"The CAMELS-CL dataset: catchment attributes and meteorology for large sample studies – Chile dataset" by Alvarez-Garreton et al.

Response to Anonymous Referees #1 and #2

We thank anonymous Referees #1 and #2 for their constructive comments on our paper. Before we address them, we would like to mention that since our manuscript was submitted, we have updated some datasets and added a new one. Firstly, 59 catchment boundaries (and their corresponding hydro-meteorological time series and catchment attributes) were updated based on more accurate locations of streamflow gauges. This new location information was provided by technicians from the Chilean Water Directorate (DGA). Secondly, we incorporated an updated water rights dataset developed for the National Water Balance project (DGA, 2017), where several water rights with missing coordinates in the former public database used in CAMELS-CL were located by using Google Earth Imagery. Finally, we added a public dataset of national dams (http://www.ide.cl/descarga/capas/item/embalses-2016.html) to identify the presence of dams within catchments. This was quantified as a binary attribute (0 if there is no dam within the catchment, and 1 if there is at least one dam) that can be used to select near-natural catchments. We think that these additions significantly improve the quality of CAMELS-CL dataset. The updated time series and catchment attributes are freely available online: http://www.cr2.cl/download/camels-cl/.

Below we provide responses to each Referee comment. For clarity, Referee comments are given in blue text, our responses are given in plain text and the proposed paper modifications in italics.

Referee #1:

This paper presents the first large-sample catchment dataset for Chile with many data sources compiled to provide an easy to use, uniform dataset. The data sources and derived statistics are clearly described in sections 3 and 4 and the authors generally discuss uncertainty and caveats to each piece of the dataset. A valuable addition is the compilation of diversion data for the catchments. Overall, the paper is easy to read and the figures are high quality.

We thank the reviewer for her/his positive comments.

However, it reads more like a data paper with relevant descriptions of the components of a dataset. Section 5 does provide some nice analysis, but more is needed before publication.

We agree that an important part of the paper is related to the description and discussion of the input datasets used to generate CAMELS-CL. Nevertheless, in our view the two scientific questions addressed by the paper are in line with HESS main scopes: 1) "*the study of the spatial and temporal characteristics of the global water resources (...)*" and 2) "*the study of interactions with human activity of all the processes, budgets, fluxes (..)*" (https://www.hydrology-and-earth-system-sciences.net/about/aims_and_scope.html). The first scope frames the scientific question addressed in Section 4, where we analyse the spatial distribution of catchment attributes, providing insights about catchment hydrologic response and dominant runoff processes, and their relation with catchment characteristics and climatic indices. The second scope frames the analysis on the impact of human intervention on catchment hydrologic response (addressed in Section 5).

In response to the reviewer's recommendation, we propose to add a new section to the manuscript where we analyse one of the main sources of uncertainty of the dataset (*New Section 6: Precipitation uncertainty analysis*). The proposed section is presented at the end of this document.

Additionally, another careful pass through the paper for typos and minor grammar issues is needed.

The complete manuscript has been proof read to correct typos and grammar issues.

Specific comments:

1) This paper lacks substantial analysis. The new dataset is very valuable, but as the manuscript stands now, it is very close to a data paper. Additional analysis is needed. One opportunity is uncertainty. The authors note many times that the input climate data, streamflow, and basin boundary data are uncertain. The authors could (should?) provide uncertainty bounds on the derived indices (e.g. runoff ratio) using the various climate indices and possibly any other known sources of uncertainty.

We have considered the reviewer's recommendation and performed an analysis of forcing uncertainty coming from the precipitation products in CAMELS-CL. This analysis is proposed as a new section (*New Section 6: Precipitation uncertainty analysis*), where we quantify the spread from all precipitation products and discuss potential relationships with physical catchment characteristics and catchment hydrologic response. This forcing spread will be incorporated as a new catchment attribute (a new climatic index called "p_mean_spread").

