 2007-2008, so liquid precipitation can be found around 4 800 m a.s.l.. In WRF3 outputs, about a third of the precipitation amount remain liquid for mesh grids around 5 000 m a.s.l.. This could have a negative 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 n°2), Shilla (station n°12) and Shancayan (station n°16) (Fig. 1, Table 1Table 1), as these three stations are representative of others located in the Sierra area. Day 1 in Fig. 87 corresponds to the beginning of the hydrological year, the 1st of August 2012. The upper panels (Fig. 78 ab-c) correspond to the three products available at the 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. 87b). 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 (Yin et al., 2004~~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. 8~~7~~a).

Concerning the finer spatial resolution (Fig. 8~~7~~ d~~-e~~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.

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 n°2), Shilla (station n°12) and Shancayan (station n°16), display a clear precipitation peak in the late afternoon, between 16:00:00 LT and 19:00:00 LT (Fig. 9~~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. 10~~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 4 000 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 (Jimenez et al., 2013 ; Weckwerth et al., 2014), and mountain-valleys breezes seem to be accurately estimated for the 3 km resolution runs.

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: rain gauge measurements, ~~krigged rain gauge measurements, TRMM3B42~~ satellite imagery ~~product~~ and atmospheric model ~~WRF-RCM~~ outputs. While

TRMM3B42 is a widely used standard, making it a natural candidate to represent the family of satellite rainfall products, there is a larger range of possibilities for selecting a ground based product and an atmospheric model product. Preliminary tests, the results of which are not detailed in this paper, were used to finally select kriging with external drift interpolation (KED) as a typical ground based product, the external drift being the alitude. As for atmospheric models, the retained product is made of WRF simulations, WRF being run in a configuration minimizing the differences between the observations and the model outputs over the Cordillera Blanca.

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 (KED27) and for WRF simulations (WRF27). Then gauge rainfall grids and WRF simulation were also produced at the finer resolutions of 9 km (KED9 and WRF9) and 3 km (KED3 and 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~~ WRF model 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 features of precipitation fields at various time scales (from annual down to daily) was analysed when no obvious quantitative reference could be used.

In line with the results of other studies, ~~Note that~~ WRF27 simulations are found to be 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 can be explained by its ~~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 that 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 5 000 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 (Yin et al., 2004). 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. 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 2012/2013 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 n°		**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 n°		**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 n°		**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~~	~~Simulation 2~~	~~Simulation 3~~
	WRF27	WRF9	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

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)

1

Table 4: Precipitation data used in this study, with their spatial and temporal resolution, and the accumulated amount precipitated over the u~~U~~pper Rio Santa watershed during the hydrological year 2012/2013. 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.

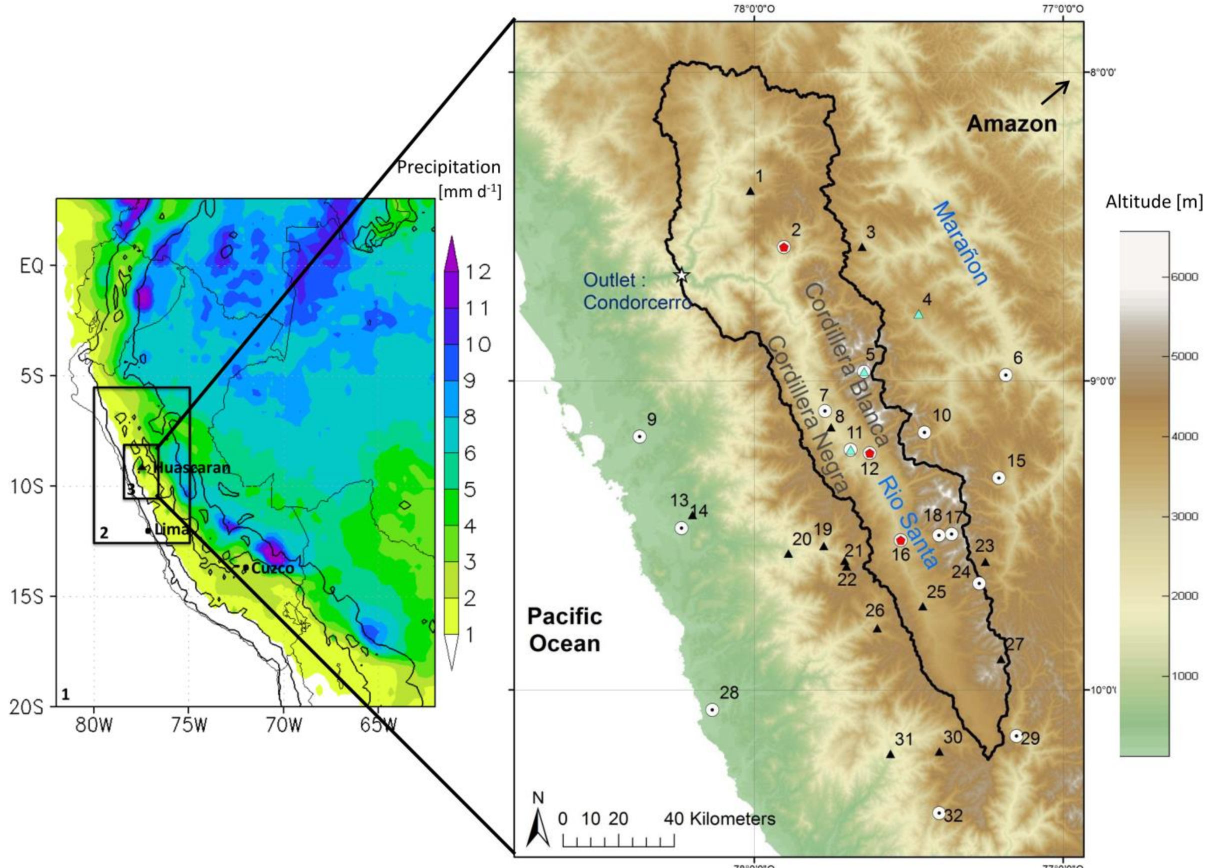
Product	**Spatial resolution**	**Temporal resolution used in this study**			**Annual precipitation over the watershed [m]**
		Hourly	**Daily**	**Yearly**	
In situ	Punctual	x	x		-
KED27	27×27 km²		x	x	0.83~~1~~
KED9	9×9 km²		x	x	1.01~~0.64~~
KED3	3×3 km²		x	x	0.95~~58~~
WRF27	27×27 km²		x	x	2.91~~08~~
WRF9	9×9 km²		x	x	1.95~~19~~
WRF3	3×3 km²	x	x	x	1.97~~25~~
TRMM	27×27 km²		x	x	0.57~~45~~

~~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

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. The B value corresponds for example to a day with no precipitation in the in situ data and precipitation > threshold mm d^{-1} in the 3 km grid product.

