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.

We sincerely thank the reviewer #2 for its 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 choice of the rainfall products that were selected as typical of the gauge product family, on the one hand, and of the model product family, on the other hand. We thus address this essential issue first, and we then provide point by point answers to the other, more technical, comments of reviewer #2.

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 Description and purpose of the WRF simulation

Reviewer comment.

- P. 6645, the simulations strongly depend on the choice of parameterization. Why did the authors choose this set op 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.

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).

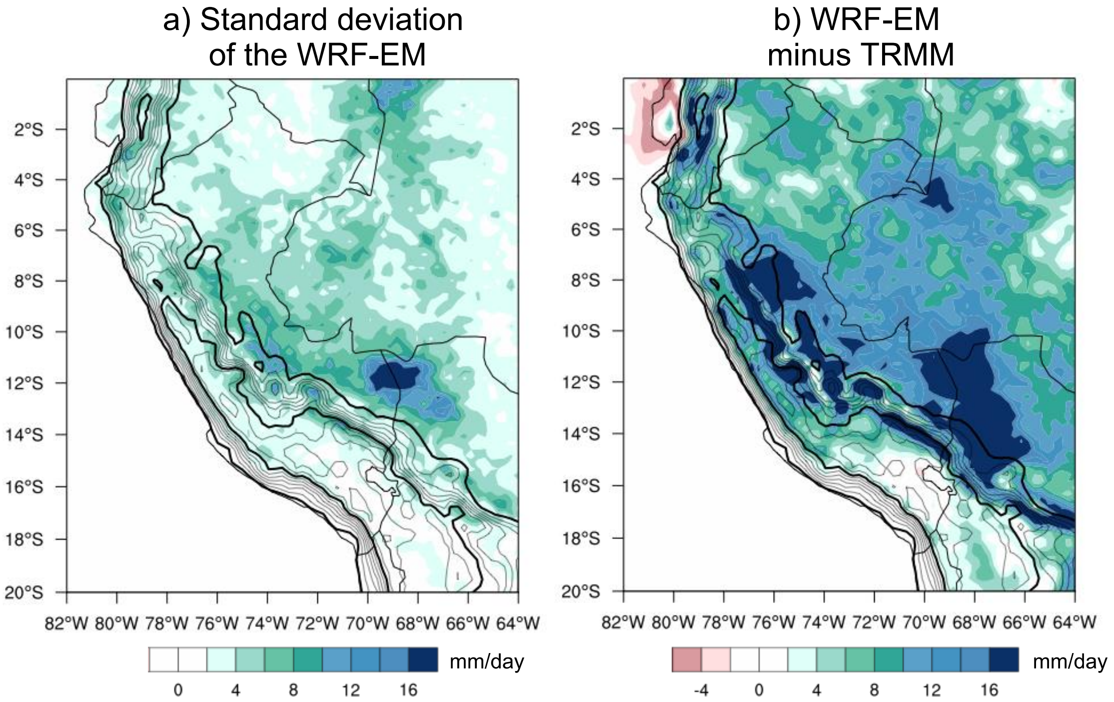

Figure R1 (not included in the manuscript): a. Standard deviation of the precipitation (mm/day) computed from the WRF-Ensemble mean (WRF-EM), six configuration of WRF-27km with different parameterization options, for the month of February 2013. b. Precipitation bias (mm/day) computed with the WRF-EM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

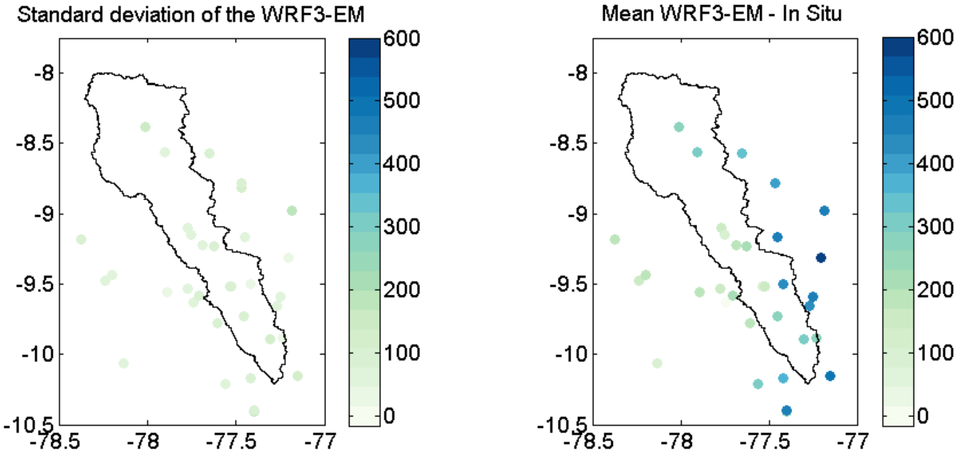

Figure R2 (not included in the manuscript): a. Standard deviation of the precipitation (mm month^{-1}) computed from the WRF3-EM (three configurations of WRF-3km with different surface scheme) for the month of February 2013. b. Precipitation bias (mm month^{-1}) computed with the WRF3-EM minus in situ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

1.2 Quality of the rainfall fields

> *- 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);*

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.

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

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.

> *- P. 6642, What QC is applied to the data? What is the error bar?*

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

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

We changed the sentence

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

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."

