Anonymous Referee #1

Received and published: 8 July 2015

Summary: The authors provide a technical overview and performance evaluation of a new global precipitation climatology derived using in situ climate normals, satellite data, physiographic variables, and a novel interpolation technique. The product is an important contribution for climate analysis in data sparse regions, both because it offers what appears to be a superior precipitation climatology relative to other widely used products and because it forms the foundation for the CHIRP and CHIRPS precipitation monitoring systems. Many researchers now employ CHIRP/S for studies of climate and hydrology in tropical regions, and this paper provides useful documentation on the process used to generate the underlying climatology.

Response: We appreciate reviewer 1's assessment of our paper, and the time spent reviewing this document.

The paper is clearly presented and includes all essential detail for potential users of the data product. I believe that it can be published in final form after only minor revision. That said, I suggest that the paper would benefit from additional figures (with associated supporting text) that address key performance indicators and product interpretation. Proposed additional figures include:

1. A map of the final product! It seems odd to read a paper that introduces a precipitation climatology and never see what the dataset looks like. It might be appropriate to show difference maps with CRU or Worldclim as well, though it might be more informative to show those differences for specific regions rather than at global scale.

Response: In response to this request we have added a figure, between the current Fig. 5 and Fig. 6, that shows maps of the CHPclim. Plots of the differences between the products have been also been added as an additional figure as described below.

2. Spatial comparisons of CHPclim performance with that of CRU and Worldclim in selected focus countries. For example, a map of bias (or MAE, or temporal correlation) at evaluation stations in Ethiopia during the rainy season would enrich the authors' claims that CHPclim offers its greatest advantages over complex terrain and data limited regions.

Response: This is a great suggestion, we have added three figures between the current Fig. 7 and Fig. 8 that addresses this request. These figures focus on Ethiopia, because we have just completed a rainfall gridding workshop at the Ethiopian meteorological agency, and hence have a good validation data set based on ~208 independent gauge observations. More heuristic than quantitative, we focus in this example on describing some specific instances where the satellite information provides valuable information about precipitation gradients in data sparse regions.

3. The general conclusion that the satellite-assisted CHPclim product offers greater reliability in complex terrain is quite interesting, considering that rough terrain is often identified as a major challenge for microwave precipitation estimates. It would be interesting to see a figure that plots error in CHPclim and in the comparison products as a function of elevation and/or other topographic characteristics in order to substantiate this claim.

Response: Please see our above response. In our Ethiopia case study we identify places where either a) very steep elevation gradients appear associated with large errors in the current state-of-the-art climatologies or b) satellite rainfall (but not elevation data) provides valuable information about rainfall extrema.

4. As a corollary to #3, it would also be interesting to see maps or scatterplots that show how CHPclim differs from other products in estimated precipitation at very high elevations–i.e., elevations higher than most or all available stations. It won't be possible to evaluate performance in these zones, but simply characterizing the difference is important for hydrological applications and trend analysis.

Response: This is a good suggestion, but rather than scatterplots we simply provide a heuristic discussion. The story that emerged from our analysis suggested that it was more about the relationship between elevation and precipitation *gradients*. Without explicit knowledge about the specific station distributions used in the other climatologies, this is the most we can do at present we feel without greatly expanding the length and complexity of the current study.

Minor comments / typos: p. 405, line 1: I only see four satellite products on this list, but the text states there were five. The "fifth predictor" introduced in line 16 is an average of two satellite products and is not an independent product.

Response: we will request that this be changed to *"Monthly means of four satellite products"*.

p. 405, line 20: slope is listed twice

Response: Thanks, we are requesting that the first slope be removed.

p. 411, line 16: please explain why the thin plate spline would fail in this regard.

Response: We are requesting that a sentence be added to this paragraph: *"Thin plate splines fit polynomial surfaces through point data, creating a generalized surface fit to latitude, longitude and elevation, the suitability of this fitting process may be problematic when the density of the gauge data is very low. Later in our paper we compare different products in Ethiopia."*

Anonymous Referee #2

Received and published: 9 July 2015

The authors introduce a very high-resolution (0.05 degrees) global monthly precipitation climatology built on three components, namely the integration of a blended set of five satellite based background climate surfaces, the climate normals from in-situ observations by combination of monthly normals published by the FAO augmented by those of GHCN and the thirdly the background information that can be taken from topographic and physiographic surfaces that are in particular helpful for a high-resolution climatology to downscale the information from station locations being very often too distant to each other to still provide for at least one station per grid cell in a 0.05 degrees resolving grid.