		In Situ	
	$\mathbf{P_j}$	Yes	No
3-km Grid product	Yes	A	B
	No	C	D



Precipitation [mm d-1]
EQ
5S
10S
15S
20S
80W
75W
70W
65W
12
11
10
9
8
7
6
5
4
3
2
1
Huascaran
Lima
Cuzco
78°0'0"O
77°0'0"O
8°0'0'
9°0'0'
10°0'0'
Amazon
Marañon
Altitude [m]
6000
5000
4000
3000
2000
1000
Outlet : Condorcerro
Cordillera Blanca
Cordillera Negra
Rio Santa
Pacific Ocean
N
0 10 20 40 Kilometers

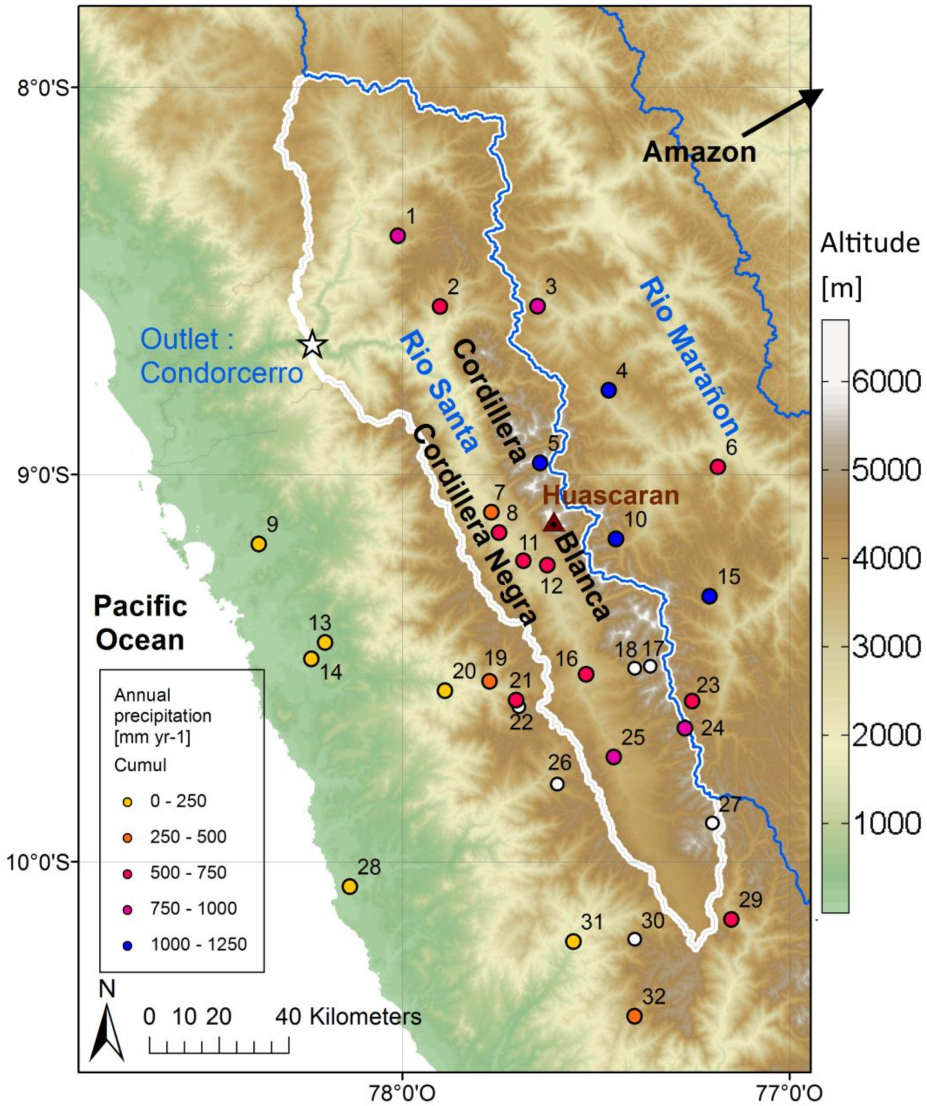


Figure 1: ~~Left: Mean daily precipitation TRMM for the hydrological year 2012/2013 and boxes of WRF simulations ([1] 27×27 km²; [2] 9×9 km²; [3] 3×3 km²). Topography contours are displayed at 500 m and 3 500 m. Right:~~ Location of the upper Santa watershed (the star marks outlet : Condorcerro). ~~White~~ Color dots indicate annual precipitation amounts at in situ stations. ~~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.~~ The Huascaran peak is indicated, as well as the Rio Marañon watershed. Topography is from SRTM (*http://srtm.csi.cgiar.org/*).

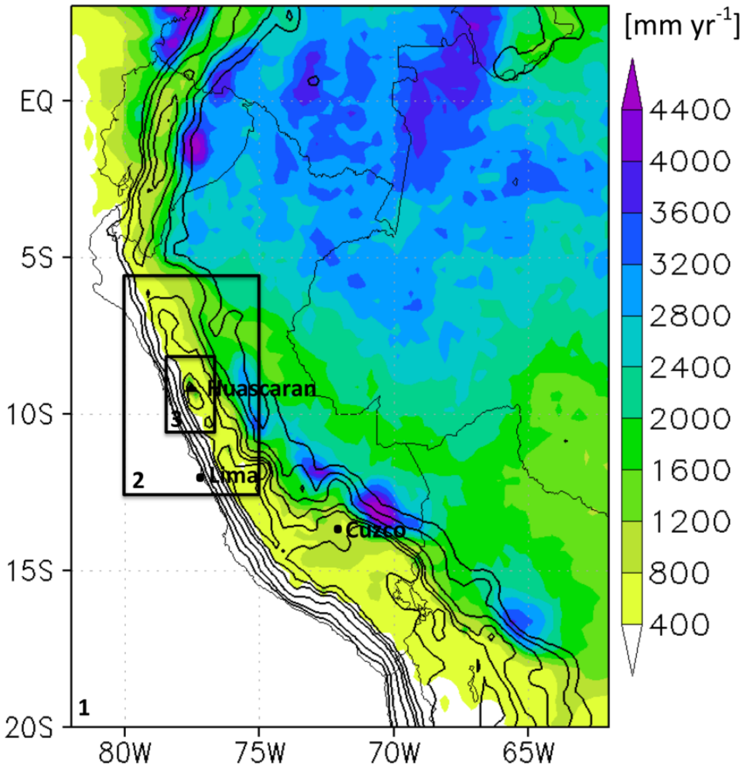
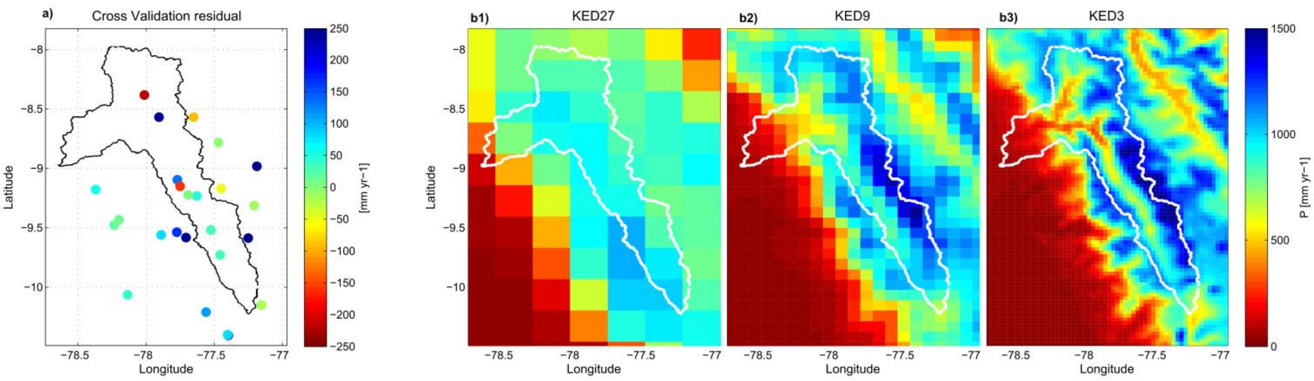


