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Discussions

Interactive comment on "Early warning and drought risk assessment for the Bolivian Altiplano agriculture using high resolution satellite imagery data" *by* Claudia Canedo Rosso et al.

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Response to reviewers

The authors thank the editor, reviewers, and third person′s comments for time spent and efforts to improve the manuscript. We have revised the manuscript accordingly taking the reviewers′ and third person′s comments into due consideration. Below follow answers to the reviewer′s comments and description of actions taken.

While the reviewers indicated that the article is of substantial interest and relevant for the journal they criticized the misleading title as well as the analysis to be "poorly executed". Furthermore, they reviewers indicated that the quality of the presented material is "not satisfactory" to support the results found. We agree with the reviewers in the sense that one major restriction to provide a sophisticated model between satellite imagery and agriculture risk is data limitation. However, the unavailability of data to be used for a sophisticated drought modelling approach are very common in a developing country context (World Bank 2016). One way to overcome this challenge is to apply a so-called iterative risk management approach, e.g. starting with baseline estimates using the best data currently available and updating risk estimates continuously over time (see IPCC 2012). Currently there are no studies for the Altiplano which relates satellite sourced imagery with agriculture risk, including possible associations with ENSO. The article tries to fill this gap. We acknowledge the fact that there are other studies in other countries which are using more sophisticated models, however, the situation in the Altiplano, especially the data limitations, restricts the use of such models and we provide a way forward to improve the data situation using high-resolution satellite imagery with a probabilistic approach for agriculture risk. Hence, for the current situation in Bolivia our approach can be regarded as one way forward, and can be used as a baseline case for further analysis in the future. As indicated, the situation is quite similar in other developing countries around the world and our approach can be seen as one way forward how to implement drought risk management under data scarcity including the important connection with the ENSO phenomenon. We also provided now much more detail on the strengths and limitations of the approach, including a detailed uncertainty analysis. Please find our detailed responses to the reviewer comments below.

The response to reviewers are structured following the recommendations of the editors:

i. Comment from referee

ii. Authors' response

iii. Author's changes in manuscript.

In addition the last section "Changes in manuscript" describes in more detail the author's changes in manuscript.

Short comment: V. Moya Quiroga 1. i. The term early warning usually refers to a time anticipation; X time before a given event the warning is emitted. In the present case, readers would expect to see the NDVI or ENSO conditions that represent a high probability of drought some months before the drought. For instance, if the September ENSO is X, there is a Y probability of drought. However, the article doesn't show any early warning. The article only analyzes the some ENSO relationships, which is nothing new. Several previous researchers (not referenced in the literature review) have already analyzed the relationship between ENSO and crop production in South America (Izumi et al., 2014; Anderson et al., 2016). Moreover, previous studies have already proposed ENSO based crop management policies in South America (Ramirez-Rodrigues et al., 2014)

ii. The authors agree with the comment, and we changed the title and aim to the study. The new title is "Drought risk assessment for the Bolivian Altiplano agriculture and its association with El Niño Southern Oscillation". And the new aim is to present a methodology for assessing drought risk to mitigate its impacts on agriculture using observed gauge data and satellite based imagery data for the Bolivian Altiplano.

In contrast of the mentioned previous research of the ENSO-based relationship with crop production and climate variables, this research aims to downscale the regional information at a local level, this permits to define hotspots where droughts could affect in large extend the agricultural production, and this information can be useful for risk management.

iii. The authors improved the introduction section and included the findings of previous research related with the study. 2. i. It is not clear which satellite data was used. The title suggests "high resolution", but the manuscript mentions 0.05 degree (about 5 km). The term high resolution satellite imagery usually refers to less than 90 m or 50 m resolution.

ii. NDVI has a grid of 0.08 degree and CHIPRS satellite precipitation data has 0.05 degree of spatial resolution.

iii. The manuscript was modified and it does not include the term "high resolution" to avoid confusions.