The basic idea to combine the three aforementioned information pools to an optimum climatology is solved by defining 56 distinct (!) modelling regions, each one characterized by its individual levels of station density, homogeneity of predictor responses, and availability of predictor fields. While the idea and methods to build the new climatology through this tiled approach is striking and convincing for regional assessments, the result post compositing has the inherent weakness that it cannot be a truly global climatology with a homogeneous methodology applied everywhere. So the data set is fit for regional assessments and purposes but has some clear limitations for global assessments, which the reader should be informed/warned of!

Response: we have added text that briefly describes how the tiles were overlapped and blended. As suggested by reviewer 1 and 2, we have also added maps of the global climate means, emphasizing a reasonable degree of continuity between tiles.

So I strongly support the first recommendation of referee#1, namely to ultimately show a global map of the final product, so the reader can convince her/himself of the global homogeneity of the product yielded. Also the three other recommendations of referee#1 mentioning the lack of demonstration of actually enhanced reliability in problematic regions with regard * to data scarcity, * mountainous areas, * areas of high natural variability of the precipitation parameter or the joint of all of them which is true in particular in Central and Eastern Africa or at the western edges of the Amazonas tropical forest along the eastern slopes of the Andes mountains.

Response: we greatly appreciate reviewer 2's comments and suggestions. As suggested, we have add five figures, addressing details all of these valid concerns and great suggestions. This expanded paper seems much more complete. We added three figures, based on this request, focused explicitly on Ethiopia.

Another Issue is the ease of access: I have tried myself to download the CHPclim v.1.0 data set from the pointer provided in the manuscript (BTW, the DOI reference to just an ftp-download-folder-tree without ANY meta information is not coping with the usual standard and should not be acceptable to ESSD!) but failed to find any easy available software tool to successfully read the TIFF file that seems to have been encoded in a very special TIFF dialect leading to my first additional recommendation to provide the user with ALL documentation and information necessary to actually access the data. With some forensic capability it is actual possible to assemble some of the essential information from http://chg.geog.ucsb.edu but that is far from the shape the material should be presented and documented to become eligible for ESSD publication!

Response: we concur that the data accessibility is a serious issue, and have made the following changes in response to this issue: i) making the DOI land on a web page, rather than an ftp data site, ii) adding OGC compliant CF formatted netCDF files and iii) adding a README file to the ftp site and more details on the web page. We apologize for this inconvenience, and appreciate the motivation to improve our data access.

I also encountered that among the state-of-the-science climatologies the authors mention those published by CRU and WorldClim (http://www.worldclim.org/methods) but are also ambiguous there. For CRU they cite New et al (1999), so it is unclear wether they actually refer to the outdated version CRU CL v.1.0 as there is also a more recent version offered under http://www.cru.uea.ac.uk/cru/data/hrg/.

I also miss mentioning and validation of the climatology against the in-situ data set built on the world-wide larges data archive, namely the one of the GPCC that has published quite a number of DOI referenced in-situ data set with ESSD (Becker et al, 2013; http://www.earth-syst-sci-data.net/5/71/2013/essd-5-71-2013.html). The most recent climatology at the much more reasonable 0.25 degrees resolution can be obtained from this DOI: http://dx.doi.org/10.5676/DWD_GPCC/CLIM_M_V2015_025 (and easily plotted, e.g. with NCAR's Panoply as it is encoded in OGC compliant CF formatted netCDF).

Response: We are requesting that clarifying text be added to the paper to make it explicit exactly which versions of the CRU and Worldclim climatologies that we are using. We have also added the GPCC climatology to all of our comparisons, and requested modifications to the corresponding sections of text and corresponding figures. The GPCC is now included throughout our paper.

