Predicting climate change impacts on water resources in the tropical Andes: the effects of GCM uncertainty

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Abstract

There is a strong demand from policy makers for predictions about the potential impacts of climate change on water resources. Integrated environmental models, combining climatic and hydrologic models, are often used for this purpose. This paper examines the impact of uncertainties related to GCMs in hydrological impact studies in the tropical Andes. A conceptual hydrological model is calibrated on data from four mesoscale, mountainous catchments in south Ecuador. The model inputs are then perturbed with anomalies projected by 20 GCMs available from the IPCC Data Distribution Centre. The results show that on average, the average monthly discharge is not expected to change dramatically. However, the simulated discharges driven by different global climate model forcing data can diverge widely, with prediction ranges often surpassing current discharge.

1 Introduction

Global climate change is expected to have a strong impact on water resources (*Huntington*, 2006; *Intergovernmental Panel on Climate Change*, 2007). Changes in precipitation patterns affect water availability and runoff directly, while changes in temperature, radiation and humidity have an effect on evapotranspiration. As such, there is a strong socio-economic value in predicting the potential effects of climate change on the timing and magnitude of stream discharge (e.g., *Vergara et al.*, 2007). A combination of climatic and hydrologic models is often used for this purpose. The projections of global circulation models (GCMs) are

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Published as: Buytaert, W., Celleri, R., Timbe, L., 2009. Predicting climate change impacts on water resources in the tropical Andes: the effects of GCM uncertainty. Geophysical Research Letters 36, L07406.

downscaled using dynamical or statistical approaches (*Fowler et al.*, 2007), and used to force smaller scale hydrological models (e.g., *Salathé Jr et al.*, 2007).

However, this approach is prone to large uncertainties at various levels of the prediction. Particularly GCMs are known to contain large errors, due to simplification of climate representation, potentially wrong assumptions about climate processes, limited spatial and temporal resolution, and errors in the forcing data (*Allen and Ingram*, 2002; *Stainforth et al.*, 2007; *Intergovernmental Panel on Climate Change*, 2007). In climate change impact studies, GCM results are used as input for hydrological, ecological and other models. In such model chains, errors may propagate in a very complex way. For instance, errors in calculations of evapotranspiration may either compensate or amplify the impact of uncertain changes in precipitation patterns on water supply. These effects may result in final model predictions that are prone to large uncertainty, jeopardizing management decisions (*Pappenberger and Beven*, 2006). This paper assess the uncertainty propagation in a coupled hydroclimatic model, originating from the projections of global circulation models (GCMs).

Many studies have addressed climate change impacts on water resources (e.g., *Andersen et al.*, 2006; *Dibike and Coulibaly*, 2007; *Wilby and Harris*, 2006; *Stahl et al.*, 2008; *Markoff and Cullen*, 2008). However, these studies use data from only a limited number of GCMs. Often only one GCM model is used (*Andersen et al.*, 2006; *Dibike and Coulibaly*, 2007). One of the largest GCM ensembles is used by *Markoff and Cullen* (2008), including 7 GCMs from the IPCC Third Assessment report. There are several reasons for not using all GCM projections. Often the access to GCM data is an important issue. Also, regional climate models tend to represent better the spatial variability in meteorological processes, which may have a strong effect on the hydrological response. However, such models are often only implemented for a limited number of GCMs. Finally, practical issues such as computational demands may be a limitation.

Although the focus on complex and powerful downscaling methods and hydrological models is a reasonable strategy to pursue more reliable projections, these studies give little insight in the potential uncertainty of the projections. Therefore, we use the entire GCM ensemble of the IPCC's Fourth Assessment Report (*Intergovernmental Panel on Climate Change*, 2007) to quantify the potential impact of climate change on the hydrological response of mesoscale catchments in the Andes. This approach, in which the range of a large ensemble of GCM models is used to provide a non-discountable climate change envelope for future climates has been advocated as a sensible way to provide uncertainty information to stakeholders (*Stainforth et al.*, 2007).

Table 1: Characteristics of the study catchments. P = precipitation, Q = discharge, PET = potential evapotranspiration, RMSE = root mean square error of the fitted model, Data = availability of daily discharge data for the study period.