> *- 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*

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

> *- P. 6639, lines 3-4 clarify what are the common features and what are the socio-economic stakes in Peru*

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.

> *- P. 6639, lines 25ff since TRMM only passes 1-2 per day, the daily data are basically surface observations.*

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.

> *- P. 6641, line2: indicate Huascaran in Fig. 1 (so that it is visible)*

We plotted Huascaran in figure 1.

> *- 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.*

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).

> *- P. 6642, line 24: explain pluviometric index*

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).

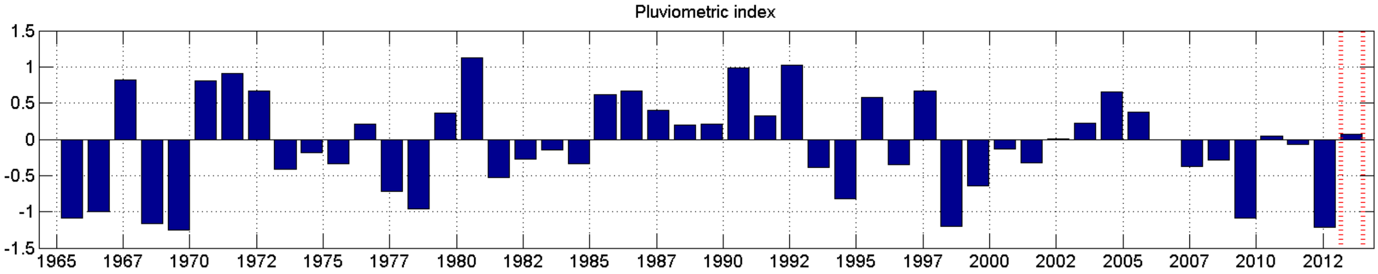

Figure R3: Pluviometric index for 10 long term SENAMHI stations. The vertical red bars delimit the studied year.

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.

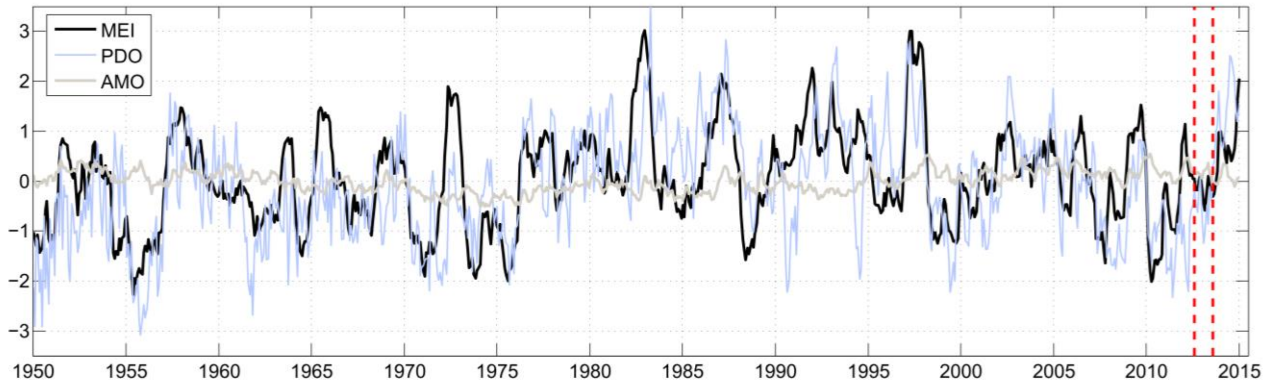

Figure R4: Variations of monthly index of MEI, PDO and AMO. Data are from the NOAA. The vertical red bars delimit the studied year.

- *P. 6644, lines 18-22: clarify and be more specific*

"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.

- *P. 6648, lines 14-21, Table 6; clarify and explain what A, B, C, D are*

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."

- *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.*

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.

- *P. 6652, lines 11-14 - Quantify why WRF overestimates rainfall and show that it is related to NCEP-FL if you claim this.*

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.

- 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

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. ».

- P. 6652, line 16: Where is the Maranon watershed?

We outlined the Marañon watershed in figure 1b (figure 1 in the new version of the paper).

- 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.

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.

Fig. 1left: enlarge figure; what are all these lines and which ones are 500 and 3500m?

In new Figure 2 a bold isoline of topography is displayed every 500m. Other thin lines are national borders.

Fig. 1right: outline all watersheds and domains that are discussed in the paper (also watershed in 1b looks different than in 2a?)

In new Figure 1, the Marañon watershed was also plotted, and to clarify the figures, we plotted in all of them the Upper Santa watershed.

Fig. 2 outline the coast and water sheds

We marked the 0 meter line, indicated the Ocean and the Upper Santa watershed.

Fig 3: light gray is hard to see

We increased the marker sizes for more visibility.

Fig. 5 what exactly are the yellow, black and white lines? Which ones are the altitude lines and what altitude is it?

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).

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

We modified the dashed line of WRF3 topography.

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

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.

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

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

References:

Andres, N., Vegas Galdos, F., Lavado Casimiro, W. S. and Zappa, M.: Water resources and climate change impact modelling on a daily time scale in the Peruvian Andes. Hydrolog Sci J, 59, 2043-59, doi: 10.1080/02626667.2013.862336, 2014.

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