Figure 2 Annual precipitation (mm yr^{-1}) from TRMM2B31 for the hydrological year 2012/2013 (August 2012/July 2013). The 3 boxes indicate the WRF simulations domain. Box [1] for 27km × 27km;box [2] for 9km × 9km; box [3] for 3km × 3km. Topography contours are displayed every 500 m.



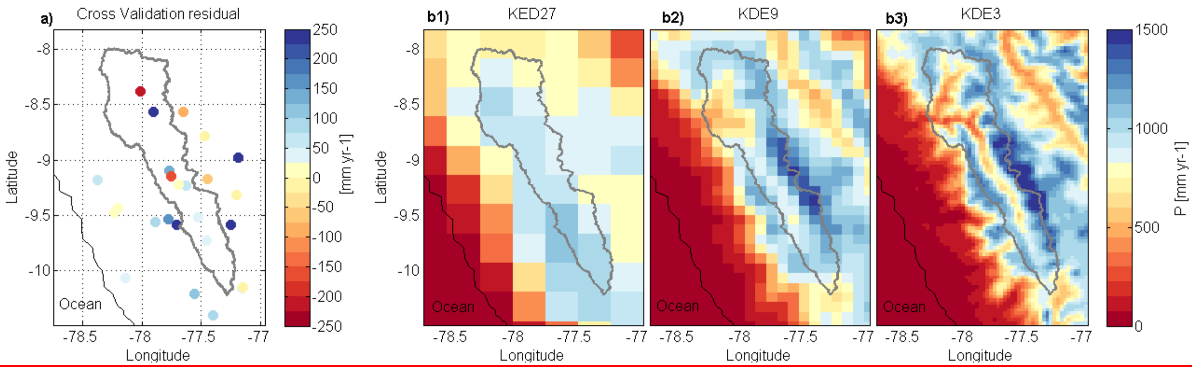
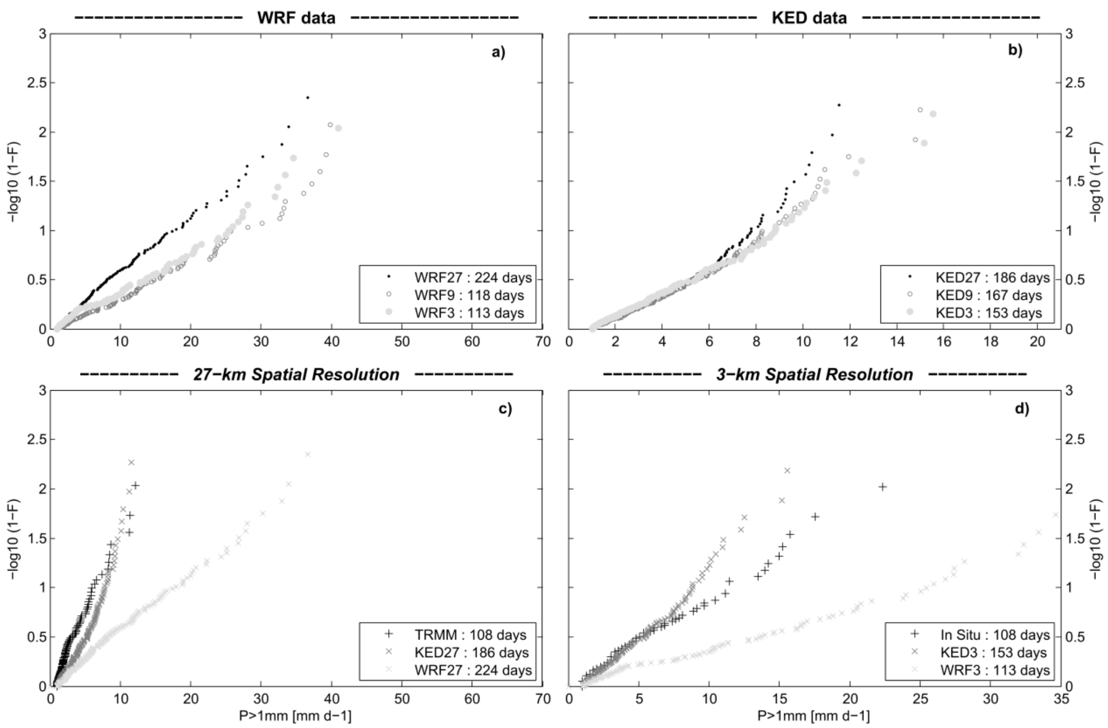


Figure 3~~2~~: a) Cross validation residuals with in-situ yearly precipitation amount. b) Annual precipitation amount from KED interpolations at 27 (b1), 9 (b2) and 3 km (b3) spatial resolutions. Delimitation of the upper Rio Santa watershed is indicated in bold gray lines. The coastline is also indicated in black~~black (a) or white (b).~~.