When introducing and presenting a global precipitation climatology it is also good fashion to present and discuss some basic house-numbers with regard to the precipitation component of the global water budget and how they fit to existing numbers a published by Trenberth KE, Smith L, Qian T, Dai A, Fasullo J (2007) Estimates of the global water budget and its annual cycle using observational and model data. J Hydrometeor 8:758–769). I would strongly recommend this to provide for better confidence in the quantitative fidelity of the resulting data product.

We have now added a table 2 that lists global and continental averages of the four climatology products. They are all in fairly close agreement. We find that the GPCC (but not the Worldclim and CRU) is wetter, and hypothesize that this is due to the GPCC's correction for undercatch. We also discuss how our CHPclim is in close agreement with Trenberth et al. (2007).

So after all I fully join referees #1 rating that the product and method presented here has the potential to enhance regional (!) climate analysis in data sparse regions and definitely merits publication. However as material and methods go already now into the CHIRP and CHIRPS monitoring systems, and are already now employed also for decision making in the crucial sector Food Security and Agriculture in particular across Africa the paper in fact needs a major revision to tackle the deficiencies stipulated above, given the high level of responsibility that is taken with the publication of such kind of basic information in the field of precipitation climatology and ultimately potable water availability!

We greatly appreciate these comments, and feel that the expanded improved paper benefits substantially from your efforts and recommendations. Thanks. We agree that these are crucial areas of endeavor, and hope in our small way we may some useful contribution.

--- REQUESTED CHANGES --

Since our paper has been typeset, it seems most efficient to make requests for specific changes.

1) On page 405, line please change the text to "**Monthly means of four satellite products**".
2) On page 405, line 19 please delete 'slope'; it is repeated twice.
3) On page 411, line 19 please add ***"Thin plate splines fit polynomial surfaces through point data, creating a generalized surface fit to latitude, longitude, and elevation – the suitability of this fitting process may be problematic when the density of the gauge data is very low. Later in our paper we compare different products in Ethiopia."***

4) Changes in the number of figures. To address the reviewer's comments we have added five figures. Please change figure references as follows:

   Old Figures 1-5 -> remains the same.
   Old Figure 6 and 7 -> become figures 7 and 8.
   Old Figure 8 becomes figure 13.

   The legends for the new Fig. 6, 9, 10, 11 and 12 are:

   Figure 6. CHPclim monthly means for January, April, July and October. While CHPclim is global, we show 50°S-50°N images to facilitate visualization.

   Figure 9. Differences in annual total precipitation for CHPclim, the 0.25° GPCC M V2015 climatology, the 0.17° CRU CL v2.0, and the 0.042° version 1.4 release 3 Worldclim climatology.

   Figure 10. Total annual rainfall, elevation, NDVI and LST for Ethiopia. Rainfall totals are from the Ethiopian National Meteorological Agency (NMA), CHPclim, the GPCC M V2015 climatology, the CRU CL v2.0, the version 1.4 release 3 Worldclim climatology, and the blended CMORPH/TRMM data used in the CHPclim modeling process.

   Figure 11. Total annual NMA rainfall, elevation and MBE maps based on the NMA minus CHPclim, the NMA minus GPCC, the NMA minus CRU and the NMA minus Worldclim.

   Figure 12. The top panels show transects of total annual rainfall at 7°N and 10°N. Also shown are transects of elevation in meters divided by 5 and annual mean NDVI, multiplied by 1500. The bottom

panels show MBE transects based on CHPclim, GPCC, CRU and Worldclim minus the NMA data. These bottom panels also show elevation in meters divided by 5.

5) In response to reviewer 1's request 1, and reviewer 2's request 1 please add the following sentences to page 410 at the end of line 14. **"Figure 6 shows monthly mean CHPclim precipitation fields. As discussed later, these seem generally quite similar, in most places, to the GPCC M V2015, the CRU CL v2.0, and the Worldclim version 1.4 release 3 products. The blending of the overlapping tiles creates generally smooth transitions from tile to tile. These products will be compared more closely later in this paper."**

   Also, on page 408, line 8 please add a sentence: **"All tiles were allowed to overlap with their neighbors, and locations within these areas of overlap were blended based on weights that were linear functions of the distances from tile edges. This helped to produce smooth transitions from tile to tile."**