3. i. The manuscript only shows the results of 1 correlation for 1 station (NDVI correlation for Tihuanacu), which is supposed to be the one with the highest correlation (Pg9 Ln21). This brings several doubts. *How is the correlation in other locations? (Maybe a thematic correlation map would be more appropriate) *Even though Tihuanacu has the highest correlation, the correlation is still quite weak (0.41). Does it means that the other correlations were even lower? *Manuscript states that it considered 23 stations, most them located in La Paz. But then it presents an average value for each department. This procedure is not appropriate for several reasons. For instance: a) It is not fair to compare the average of La Paz (more than 15 stations) with the average of Potosi (only 3 stations poorly distributed) b) In the present methodology the stations were clustered based on political boundaries. Does it mean that bolivian climate behaves according to its political boundaries? I don't believe so. For instance, the stations near Titikaka lake (in La Paz) have very different climatic characteristics than other stations also in La Paz (for instance El Alto or Santiago de Machaca).

ii. A new analysis was done in order to find out the relationship between NDVI and crop production. The maximum NDVI during the months of major development of potato and quinoa crops (March to May) was selected and compared with the annual crop yield of quinoa and potato at La Paz, Oruro and Potosi. The results of this analysis present a positive relationship between crop yield and vegetation. Only the pixels that presented a significant correlation above 0.6 were selected for the following regression with the climate variables.

Using the new described methodology we avoided possible errors that could bring the analysis of the mean NDVI and the annual crop at regional level. As the comment mentions, the Bolivian climate does not behave as the political boundary, and therefore the mean of the maximum NDVI at the administrative level is no longer used in the manuscript. * i. The correlations from FigA6 are different than the values from Table 2 (because of rounding decimals).

ii. The authors revised and corrected the decimals shown in the figures and tables.

* i. Manuscript states that Tihuanacu has the highest correlation, but Table 2 shows that Potosi has higher correlation.

ii. Manuscript states that Tihuanacu has the highest correlation coefficient between NDVI and climate variables, and Table 2 shows that Potosi has higher correlation (spearman correlation, p=0.001) between crop yield and NDVI. These are two different analysis, and therefore the results are also different.

iii. We applied a different analysis to seek the relationship of NDVI and crop production. We no longer considered the relationship of the mean NDVI and crop yield at local level (La Paz, Oruro, and Potosi), instead the analysis the relationship of every NDVI grid (0.08áţŠ) with the crop yield. The new results are included in the manuscript.

* i. The highest correlation (0.51) is still a weak correlation. What is the confidence of a prediction based on such a weak linear correlation? What would be the confidence of predictions for Oruro based on a linear correlation of 0.12? Unfortunately, it seems that the present results suggest that the present methodology does not provide a reliable drought estimations.

ii. The authors agree with the comment and therefore we improved the analysis by selecting the locations where NDVI and crop production have a correlation above 0.6*** for the subsequent regression of NDVI and the climate variables.

iii. The method and results of the analysis are described in Changes in manuscript

Changes in manuscript

In general, there was an improvement in the manuscript redaction and structure. The title was modified to “Drought risk assessment for the Bolivian Altiplano agriculture and its association with El Niño Southern Oscillation”. The new objective of our paper is to present a methodology for assessing drought risk to mitigate its impacts on agriculture using observed gauge data and satellite based imagery data for the Bolivian Altiplano. The description of the modifications of the manuscript will be dived by sections: 1) Introduction, 2) Data Description, 3) Methods, 4) Results, 5) Discussion and, 6) Conclusion. The sections 1) Introduction and 2) Data Description where shortened to the relevant information. The section 3) Methods was modified as well, a new analysis of the relationship of the NDVI and the crop yield was done. The section with major changes is 4) Results, because we incorporated the new results of the relationship between NDVI and crop yield, and the new regression of NDVI and climate. Finally, the section 5) Discussion was also modified to suit with the new aim and findings, and 6) Conclusions” were adapted to the new manuscript content.

1. Introduction

Agricultural production is highly sensitive to weather extremes, including droughts and heat waves. Losses due to such extreme hazard events pose a significant challenge to farmers as well as governments worldwide (UNISDR, 2015). Worryingly, the scientific community predicts an amplification of these negative impacts due to future climate change (IPCC, 2013). Especially in developing countries as Bolivia, drought is as a major natural hazard. However, the impacts vary on a seasonal and annual timescale, on the hazard intensity, and the capacity to prevent and respond to droughts (UNISDR, 2009). Regarding the former, the El Niño Southern Oscillation (ENSO) plays an important role. ENSO triggers droughts in several regions around the world, driving losses in agricultural crops and increased food insecurity (Kogan and Guo, 2017).