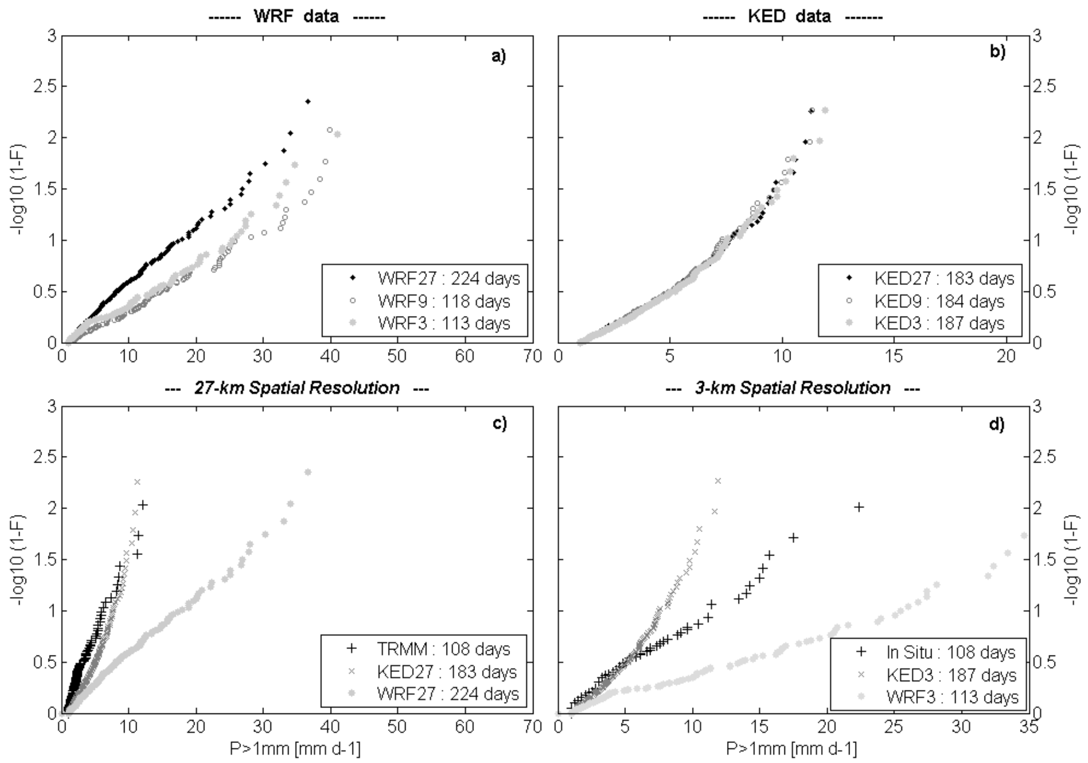
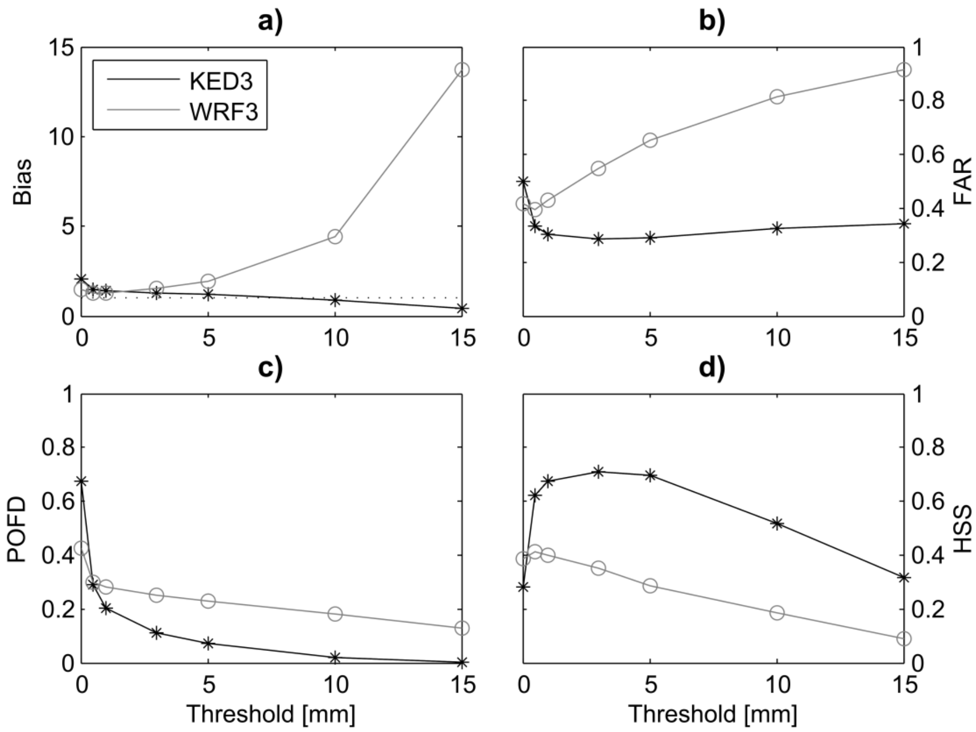


Figure 34: Frequency diagram of Corongo (station n°2) of daily precipitation data > 1 mm d^{-1} for WRF outputs (a) and KED products (b) at three different spatial resolutions, and for all products at 27 km (c) and 3 km spatial resolution (d). Numbers in the bottom right corner indicates the number of days with precipitation > 1 mm d^{-1} for each dataset.