An interesting aspect that could be explored is quality control of the various climate data using metrics like runoff ratio to identify suspect datasets (e.g. long-term runoff ratio > 1 in areas of little glacial melt or groundwater). This can then be parlayed into analysis on how uncertainty may impact the significance of any spatial trends in the catchment hydrologic signatures or climate indices. This does not need to be exhaustive, but a nice example of how to use the uncertainty data provided would be useful to the community.

We thank the reviewer for this excellent idea. We computed runoff ratios for near-natural catchments to evaluate the different forcing products. Based on this, we provide insights on which regions and catchment characteristics are more prone to precipitation errors (*New Section 6: Precipitation uncertainty analysis*).

2) The results of section 5 seem very logical, yet I don't see any citations in the paper discussing basin response with human intervention. There must be some previous work that can be cited?

The results are indeed logical and intuitive. However, they are not commonly found in large sample studies (over 100 catchments) using water extractions to quantify the degree of human intervention. We propose to add the following references to Section 5, where different types of human intervention are related to catchment response:

Poff et al. (2006) examined the effects of land use on hydrological regimes (e.g., peak and low flows, runoff variability) in 158 basins across the conterminous United States, finding region-dependent changes in specific metrics. Ochoa-Tocachi et al. (2016) analysed the impacts of land use on the hydrology of 25 Andean catchments, finding that anthropogenic influence translates into increased streamflow variability and decreased catchment regulation capacity and water yield. More recently, Tijdeman et al. (2018) examined the effects of human intervention on streamflow drought characteristics across 187 catchments in England and Wales, concluding that most human-influenced catchments did not have flow drought characteristics different from those expected for near-natural conditions.

References:
Poff, N. L., Bledsoe, B. P., & Cuhaciyan, C. O. (2006). Hydrologic variation with land use across the contiguous United States: geomorphic and ecological consequences for stream ecosystems. Geomorphology, 79(3-4), 264-285.
Ochoa-Tocachi, B. F., Buytaert, W., De Bièvre, B., Célleri, R., Crespo, P., Villacís, M., ... & Gil-Ríos, J. (2016). Impacts of land use on the hydrological response of tropical Andean catchments. Hydrological processes, 30(22), 4074-4089.
Tijdeman, E., Hannaford, J., & Stahl, K. (2018). Human influences on streamflow drought characteristics in England and Wales. Hydrology and Earth System Sciences, 22(2), 1051.

3) Additionally, this paper appears to only focuses on diversions, not urban fraction. Catchment response changes with urban fraction as well, which is obviously another component of human intervention in watersheds. If this is negligible in these catchments, the authors should note it.

The reviewer is right. Urban fraction is another important factor modulating catchment response, and it can be obtained from land cover attributes, since urban areas are usually classified as impervious surfaces. In the submitted manuscript, the imp_frac attribute (Table 3) included two classes: impervious surfaces and barren lands. To enable the quantification of urbanised areas within a catchment, we propose to compute these classes as two different land cover attributes: imp_frac and barren_frac. By doing this, the urban fraction of the catchments (assumed to be equal than the impervious area, imp_frac) varies between 0% and 7% for most catchments (only one catchment had imp_frac = 25%). This is considered negligible and it will be stated in a revised Section 4.3 (Land cover attributes). It should be noted, however, that there is uncertainty in this estimation. Zhao et al., (2016) – whose land cover map was used to produce CAMELS-CL – highlighted that the impervious surface class is the worst classified class, since urban areas have mixed pixels of vegetation and paved surfaces. This discussion will be also added to revised Section 4.3.

4) The concluding remarks section is very repetitive. Key contributions from this paper are restated several times in different ways across the section and should be condensed.

The conclusion section was condensed, deleting repetitions.

Referee #2:

The paper describes a new dataset of catchment attributes for Chile, as well as a short analysis using this dataset. The dataset itself should be very useful to those studying hydrology in the area. Similar datasets in other regions have proven to be enormously useful and widely used. The paper provides a good description of the attributes included in the dataset. In addition, the analysis provides a good overview of hydrologic and land use conditions in Chile, with a few observations about correlation between different variables.

We thank the reviewer for her/his positive comments.

A few more specific comments:
- In the description of water rights, many different types of water use are mentioned. Are there types or amounts of water use that do not require a permitted water right? (For example, below a threshold amount?)