6) In response to reviewer 1's request 2, and the comments expressed by reviewer 2, please add 'Section 2.3 Product comparisons' at the bottom of page 411:

   Section 4.3 Product Comparisons

   Here we briefly examine differences between quasi-global total annual precipitation from the CHPclim, GPCC M V2015, CRU CL 2.0 and Worldclim version 1.4 release 3 (Fig. 9) and their global and continental averages (Table 2). The left hand panels show differences between the CHPclim and the three other products. The largest differences appear over the north half of South America, where annual precipitation is very high (Fig. 6). These differences may arise from the local influence of the satellite rainfall fields, which are well correlated in this region (Fig. 1). Note that the GPCC, CRU, and Worldclim also vary substantially amongst themselves in this area. In Europe, northern Asia, North America, and Australia, the differences are fairly limited, most likely due to the high station density in these regions. There are large differences near the Himalayas. The CHPclim appears to be producing more precipitation across the Himalayan plateau and less precipitation on the south facing mountain slopes. More research will be required to evaluate if this is appropriate or not. CHPclim also appears to be substantially drier over some parts of Africa. A recent study in Mozambique (Tote et al. 2015) of the Climate Hazards group Infrared Precipitation with Stations (CHIRPS, Funk et al. 2014b), which is based on the CHPclim, found low bias over that country. Stations in Africa tend to be biased towards wet locations, and the use of satellite fields as guides to interpolation may help limit this bias. We explore this idea in more detail in the next section, which focuses on an Ethiopia test case.

   Before proceeding to that analysis, we note that the global (excluding Antarctica) and continental averages from our four products are in quite close agreement (Table 2), even in Africa. The two outlier's appear to be the GPCC M V2015 averages for Asia (688 mm) and for the globe (880 mm). The global GPCC M V2015 value of 880 mm is close to the 850 mm figure reported in Schneider et al. (2014). The discrepancy between the GPCC results and the other products is likely due to the way they corrected for systematic under-catch by the rainfall gauges. The CHPclim does not incorporate this correction which increases precipitation observations based on estimated under catch values. The global (excluding Antartica) total annual rainfall values, expressed in 'units' of global precipitation of 10^3 km^3 yr^{-1} as in Trenberth et al. (2007) agree quite well with that study's reported values (110 units CRU; 112 units GPCP). We found the CHPclim precipitation resulted 120 units. This difference may relate to CHPclim's interpolation procedure in northern South America and the Maritime Continent where the CHPclim is wetter (Fig. 9, Table 2), perhaps because of guidance provided by satellite observations (Fig. 1).

This section will refer to Table 2:

	Globe, excl Antartica	Europe	Asia	Australia	Maritime Continent	North America	South America	Africa
CHPclim	810	707	625	485	2,829	702	1,594	613
GPCC CL2.0	880	710	688	576	2,702	732	1,563	631
CRU	804	707	607	496	2,756	695	1,580	624
World Clim	796	693	596	487	2,750	682	1,556	611

Table 2. Comparison on annual total precipitation [mm] for different regions.

Please also add these references:

Trenberth, K. E., Smith, L., Qian, T., Dai, A. and Fasullo, J.: Estimates of the global water budget and its annual cycle using observational and model data, J. of Hydromet., 8(4), 758-769, 2007.

Toté, C., Patricio, D., Boogaard, H., van der Wijngaart, R., Tarnavsky, E. and Funk, C.: Evaluation of Satellite Rainfall Estimates for Drought and Flood Monitoring in Mozambique. Remote Sensing, 7(2), 1758-1776, 2015.

Schneider, U., Becker, A., Finger, P., Meyer-Christoffer, A., Ziese, M., & Rudolf, B.: GPCC's new land surface precipitation climatology based on quality-controlled in situ data and its role in quantifying the global water cycle. Theor. and Appl. Clim., 115(1-2), 15-40, 2014.