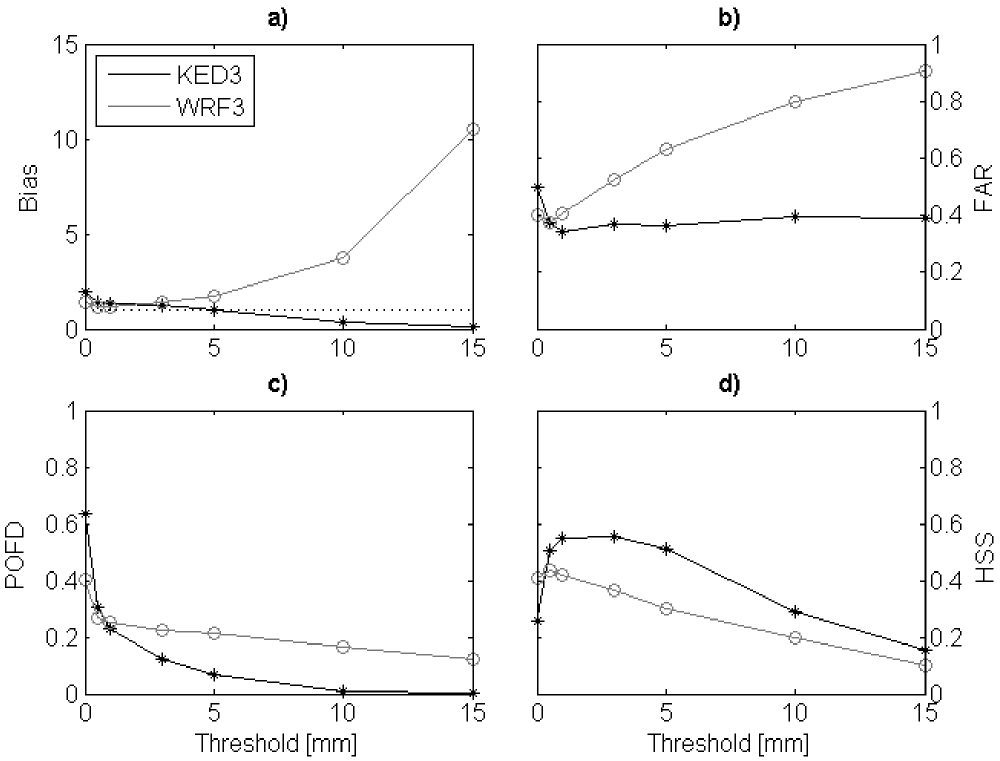
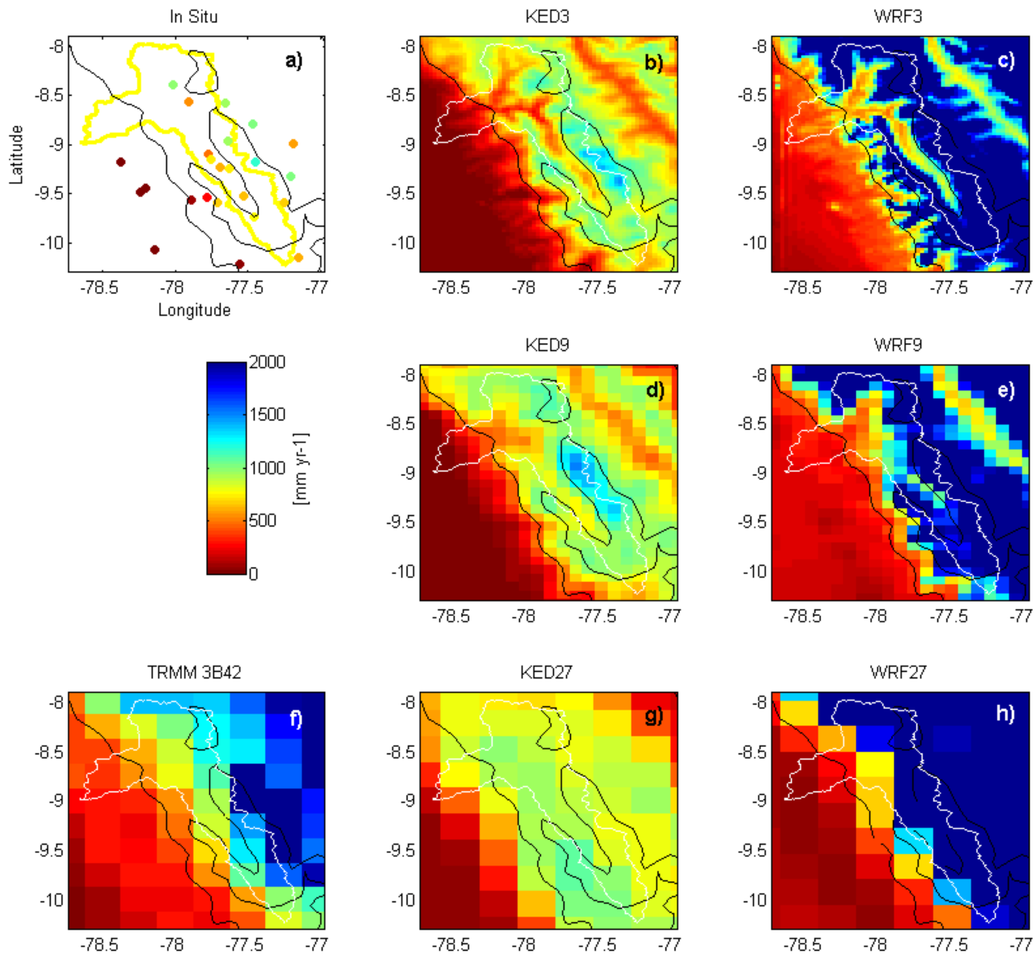


Figure 54: Daily precipitation indices: BIAS (a), False Alarm Rate (b), Probability Of False Detection (c) and Heidke Skill Score (d). Calculated for KED3 (black) and WRF3 (gray) against rain gauges precipitation data located in the Sierra area. Scores have been evaluated for several daily precipitation thresholds: 0.1, 0.5, 1, 3, 5, 10 and 15 mm.



In Situ
KED3
WRF3
KED9
WRF9
TRMM 3B42
KED27
WRF27
a)
b)
c)
d)
e)
f)
g)
h)
Latitude
Longitude
[mm yr-1]
2000
1500
1000
500
0
-8
-8.5
-9
-9.5
-10
-78.5
-78
-77.5
-77