Strictly speaking, the Chilean Water Code (Congreso De La República De Chile, 1981) states that any water use should be associated with a water right allocated by the Chilean Water Directorate (DGA), even for low volumes. However, there are many extractions that are not informed to DGA and are not detected in subsequent inspections (due to lack of human resources devoted to carry out field inspections), which is the main challenge of quantifying human intervention within a catchment. This will be clarified in Section 3.11 (Water rights).

Reference:
Congreso De La República De Chile, 1981: Decreto Fuerza de Ley 1122. Fija Texto del Código de Aguas. 1–68.

- There is a missing band of elevation between 1000 m.a.s.l. and 3500 m.a.s.l, if I understand the categorizations described in 4.1 correctly. Why is this?

Thanks for pointing this. There was an error in the elevation bands description in Section 4.1. The text will be now consistent with Table 3:

Section 4.1, page 12, line 13: We proposed the attribute location_type (see Table 3 and Fig. 7f) with three categories: coastal (or low elevation), foothills and altiplano catchments, defined by gauge elevations lower than 50 m a.s.l., between ~~900 and 1000~~ 1000 and 1200 m a.s.l., and above 3,500 m a.s.l., respectively.

- Section 5 and 6: be careful to be precise in the wording so as not to confuse correlation and causation. (See sentences page 17, line 16; page 18, line 29)

We agree. Our analyses demonstrate correlation, but do not permit to establish causation. The wording in Sections 5 and 6 will be carefully revised to reflect this. In particular, the sentences mentioned by the Referee will be changed as follows:

Section 5, page 17, line 16: Larger human intervention ~~results in~~ is correlated with decreased annual flows and runoff ratios, especially in drier catchments.

Section 6, page 18, line 29: The analysis on the impacts of human activities on catchment behaviour leads to several important insights. We showed that larger human intervention ~~results in statistically significant~~ is correlated with decreased annual flows, runoff ratios, decreased elasticity of runoff with respect to precipitation, and decreased flashiness of runoff, especially in drier catchments.

- Throughout the paper, there are a number of small grammatical issues that could be improved by a close reading.

The complete manuscript has been proof read to correct typos and grammar issues.

I recommend publication of this paper as a means of making this dataset available and as a demonstration of its utility, provided this type of paper is within the scope of HESS. Note that the analysis portion of this paper is not extensive.

We are very pleased that the Referee appreciates the contributions of this study. We truly hope that the analyses of the paper about dominant spatial patterns of physical, climatic and hydrological attributes, impacts of human intervention on catchment hydrologic response, and the new analyses presented here (*New Section 6: Precipitation uncertainty analysis*), contain the scientific relevance needed for publication in HESS.

Sincerely,

Camila Alvarez Garreton

New Section 6: Precipitation uncertainty analysis

We provide a first-order analysis of inter-product differences across the domain. To this end, we define and compute a precipitation spread attribute (p_mean_spread) for each catchment as the coefficient of variation of the mean annual precipitation from different products (standard deviation of mean annual precipitation values from the four precipitation products, normalised by their mean). To allow the comparison of the four products, we use data for the common record period 1998-2014 (Table 2). The spread attribute represents differences among the various precipitation estimates, which can be associated with precipitation uncertainty. The underlying assumption is that similar values from different sources indicate regions with higher confidence in precipitation estimates.

Fig. x1 displays catchment-scale mean precipitation and the precipitation spread index for three main regions: North (northern than 34°S), which includes the Far North and Near North macrozones; Central-South (between 34°S and 44°S); and Austral-Patagonia (southern than 44°S). Mean precipitation (p_mean) estimates have a larger spread in the North (top and middle rows in the boxplots in Fig. 1x. Note the different scale use for p_mean in the North), mainly due to the low mean annual precipitation values typical in these (hyper-) arid regions. Although the absolute difference between products is low, the normalisation by a low mean value increases their dispersion. By contrast, considerably larger precipitation amounts and lower spread values are obtained in Central-South and Austral-Patagonia. However, it should be noted that the ensemble spread of precipitation estimates does not necessarily quantify the accuracy associated to each product, which is typically assessed using ground observations as the "truth" (e.g., Zambrano-Bigiarini et al. 2017). Such analysis is beyond the scope of this article, because the assessment of different precipitation products at the basin scale is typically carried out by forcing (one or more) hydrological model(s) with the different precipitation datasets over the selected study area (e.g., Bisselink et al. 2016; Thiemig et al. 2013; Su et al. 2008).