River	Station	Area (km^2)	Altitude range (m)	Mean P [mm $year^{-1}$]	Mean Q [mm $year^{-1}$]	Mean PET [mm $year^{-1}$]	RMSE [mm $month^{-1}$]	Data [%]
Matadero	Sayausi	294.6	2742 – 4264	1086	735	981	15.5	86
Jadan	Jadan	292.1	2337 – 3332	743	144	1095	5.9	49
Tomebamba	Monay	1250.9	2434 – 4264	883	397	1028	9.7	81
Paute	Jadan	2460.4	2297 – 4264	854	377	1049	9.1	51

2 Methods

Four mesoscale hydrological catchments were studied in the Paute river basin, south Ecuador (Table 1, Fig. 1). The subcatchments are representative for the main land covers types in the basin, ranging from wet high altitudinal grasslands (Matadero) to drier, eroded badlands (Jadan). The Paute river plays a key role in the socio-economic development of the region. It provides water to the city of Cuenca and many irrigation schemes in the region, and hosts the largest hydro-power plant of the country (Daniel Palacios, 1000 MW). As such, there is an urgent need for adequate climate change adaptation strategies (*Myers et al.*, 2000; *Bradley et al.*, 2006). Due to the regional topography dominated by the Andes, climatic and hydrologic processes are extremely complex (*Buytaert et al.*, 2006; *Celleri et al.*, 2007). A detailed representation of these processes in a hydrological model is impossible in view of the available data. Therefore a simple, conceptual hydrological model was implemented. The model consists of a loss module to calculate evapotranspiration losses, and a routing module representing the delay between precipitation and discharge. In the study region, actual evapotranspiration may be significantly lower than potential evapotranspiration due to soil moisture deficits. Both potential evapotranspiration and soil moisture are strongly dependent on climatological conditions which may change in future scenarios. These changes are accounted for by applying the catchment moisture deficit store of *Croke and Jakeman* (2004) as a loss module. For the routing module, the frequently used linear store was implemented (*Beven*, 2001).

Potential evapotranspiration was calculated by means of the FAO-Penman Monteith method (*Allen et al.*, 1998), using data from 4 nearby meteorological stations. To account for altitudinal gradients, the evapotranspiration data were extrapolated using a high resolution digital elevation map. For this, the Thornthwaite relation between temperature and potential evapotranspiration was combined with the local lapse rate obtained from 24 temperature stations ($-0.54°\mathrm{C}\ 100\ \mathrm{m}^{-1}$). Area averages of precipitation were obtained from 13 rain gauges (*Celleri et al.*, 2007) using Thiessen interpolation. Some gaps in the rain gauge data were filled using extrapolation from nearby stations using linear regression. The model was run with a daily timestep for the period from 1978 to 1991, and calibrated on available discharge observations (Table 1). The modelled daily discharges were aggregated at a monthly timescale for a clearer representation of the intra-annual variability.

GCM projections were obtained from the IPCC Data Distribution Centre for the A1B scenario. Twenty year averages for the period 2011 – 2030 were used, as this period is most relevant for current management decisions. An additional advantage of this period is the fact that ecosystem adaptation is less likely to occur compared to periods further in the future. Such alterations would have to be accounted for in the hydrological model. As some GCMs do not provide projections for this scenario and period, the GCM ensemble consists of 20 of the 25 IPCC models. The delta method was used to generate future scenarios of precipitation and evapotranspiration (*Fowler et al.*, 2007).

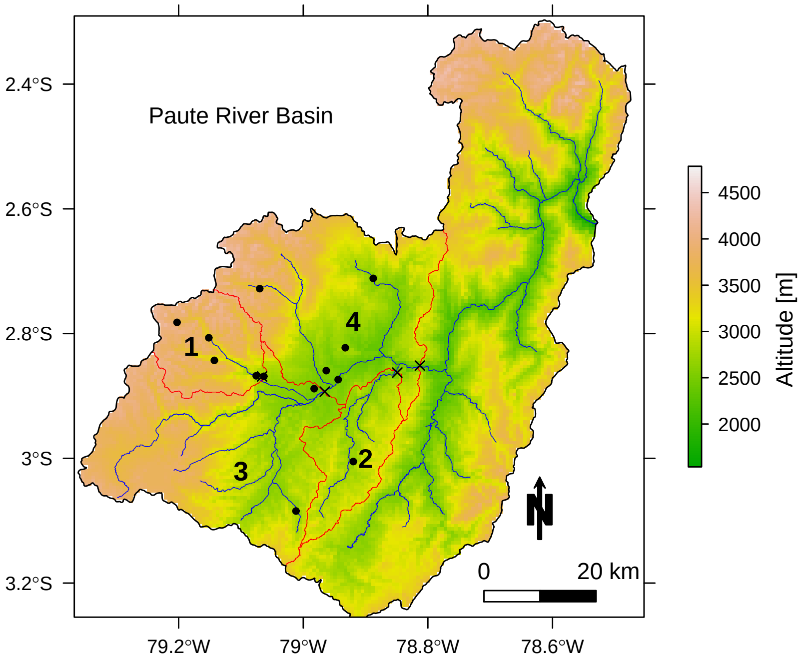


Figure 1: Map of the Paute river basin, with the 4 studied subcatchments: (1) Matadero; (2) Jadan; (3) Tomebamba; (4) Paute. Note that Matadero is a subcatchment of Tomebamba, and that Tomebamba and Jadan are subcatchments of Paute. ● = precipitation stations, X = discharge stations used in this study.