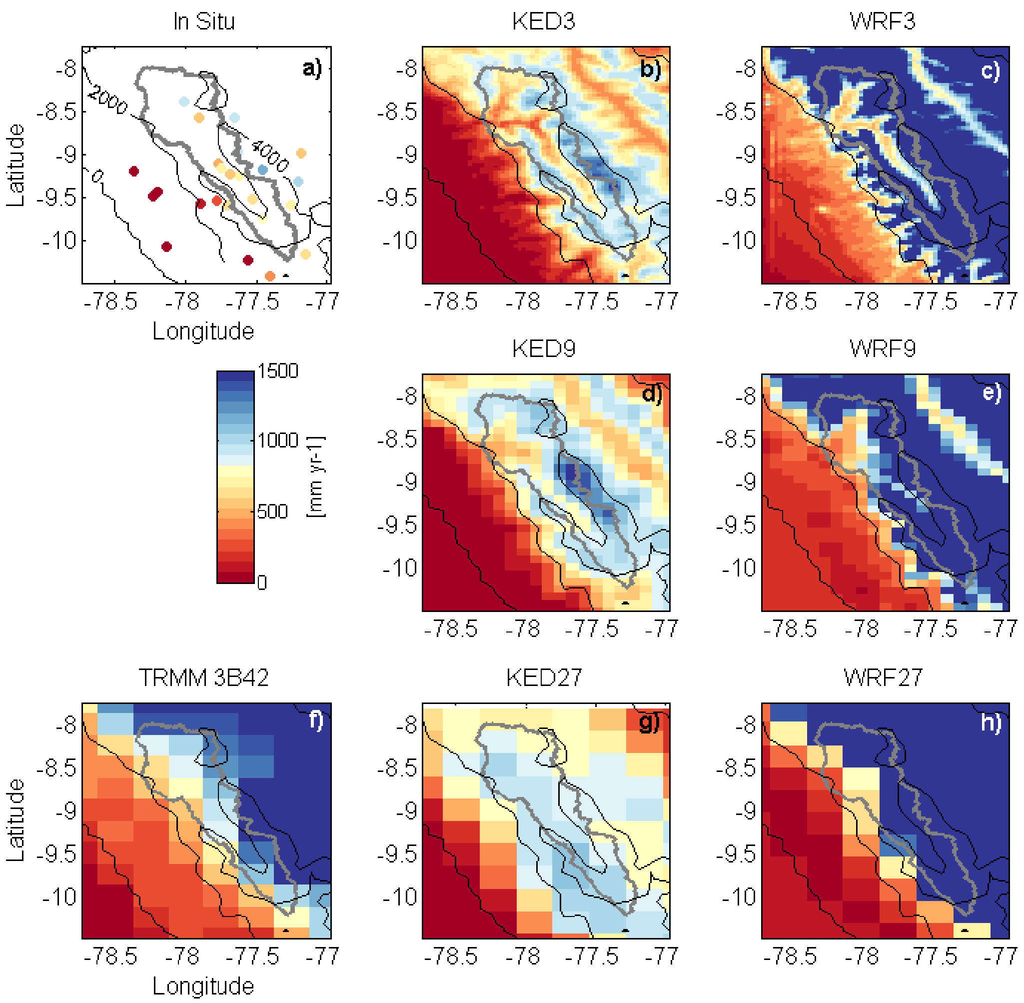
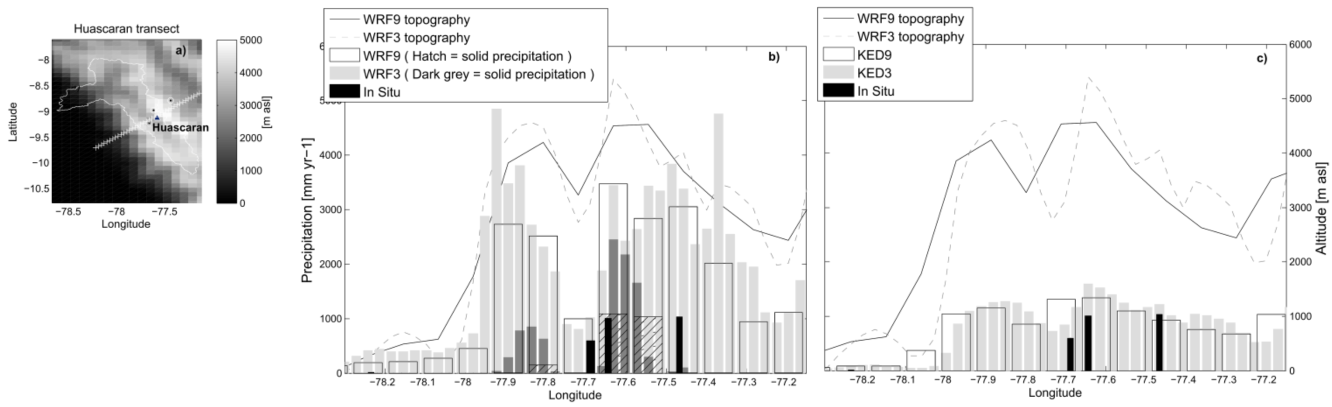


Figure 6~~5~~: Annual precipitation amounts for all products. Altitudinal contours of WRF9 are drawn every 2 000 meters (altitudes indicated in a). Delimitation of the upper Rio Santa watershed is in bold gray line~~black (a) or white~~.



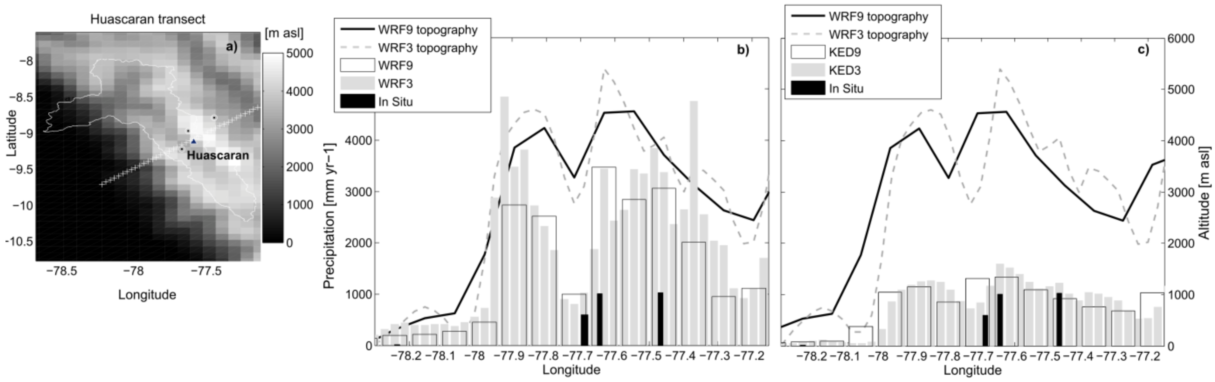
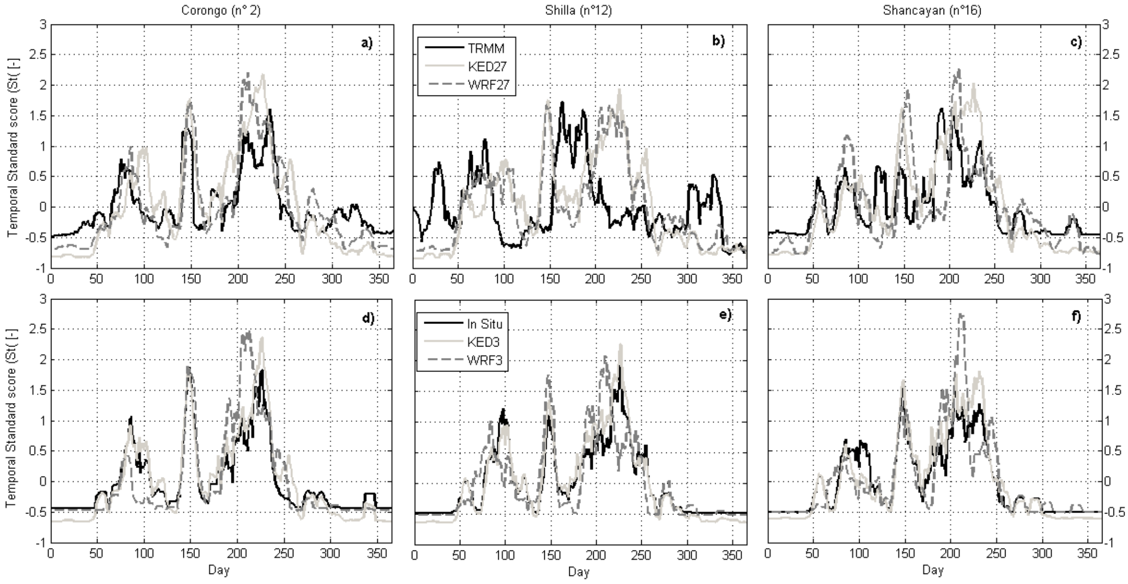


Figure ~~6~~7: Annual precipitation along a longitudinal transect (white squares in a)). Black bars in b) and c) corresponds to measured precipitation or accumulation. Elevation at 9 km spatial resolutions is in solid black line~~dark~~, at 3 km in dotted gray line. WRF9 ~~liquid~~ (empty bar) ~~and solid (hatched bar) precipitation,~~ and WRF3 precipitation ~~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).