As an alternative to the model-based approach, we examine the consistency of catchment precipitation estimates based on the water balance at the basin outlet, which is quantified by the long-term runoff ratio in 119 near-natural catchments (bottom row in the boxplots in Fig. x1). These catchments share the following characteristics: interv_degree lower than 0.1 (less than 10% of the annual streamflow allocated to surface rights), large_dam equal to zero (no presence of large dams within the catchment), glacier_frac lower than 5% (negligible glacier contribution), imp_frac lower than 5% (negligible urban areas), and copr_frac lower than 20% (negligible irrigation effects). Although there is large dispersion of runoff ratios in the North (consistent with large p_mean_spread values), there are no inconsistent runoff ratios within this domain. By contrast, there are catchments with runoff ratios larger than 1 in Central-South and Austral-Patagonia, indicating that more water is leaving the catchment than the total amount entering as precipitation. Assuming that streamflow data and catchment area are reliable, such cases indicate precipitation underestimation.

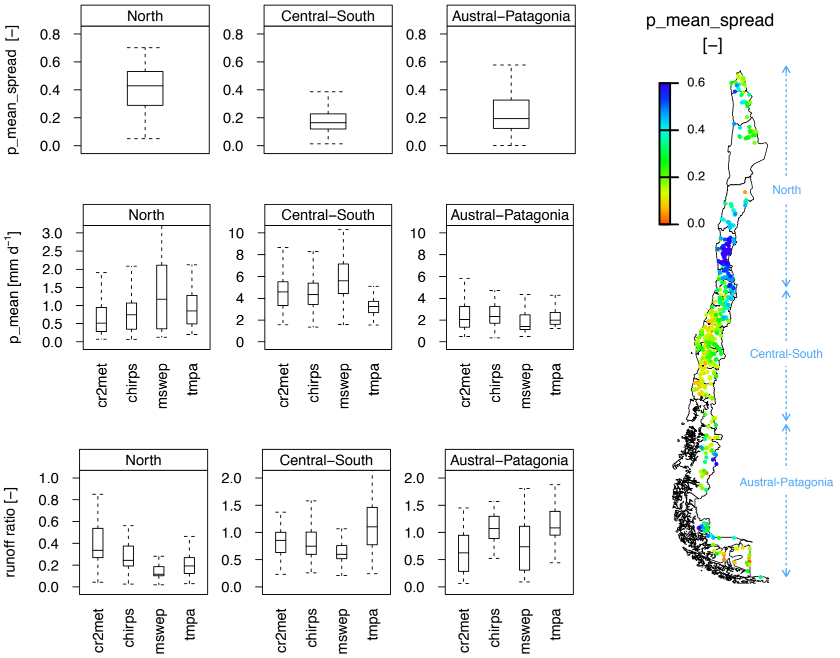

Figure x1: (Left) Precipitation spread (p_mean_spread in top row), mean annual precipitation (middle row), and runoff ratio (bottom row), for the different precipitation products. (Right) Distribution of p_mean_spread in three main regions: North (northern than 32°S); Central-South; and Austral-Patagonia.

In the Central-South region, the MSWEP dataset provides the smallest percentage of catchments (9%) with runoff ratio > 1, whereas in the Austral-Patagonia domain, the product CR2MET provides the smallest percentage (15%). In both domains, the TMPA dataset provides the largest percentage of catchments with runoff ratio > 1 (55% in Central-South and 66% in Austral-Patagonia). The precipitation underestimation in TMPA product was also found by Zambrano-Bigiarini et al. (2017).