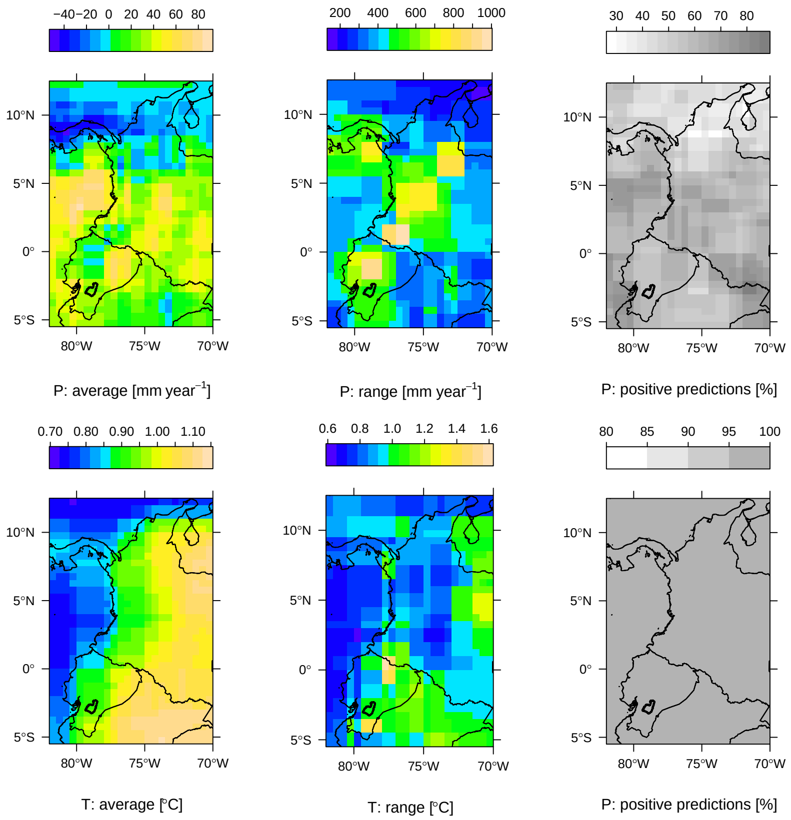
In this method, differences between the control and future GCM simulations are applied to historical observations by simple scaling. The delta method makes strong assumptions about the nature of the changes, including a lack of change in variability and spatial patterns of climate. However, the lack of data and the high complexity of the climate system in the region highly complicate the use of more complex downscaling models.

3 Results and discussion

Fig. 2 gives the average, range, and consistency of the projected anomalies in temperature and precipitation in the tropical Andes, during the period 2011 – 2030 and for the A1B emission scenario. Anomalies are relative to the 1961-1990 mean of the 20th century simulation. The average projections in temperature show a consistent behaviour, with all models predicting an increase in temperature, which ranges from +0.72 to +1.12°C. Average projections of precipitation anomalies are very variable (between -44.2 and +84.0 mm year $^{-1}$), with a decrease in precipitation in the Caribbean coast, and an increase in regions influenced by the airmasses of the Pacific Ocean. However, discrepancies between individual models can be very high and in most areas there is little agreement even on the direction of the change (Fig. 2, right). Especially in the Andes region, model projections diverge up to 950 mm year $^{-1}$, which is often more than the average actual precipitation in the region. The highest variations in temperature are also found in the Andes region.

The diverging projections can also be observed in the monthly projections for the Paute river basin (Fig. 3). Again, average predicted changes are relatively low. A slight increase in seasonality is observed, which is consistent with other findings (*Giorgi and Bi*, 2005) and may have important consequences for water managers. However, the extremes in the prediction have a similar order of magnitude as the actual precipitation (Table 1). This pattern propagates to the average monthly discharge as predicted by the hydrological model (Fig. 3).