Bolivia have experienced large socio-economic losses in the past due to droughts. Generally, agricultural productivity in the Bolivian Altiplano is low due to high susceptibility to the climate, poor soil conditions, and the mainly manual labour. Poor agricultural production is also associated with the ENSO climate phenomena (Buxton et al., 2013). Droughts are generally driven by the ENSO warm phases (Vicente-Serrano et al., 2015; Garreaud and Aceituno, 2001; Thompson et al., 1984). Most important rainfed crops in the region include quinoa and potato. The Sustainable Development Goals (SDGs) state that the priority areas for adaptation to climate change are water and agriculture. These in turn, are related to the largest climate hazards including floods, droughts, and higher temperatures (UN, 2016). Additionally, the implementation of early warning is fundamental for drought disaster risk management, proactive planning, and mitigation policy measures in vulnerable regions, including Latin American countries such as Bolivia (Verbist et al., 2016).

Various studies of the relationship between ENSO and precipitation were developed previously, and they show a negative relationship between ENSO warm phase (El Nino) and precipitation, meaning that El Nino periods have been linked with a decrease of precipitation (Vicente-Serrano et al., 2015; Garreaud and Aceituno, 2001; Thompson et al., 1984; Francou et al., 2004; Vuille et al., 2000; Vuille, 1999). Other authors have studied ENSO-based seasonal forecasting (Lupo et al., 2017), and crop relation with climate variability (Garcia et al., 2007; Porter and Semenov, 2005). On the other hand, previous research of the relationship between ENSO and crop production was developed at global scale (Iizumi et al., 2014) and in South America (Anderson et al., 2017). Moreover, previous studies have already proposed ENSO based crop management in South America (Ramirez-Rodrigues et al., 2014). However, few studies have incorporated remote sensing data to relate drought events and ENSO (e.g. Liu and Juárez, 2001), and they are not developed in the Altiplano. In consequence, there is a gap of a drought risk assessment for the Bolivian Altiplano agriculture and its association with El Niño Southern Oscillation, using observed gauge data and satellite based imagery data. To lessen the long term impacts of these events, the national government has allocated a large budget for emergency operations to compensate part of the losses, which are usually evaluated in an ex-post approach. However, based on ENSO forecasting, an El Nino event can be predicted 1 to 7 months ahead (Tippett et al., 2012).

For this time period it may be possible to implement ex-ante policies to reduce societal vulnerability to droughts, stressing preparedness, and improve risk management strategies. We are especially interested in how a risk based approach can be used to determine the potential need of resources as well as ways to determine hotspots where it is likely that these resources need to be distributed. A constraint to study drought occurrence is the uneven and scarce distribution of weather and crop related ground data in the region. We therefore use precipitation and vegetation satellite data that present full coverage of the spatial distribution in the study area. We combine this information with gauged precipitation, temperature, and crop yield data to enhance the knowledge and provide consistent results for climate and vegetation variability. Based on these observations, the objective of our paper is to present a methodology for assessing drought risk to mitigate its impacts on agriculture using observed gauged data and satellite based imagery data for the Bolivian Altiplano.

Our paper is organized as follows. Given the importance of data limitations in our case study region, we first introduce in section 2 the recently available datasets employed for our analysis. In section 3 we discuss the methods employed to (i) test the validity of the new datasets in our analysis, (ii) show how the relationship between climate and vegetation data was estimated, and (iii) how ENSO was incorporated in our analysis. After this, section 4 presents results and our proposed framework. Finally, section 5 ends with a conclusion, ways forward, and outlook to the future.

2. Data Description

The Bolivian Altiplano covers about 150,000 km2. It contains more than 70% of the total Altiplano surface area, the remaining percentage is located in southern Peru and northern Chile. La Paz, Oruro, and Potosi are the major administrative regions in the Bolivian Altiplano. The Altiplano has a pronounced southwest-northeast gradient (200–900 mm year-1) in annual precipitation with the wet season occurring from November to March (Garreaud et al., 2003). Over 60% of the annual precipitation occur during the summer months (DJF) in association with the South American Monsoon (SAM) (see

Fig. A1).