A natural question that arises is: what are the main catchment characteristics associated with inter-forcing differences? Figure x2 shows the relationship between runoff ratios and catchment outlet latitude (first column), maximum catchment elevation (second column), and mean catchment slope (third column). These three attributes are the strongest predictors among all topographic, geologic and land cover attributes (Table 3) used in a generalised linear model (not shown). Because runoff mechanisms are highly non-linear, we use the Spearman rank correlation coefficient to explore the relationship between runoff ratios and these attributes. The results in Figure x2 show that runoff ratios greater than one (pink markers) are associated with catchments southern than 34°S (consistent with Fig. x1), showing a significant (p-value lower than 0.05) negative correlation with latitude (first column in Fig. x2).

Since only runoff ratios larger than 1 are indicative of precipitation under-estimation (lower than one informs that the water balance is not violated, but does not provide further information about precipitation quality), we pay close attention on Central-South and Austral-Patagonia regions. To this aim, the correlations with elevation (second column in Fig. 2x) and slope (third column) are computed disregarding Northern catchments (i.e., yellow markers). These plots show significant positive correlation coefficients between runoff ratios and maximum catchment elevation and slope, with runoff ratio values above one for all precipitation products (one product per row). Further, one can note that Northern catchments (yellow symbols) behave very differently in terms of hydroclimatology compared to southern ones (blank and pink markers). Indeed, if these catchments were included in the analysis, the correlation would not be positive nor statistically significant, which supports the idea of clustering the catchments for the analysis.

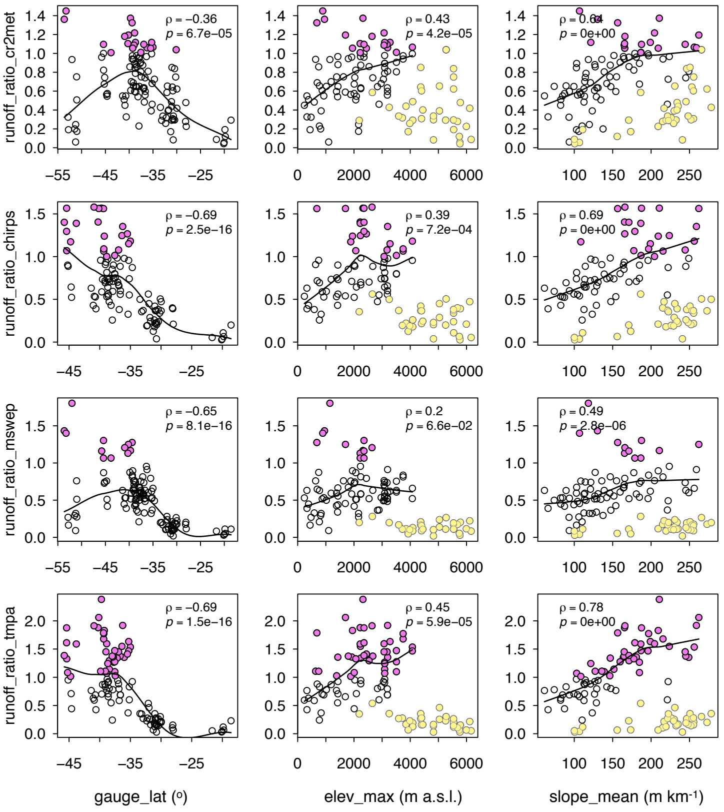

Figure x2: Correlation between runoff ratios calculated for the different precipitation products and outlet latitude (first column), maximum elevation of the catchment (second column), mean slope of the catchment (third column). The Spearman correlation coefficient (ρ), p-value and fitted regression curves are presented in each plot. Pink markers represent runoff ratios above one. Yellow markers represent catchments with gauge latitude northern than 34°S.