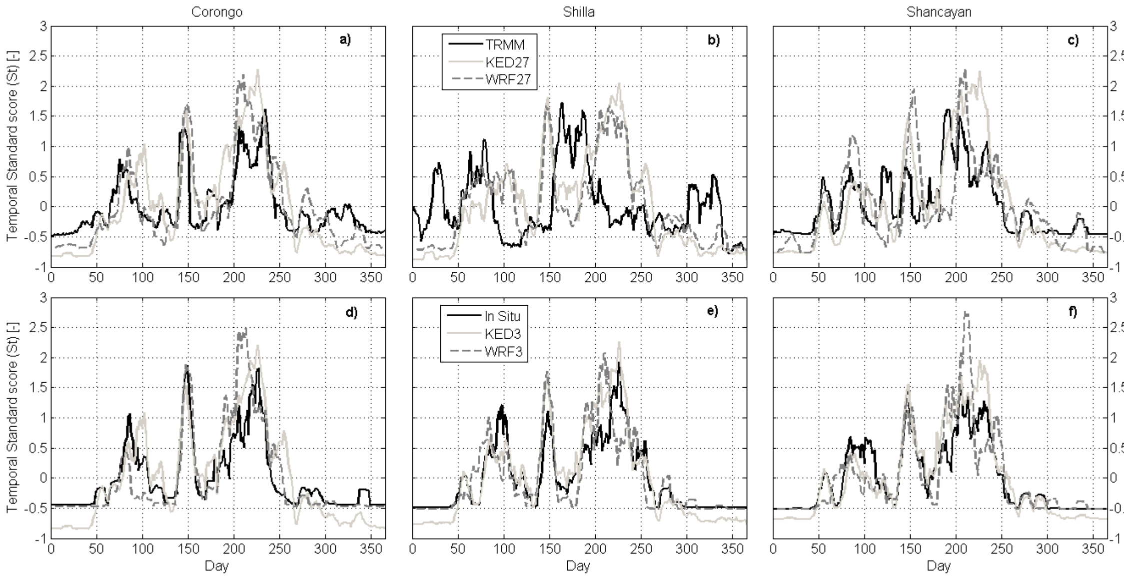
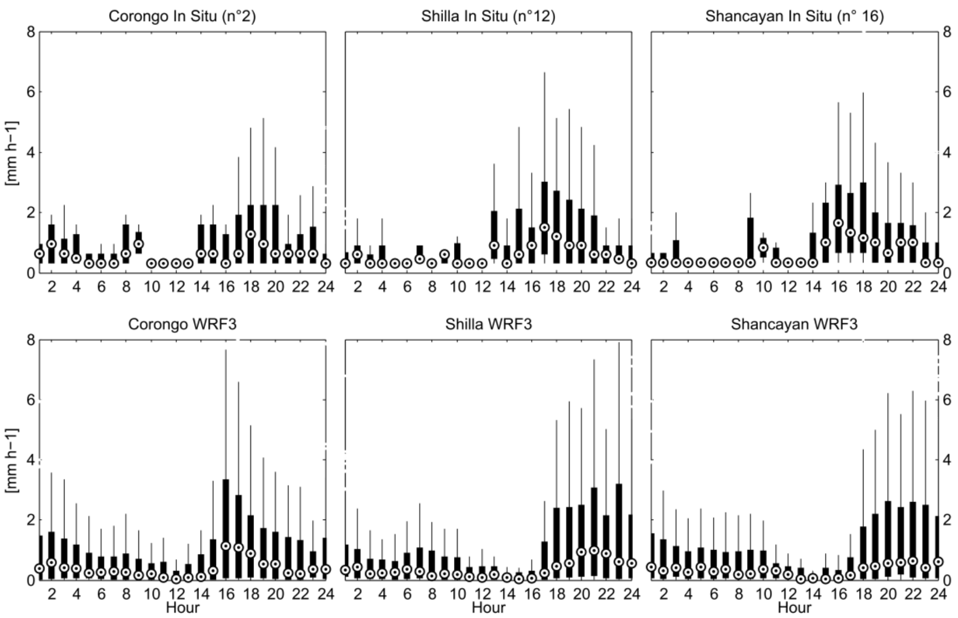


Figure ~~7~~8: Temporal Standard score of running means of daily precipitation amounts aver 10 days for three stations along the Rio Santa valley, for 27 km (a~~-b~~-c) and 3 km (d~~-e~~-f) spatial resolutions. Gray line is for KED, dotted line for WRF, and dark line either for TRMM (upper panels) or in situ (lower panels). Day 1 corresponds to the 1st ~~of~~ August 2012.