7) In response to reviewer 1's request 3 and 4, and the comments expressed by reviewer 2, please add 'Section 2.4 An Ethiopian validation study' at the top of page 412:

Section 4.4. An Ethiopian validation study

In February of 2015 one of the co-authors led a rainfall gridding workshop in Addis Ababa, in collaboration with lead scientists from Ethiopian National Meteorological Agency (NMA). This workshop used the GeoCLIM tool to blend CHIRPS satellite rainfall estimates with 208 quality controlled gauge observations (Fig. 10 and 11, top left) to monthly 1981-2014 grids of precipitation. In this section we compare the 1981-2014 average of the blended CHIRPS/NMA station data to the CHPclim, GPCC, CRU and Worldclim data sets. We acknowledge that since the CHPclim is used in the CHIRPS as a background climatology the NMA and CHPclim data sets are not completely independent. Nonetheless, the 35 years of 208 NMA rain gauge observations have not been included in the CHPclim, and hence provide a valuable validation data set, especially within the areas with good gauge density.

Figure 10 shows the mean 1981-2014 annual rainfall totals based on the gridded NMA data, similar to maps from the CHPclim, GPCC M V2015, CRU CL 2.0, and Worldclim version 1.4 release 3. Also shown are annual totals of the elevation, CMORPH/TRMM precipitation and MODIS LST that were used in the CHPclim modeling process. Annual mean MODIS Normalized Difference Vegetation Index (NDVI) values are also shown as an independent proxy for moisture availability. All the precipitation products and the NDVI agree on the broad patterns of rainfall variability, which are extreme, with the wettest regions receive more than two meters of rainfall each year while the driest receiving less than 200 mm. The CMORPH/TRMM satellite observations seem to capture these dry areas well – with no ground data at all, the brown areas in the CMORPH/TRMM agree quite will with the NMA/CHPclim, which agree closely. Within wet areas, the discriminatory power of the satellite observations seems to diminish, indicating (incorrectly) that northwest Ethiopia is as wet as southwest Ethiopia. The similarity between the completely independent NDVI and NMA/CHPclim fields is quite compelling. Many subtle features, such as the humid highlands in north-central, east-central, and south-eastern Ethiopia appear well demarcated by these precipitation fields. These seem fairly well captured by the Worldclim and CRU as well.

Note that there are important differences between the elevation and the very similar LST field and the NMA/CHPclim precipitation and NDVI mean fields. While there are certainly some important correspondences, there are also critical differences, such as in north-central Ethiopia which is high and cool, but dry. Conversely, northwest Ethiopia is relatively wet, but relatively low.

Figure 11 shows the differences from NMA data, along with the NMA mean field, and elevations, to support analysis. Purple lines have been drawn showing transects plotted in Fig. 12. The CHPclim follows the NMA climatology closely. The GPCC, CRU, and Worldclim all exhibit substantial (>|300 mm|) deviations, with the Worldclim performing substantially better than the GPCC/CRU. This helps to confirm the visual impression from Fig. 10 that the Worldclim data follows the NMA data quite closely. The GPCC, CRU and Worldclim all underestimate precipitation in the blue regions in the northwest and southwest of these maps, which are relatively low areas. The CMORPH/TRMM finds rainfall in these areas, and the CHPclim MBE in these areas is quite modest. Conversely, dark brown areas in the bottom panels of Fig. 11 denote areas where rainfall is substantially overestimated in the GPCC, CRU, and Worldclim. This appears to be of gravest concern in the center and center-east of the country, which has high elevations and extremely steep rainfall gradients. While not perfect, the CMORPH/TRMM (Fig. 10) seems to capture these gradients with reasonable fidelity, and building on these gradients produces a CHPclim with low bias in these areas.

We explore this topic more fully in Fig. 12, which shows transects of our data sets at 10°N and 7°N. We have multiplied the NDVI data by 1500 and divided the elevation data by 5 to facilitate visualization. Begin by noting in the top two panels the similarities between mean NMA data, the CMORPH/TRMM , and the NDVI. This reinforces the utility of the TRMM/CMORPH, and the NMA fields are an effective representation of the 'true' climatology. The CRU and Worldclim seem to follow the NMA transect quite well, with some substantial deviations shown in the bottom panels. Some of these errors appear to coincide with areas having extreme elevation changes, such as 36.5°E, 37.5°E and 40°E at 10°N. At 37°E, 7°N, the CRU, GPCC and Worldclim substantially underestimate rainfall. The CHPclim, assisted by the CMORPH/TRMM, which is quite wet in this region, captures the rainfall well. In the eastern part of the country, where we find the largest percent discrepancies, we find overestimates at 41°E, 10°N and 41.5°E, 7°N. Estimates of rainfall gradients in these poorly instrumented regions are very difficult based on just station data. The CMORPH/TRMM, however, seems to capture these gradients well, and the CHPclim builds on this local gradient information.