In summary, the above results provide two main insights. Firstly, there is large precipitation uncertainty in the Far North and Near North regions due to the relatively rare occurrence of precipitation events. These meteorological characteristics pose methodological challenges for detecting events and estimating their intensities. Although the implications of precipitation uncertainty on streamflow modelling are not straightforward to assess in this sub-domain, some insights can be gained from previously presented results. For example, we have showed that surface runoff is not very sensitive to variations in precipitation (see low values of runoff elasticity to precipitation in Fig. 11f), which may suggest a weak *transferring of precipitation errors within a model. On the other hand, groundwater has the largest contribution to streamflow in this domain (largest baseflow indices in Fig. 11e and sedimentary rocks as the most common geologic class illustrated in Fig. 8a), which suggests that an important source of uncertainty would be related to the representation of groundwater mechanisms in a model. Furthermore, aquifer boundaries may be different from the topography-based catchment delineation performed here, thus a sound identification of the existing aquifers should be carried out to ensure a good representation of the surface-groundwater interaction (e.g., Sar et al. 2015; Arkoprovo et al. 2012; Ivkovic et al. 2009).*

The second insight from this uncertainty analysis is that all precipitation products tend to underestimate precipitation in catchments located south of 32°S, featuring high elevations and steep slopes (the general case for headwater catchments in the Andes). Such limitation is well known and it may be attributed to several factors, including the complex topography of mountain catchments and the corresponding orographic effects that are not fully accounted for at the satellite and reanalysis grid resolution. Another reason is the lack of ground-based data in headwater catchments (90% of the 500 rain gauges located south of 32°S are placed below 1,000 m a.s.l.), a critical issue considering that elevations in Chile goes up to 7,000 m a.s.l. and most of the water feeding the whole system occurs there. This poses challenges for streamflow modelling, water management and allocation, since it restricts the full understanding of hydrological processes. To alleviate these limitations, more monitoring stations are needed at high elevations (above 2,000 or 1,500 m a.s.l. at least) to improve remotely-sensed and model-based precipitation estimates in complex terrains.

New References:

Arkoprovo, B., J. Adarsa, and S. S. Prakash, 2012: Delineation of Groundwater Potential Zones using Satellite Remote Sensing and Geographic Information System Techniques : A Case study from Ganjam district , Orissa , India. Res. J. Recent Sci., ***1****, 59–66.*

Bisselink, B., M. Zambrano-Bigiarini, P. Burek, and A. de Roo, 2016: Assessing the role of uncertain precipitation estimates on the robustness of hydrological model parameters under highly variable climate conditions. J. Hydrol. Reg. Stud., ***8****, 112–129, doi:10.1016/j.ejrh.2016.09.003.*

DGA, 2017: Actualizacion del Balance Hídrico Nacional.

Ivkovic, K. M., R. A. Letcher, and B. F. W. Croke, 2009: Use of a simple surface-groundwater interaction model to inform water management. Australian Journal of Earth Sciences, Vol. 56 of, 71–80.

Sar, N., A. Khan, S. Chatterjee, and A. Das, 2015: Hydrologic delineation of ground water potential zones using geospatial technique for Keleghai river basin, India. Model. Earth Syst. Environ., ***1****, 25, doi:10.1007/s40808-015-0024-3. http://link.springer.com/10.1007/s40808-015-0024-3.*

Su, F., Y. Hong, and D. P. Lettenmaier, 2008: Evaluation of TRMM Multisatellite Precipitation Analysis (TMPA) and Its Utility in Hydrologic Prediction in the La Plata Basin. J. Hydrometeorol., ***9****, 622–640, doi:10.1175/2007JHM944.1. http://journals.ametsoc.org/doi/abs/10.1175/2007JHM944.1.*

Thiemig, V., R. Rojas, M. Zambrano-Bigiarini, and A. De Roo, 2013: Hydrological evaluation of satellite-based rainfall estimates over the Volta and Baro-Akobo Basin. J. Hydrol., ***499****, 324–338, doi:10.1016/j.jhydrol.2013.07.012.*

Zambrano-Bigiarini, M., A. Nauditt, C. Birkel, K. Verbist, and L. Ribbe, 2017: Temporal and spatial evaluation of satellite-based rainfall estimates across the complex topographical and climatic gradients of Chile. Hydrol. Earth Syst. Sci., ***21****, 1295–1320, doi:10.5194/hess-21-1295-2017.*