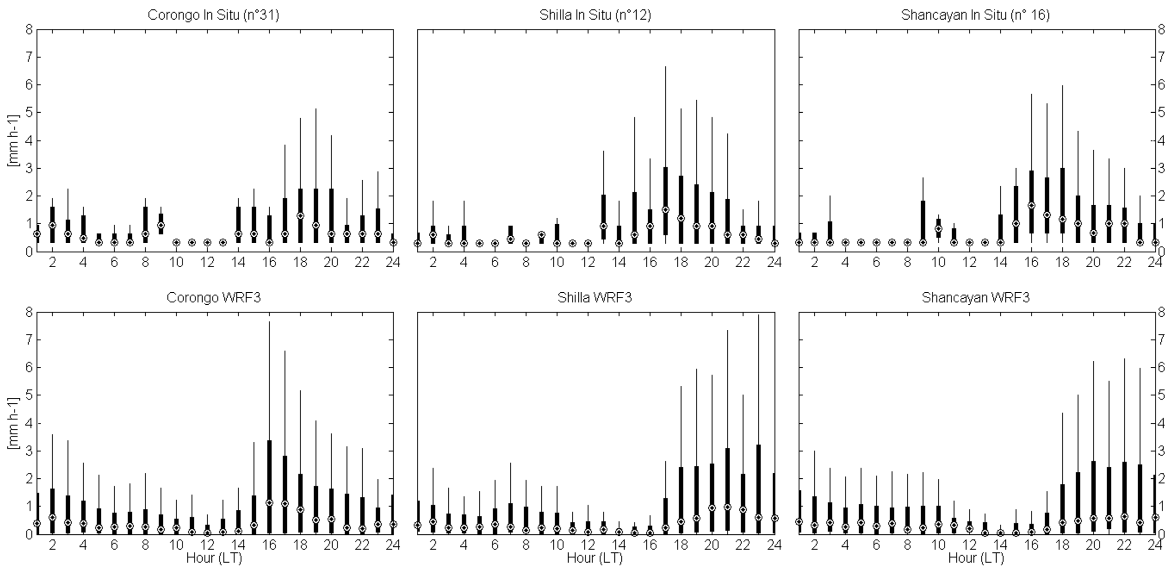
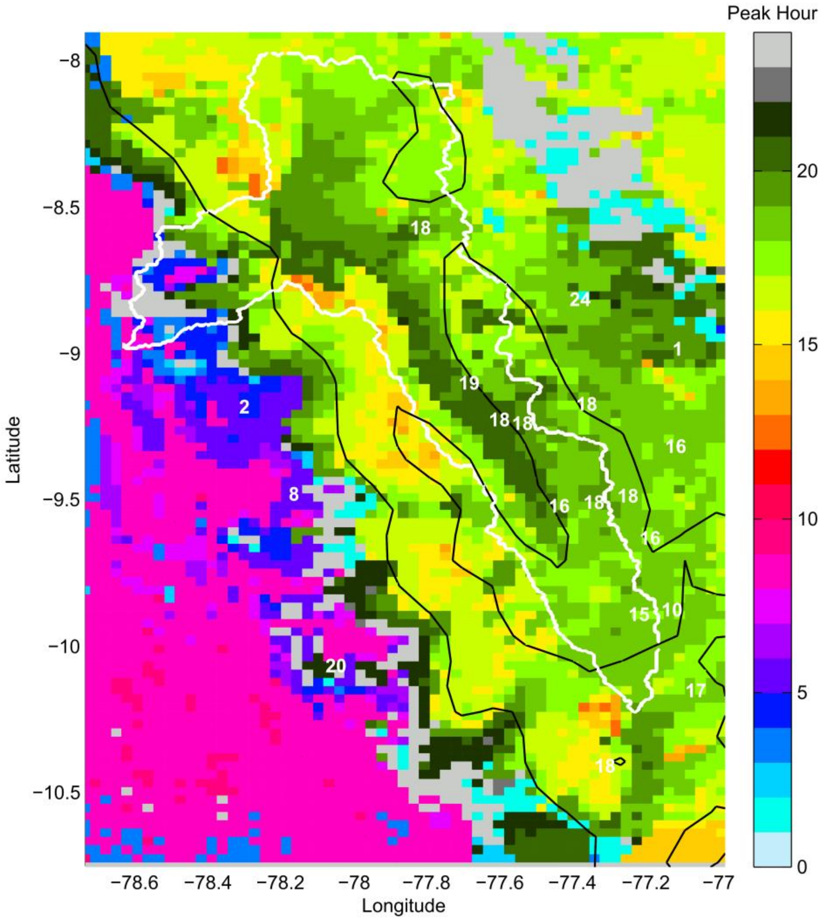


Figure ~~8~~9: Box plot of hourly precipitation amounts normalized by the mean of hourly data during one year (August 2012 / July 2013) for three rain gauges along the Rio Santa valley (Corongo, Shilla and Shancayan). In situ data are plotted in the upper panel, while WRF3 outputs are plotted in the lower panels.



Peak Hour
20
15
10
5
0
Latitude
−8
−8.5
−9
−9.5
−10
−10.5
Longitude
−78.6
−78.4
−78.2
−78
−77.8
−77.6
−77.4
−77.2
−77
18
24
1
2
19
18
18
18
16
8
16
18
18
16
15
10
20
17
18

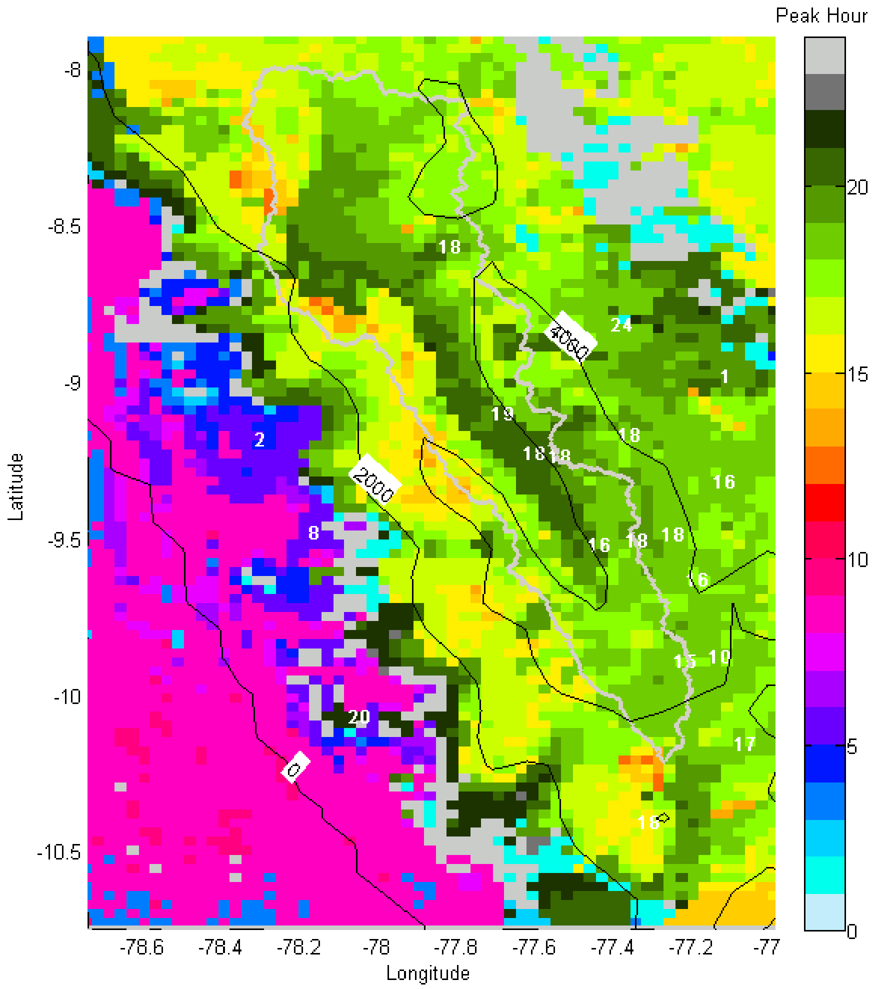


Figure 109: Peak hour of precipitation in WRF3. White numbers correspond to peak hour for the in situ data. The altitude of WRF9 is drawn every 2000 meters (black lines). Delimitation of the upper Rio Santa watershed is in whitegray.