8) In response to reviewer 2's request 3 to add the GPCC climatology, please make the following modifications:

   a. Change page 403 lines 11-18 to:

   The most widely used current global climatologies, such as those produced by the University of East Anglia's Climatological Research Unit (CRU) (New et al., 1999**; New et al. 2002**), and the Worldclim (Hijmans et al., 2005) global climate layers, typically base their estimates on elevation, latitude, and longitude. Daly et al. (1994) used locally varying regressions fit to the topographic facets, while the CRU and Worldclim climatologies use thin-plate splines (Hutchinson, 1995) to minimize the roughness of the interpolated field, with the degree of smoothing determined by generalized cross validation. **The Global Precipitation Climatology Centre (GPCC) generates their climatology products based on the interpolation of a very large database of precipitation normals (Becker et al., 2013; Schneider et al. 2014).**

   b. Please revise the sentence on page 404, lines 5-7 to read:

   The CHPclim version 1, Worldclim version 1.4 release 3 (Hijmans et al., 2005), CRU CL 2.0 (New et al., 2002; New et al., 1999), and the GPCC CLIM M V2015 (DOI: 10.5676/DWD_GPCC/CLIM_M_V2015_025, Becker et al. 2013; Schneider et al. 2014) climatologies are compared with independent sets of station normals for Colombia, Afghanistan, Ethiopia, the Sahel, and Mexico. The climatologies are also compared with each other, and with a gridded validation data set in Ethiopia.

   c. Please revise page 410, lines 22-26 as:

   For each validation station, the closest CHPclim, CRU, or Worldclim grid cell was extracted. The CHPclim percent biases were substantially smaller in magnitude than the CRU or Worldclim biases, ranging between -2 to +5%, as compared to -28 to +16% (CRU) or -16 to 0% (Worldclim) or -1 to -17% (GPCC). Note that the GPCC gauge observations were corrected for systematic under-catch errors (Becker et al. 2013; Schneider et al. 2014).

   d. and Please revise page 411, lines 1 to 5 as:

   in data sparse areas like the Sahel, Ethiopia, and Afghanistan. Averaged across the study regions, the CHPclim/CRU/Worldclim/GPCC datasets had overall mean absolute error (MAE) values of 16, 26, 20 and 20 mm month^{-1}, respectively. The average spatial R^2 values for the four climatologies were 0.77 (CHPclim), 0.58 (CRU), 0.67 (Worldclim), and 0.51

(GPCC). Overall, the CHPclim compared favorably to the CRU, Worldclim and GPCC data sets.

And please add these reference:

New, M., Lister, D., Hulme, M., and Makin, I.: A high-resolution data set of surface climate over global land areas. Climate Research, 21(1), 2002.

Becker A., Finger P., Meyer-Christoffer A., Rudolf B., Schamm K, Schneider U., Ziese M.:A description of the global landsurface precipitation data products of the Global Precipitation Climatology Centre with sample applications including centennial (trend) analysis from 1901–present. Earth. Syst. Sci. Data Discuss. 5:921-998. doi:10.5194/essd-5-71-2013. (2013).

And please add the following statistics to Table 1.

		N stn	Stn mean	GPCC mean	MBE	MAE	Pct MBE	PCt MAE	R2
GPCC	**Colombia**	194	168	185	-17	51	-10	31	0.75
	Afghanistan	22	35	43	-8	15	-23	43	0.29
	Ethiopia	76	97	99	-3	22	-2	22	0.84
	Sahel	28	55	70	-15	8	-27	15	0.78
	Mexico	1814	77	78	-1	21	-1	28	0.84