2.1 Climate Variables: Precipitation and Temperature Data

Time series of observed monthly precipitation at 23 locations and mean, maximum, and minimum temperature at 15 locations from July 1981 to June 2016 were obtained from the National Service of Meteorology and Hydrology (SENAMHI; see Appendix Table A1). Initially, the available precipitation data sets included 65 gauges but only 23 were used since they have less than 10% of missing data. The data gaps were filled with the mean monthly value of the whole dataset to provide full time series. Outliers were identified by comparing with neighbouring monthly data. The inter-annual temperature at the 15 locations varied considerably between summer (DJFM) and winter (JJAS), including a larger variance for the minimum temperature (Fig. A2a). Regions close to the Lake Titicaca present lower inter-annual variability (Copacabana [10], Fig. A2b). In contrast, Uyuni [22] presents larger inter-annual oscillations (Fig. A2c). The precipitation gauges have an uneven spatial distribution and are mainly concentrated in the northern Bolivian Altiplano. To improve the spatial coverage of rainfall data, monthly quasi-rainfall time series from satellite data were included in our study. The Climate Hazards Group InfraRed Precipitation with station data (CHIRPS) quasi-global rainfall dataset was used. CHIRPS presents a 0.05° resolution satellite imagery and is a quasi-global rainfall dataset from 1981 to the near present with a satellite resolution of 0.05° (Funk et al., 2015). The information about CHIRPS is described in http://chg.geog.ucsb.edu/data/chirps/.

2.2 El Niño Southern Oscillation Data

The Oceanic Niño Index (ONI) is usually used to identify El Niño (warm) and La Niña (cool) years (http://www.cpc.ncep.noaa.gov/). ONI is the 3 month running mean of Extended Reconstructed Sea Surface Temperature (ERSST v5) anomalies in the El Niño 3.4 region. The El Niño 3.4 anomalies represent the average equatorial SSTs in the equatorial Pacific Ocean (5oN to 5oS latitude, and 120o to 170oW longitude). Five

consecutive overlapping three month periods at or above +0.5°C anomaly represents warm events (El Niño), and at or below the -0.5 anomaly are cold (La Niña) events.

2.3 Crop Production and Vegetation Data

As indicated above, quinoa and potato are the main crops in the Bolivian Altiplano and still gaining importance. The quinoa growing season is from September to April and, for potato from October to March. Data for quinoa and potato yield were obtained from the National Institute of Statistics (INE) of Bolivia from July 1981 to June 2016 for La Paz, Oruro, and Potosi (Fig. 1). No crop yield data at local scale are available and this is a major limitation that needs to be addressed in the future. The annual datasets represent production (t) in relation of the area (ha) at regional level.

Additionally, the Normalized Difference Vegetation Index (NDVI) can be used to estimate the vegetation vigour (Ji and Peters, 2003) and crop phenology (Beck et al., 2006). NDVI was assembled from the Advanced Very High Resolution Radiometer (AVHRR) sensors by the Global Inventory Monitoring and Modelling System (GIMMS) at semi-monthly (15 days) time steps with a spatial resolution of 0.08áţŠ. NDVI 3g.v1 (third generation GIMMS NDVI from AVHRR sensors) data set spans from July 1981 to December 2015. Note, the NDVI is an index that presents a range of values from 0 to 1, bare soil values are closer to 0, while dense vegetation has values close to 1 (Holben, 1986). NDVI 3g.v1 GIMMS provides information to differentiate valid values from possible errors due to snow, cloud, and interpolation errors. These errors were eliminated from the dataset and where replaced with the nearest neighbour value. In our study we used the NDVI to simulate crop production.

3. Methods

3.1 NDVI simulation of crop yield

The maximum 15-days NDVI of March, April and May for every year was identified. Only the time from March to May was considered because this period represents the maximum phenological development of quinoa and potato crops. The maximum NDVI of each grid was compared to the annual crop yield at La Paz, Oruro, and Potosi. The NDVI grids and crop yield correlations larger than 0.6 (spearman correlation, p = 0.001) were considered as adequate for crop yield estimation, and only these grids were considered for further study. A similar approach was used by (Huang et al., 2014). Afterwards, a regression of the selected NDVI grids and the precipitation was developed. The satellite precipitation data was used for the regression. For this analysis, the NDVI grids were compared to the same spatial location of satellite precipitation data.

4. Results

4.1 Validation of Chirps satellite precipitation data

The mean annual gauged precipitation and CHIRPS satellite data product (Fig. R1) shows the relevance of the application of satellite data in the studied region.

The RMSE and ME (Fig. R5) shows the locations where satellite data overestimates or underestimates the gauged precipitation. Generally, the precipitation is under/overestimated in a range of -10 to +10 mm per month [6] (Fig. R5b). However Charazani [6] present a large bias of 40.7 mm/month. As well, most of the stations present a RMSE between 15 to 30 mm/month, Charazani [6] had a RMSE of 58 mm/month.

4.2 NDVI simulation of crop yield

Figure R6 presents the locations where NDVI simulates the crop yield with a correlation larger than 0.6 (spearman correlation, p = 0.001). The NDVI grids that better simulates the quinoa crop are shown in Fig. R6a, and the NDVI that better simulates the potato crop are shown in Fig. R6b. We can see that NDVI can simulate the proper production of the crop land area in La Paz, Oruro, and Potosi.

4.3 NDVI association with precipitation

Only the NDVI grids with larger correlation of 0.6 with crop yield were considered for

the climate regression. The results for stepwise linear regression between NDVI and accumulated precipitation were statistically significant at the 0.01 level. The analysis was firstly applied with the NDVI that best simulates the quinoa yield and afterwards with the NDVI that best simulates the potato yield. In La Paz, the mean correlation coefficient resulting from the regression of the NDVI that best simulates the quinoa and accumulated precipitation is 0.7 in La Paz, and above 0.6 in Oruro and Potosi. The regression of the NDVI that best estimates the potato yield and the accumulated precipitation shows a mean correlation coefficient of 0.7 in La Paz, 0.6 in Oruro, and 0.5 in Potosi.

4.4 Analysis of the ENSO impact on crop yield

Large reductions of crop yield are shown during El Nino events. The crop yield difference between the mean of the crop yield from 1981 to 2016 and the crop yield during a strong El Nino event 1982/1883 is shown in Fig R7. Quinoa yield reduces 65%, 10% and 73% at La Paz, Oruro, and Potosi respectively. And potato yield reduces 42%, 83% and 32% at La Paz, Oruro, and Potosi. In addition, the comparison between the mean NDVI from 1981 to 2016 and the NDVI during El Nino event of 1982-1983 is shown in Fig R8. Around the Lake Titicaca in the northern Altiplano the NDVI reduction is from 0 to 10%. And, in some locations of the southern Altiplano the reductions of NDVI are above 30%, and few locations reaches reductions above 40%, meaning great losses.

5 Discussion

We employed a satellite product dataset and tested it for accuracy as well as performance to similar (but with coarser resolution) datasets available for our region. Using this dataset, it was shown that during El Nino years the crop yield reduces (Fig. R7), and as a consequence the socio-economic vulnerability of the farmers increases. Furthermore, it was found that NDVI can be related to crop yield and therefore, NDVI could be used to target specific hot spots depending on NDVIs availability at a local scale. As a consequence, ENSO forecasts as well as possible magnitudes of crop deficits could be established by the authorities, including identification of possible hotspots of crop deficits during the growing season. Our approach therefore, can not only help for determining the magnitude of assistance needed for farmers at the local level but also enable a pro-active approach to disaster risk management against droughts. This may include not only economic related instruments such as insurance but also risk reduction instruments such as irrigation needs. In fact, early warning based financing is gaining increasing attraction in some real world settings as it has several advantages. However, it should be acknowledged that large challenges still remains (French and Mechler, 2017). Drought severity could be measured via shifts from normal conditions of climatic parameters such as precipitation. As in our case, we not only provided shifts but the difference in risk for El Nino and neutral/moderate years. However, one of the main challenges of drought risk analysis is data-scarcity, e.g., low density or not evenly distributed stations for hydro-meteorological data networks, poor data quality due to missing data, and restricted use of data between government agencies or other institutions. As it was shown here, ENSO warm phase related characteristics are especially important in the context of extreme drought events and should therefore be incorporated within early warning systems as standard practice. Despite these challenges for development of drought risk assessment, applications have been successful in the past. There are numerous cases in many countries around the globe. As in our case, particularly in the mid-latitudes weather patterns are strongly influenced by ENSO. Monitoring and predicting ENSO can therefore significantly contribute to reduce the risk of disasters.

6 Conclusions

This study is a first attempt to provide an agricultural drought risk assessment in relation to the ENSO phenomenon for the Bolivian Altiplano. Given the large differences in risk, and corresponding strategies to lessen the impacts could be implemented in the Bolivian Altiplano. In doing so, we introduced and tested a satellite product that was used for estimating crop risk. The ENSO impact on crop production was evaluated

by studying the relation of crop yield, vegetation and climate variables, considering that El Nino generally drives a drought event. Our study provides valuable information for drought risk reduction, primarily by providing information of the hotspots where crop yield is more affected for droughts. Moreover, we showed that ENSO phases are strongly related to crop yield, and with this information the prediction of ENSO could be used to define risks in terms of decrease in crop yields in the studied region. While overall good fit among climate, ENSO, and crop yield variables were found, it is important to consider other parameters, such as evapotranspiration and soil moisture in improved models. With such information also agricultural models could be set up and risk management plans with better accuracy determined.

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