In the short term, the impact of climate change on water resources is mainly through alterations of evapotranspiration and precipitation. The increase in temperature results in a modest increase of potential evapotranspiration (between 17.4 and 65.4 mm year^{-1}, data not shown). The hydrological model predicts changes in actual evapotranspiration, however, between -162 and +185 mm year^{-1}. This broad range is mainly caused by divergent projections for future precipitation, as these affect the soil moisture deficit and thus actual evapotranspiration. Some compensation occurs in the hydrological model: the wettest climate scenarios will also have the highest soil moisture and therefore the highest actual evapotranspiration predictions. However, most uncertainties in precipitation and evapotranspiration propagate through the hydrological model. Final average monthly discharge projections range from 23% to 518% of the current conditions, while the 10% and 90% quantiles are respectively 70% and 148% of the current conditions. These are potential changes in the average monthly discharge over the studied period, and do not represent inter-



P: average [mm year^{-1}]

P: range [mm year^{-1}]

P: positive predictions [%]

T: average [°C]

T: range [°C]

P: positive predictions [%]

Figure 2: Average, range and consistency in prediction for the predicted anomalies in temperature (T) and precipitation (P) in the tropical Andes, during the period 2011 – 2030 and for the A1B emission scenario. The maps on the right hand side show the precentage of models predicting a positive change, i.e. respectively an increase in precipitation and an increase in temperature. The models used in the GCM ensemble are: UKMO-HADCM3, UKMO-HADGEM1, NCAR-CCSM3, NCAR-PCM, BCCR-BCM2, CCCMA-CGCM3_1-T47, CNRM-CM3, CONS-ECHO-G, CSIRO-MK3, GFDL-CM2, GFDL-CM2_1, INM-CM3, IPSL-CM4, LASG-FGOALS-G1_0, MPIM-ECHAM5, MRI-CGCM2_3_2, NASA-GISS-AOM, NASA-GISS-EH, NIES-MIROC3_2-HI, NIES-MIROC3_2-MED. All models were rescaled to a common resolution of 0.5° using the nearest neighbour approach before averaging. The Paute river basin is outlined in black.

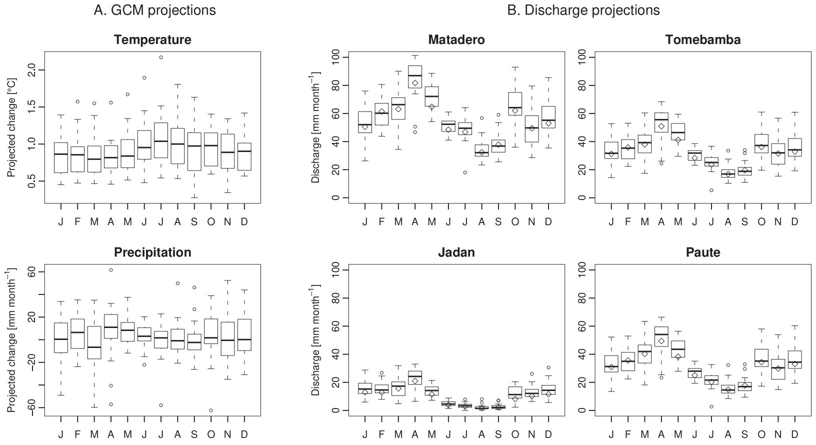


Figure 3: Boxplots of (A) variability in the GCM projections for monthly temperature (T) and precipitation (P) anomalies for the Paute river basin, Ecuador (period 2011 – 2030 and A1B emission scenario), and (B) variability of projected average monthly discharge for each study catchment under these projections. ◊ = average modelled discharge for the 1978 – 1991 period. The boxplots show median, quartiles, and range of the data. Any value which lies more than 1.5 times the interquartile range below the first quartile or above the third quartile is considered an extreme value (○).

annual streamflow variability. In the study region, the interannual variability in monthly discharge ranges typically between +/- 30% to +/- 65%, depending on the time of the year, the properties of the basin, and the precipitation regime. However, despite the large natural variability, it is clear that the obtained projection ranges will have limited value for most adaptation measures.

Despite the broad ranges, the obtained values should be seen as minimum prediction uncertainties. It is unlikely that current GCMs cover the uncertainty of future projections completely (*Stainforth et al.*, 2007; *Allen and Frame*, 2008). Additionally, this study does not take into account deficiencies in the hydrological model and the downscaling, which may be significant (*Wilby and Harris*, 2006; *Prudhomme and Davies*, 2009). For reasons of data scarcity and parsimoneity, very simple models were applied here. They can be improved by additional data collection and the development of more sofisticated models.

The development of better hydrological models is not only important to decrease the predictive uncertainty, they are also necessary if we are to plan adaptation of the hydrological system for future conditions. Environments with high spatial and temporal gradients, such as the tropical Andes, will be particularly sensitive. For instance, in the hydrology of the northern Andes, tropical alpine wetlands take an important place. Their hydrological functioning is strongly dependent on soil carbon dynamics, which regulate the soil infiltration and storage capacity (*Buytaert et al.*, 2006). These properties are very sensitive to soil humidity and temperature, which may alter strongly in climate change conditions. For long term projections, it is important to include such feedbacks in hydrological models. At the same time, a better understanding of these processes will be useful to detect signals of climate change in the hydrological cycle.

Similarly, development and implementation of better downscaling techniques has an important role to play. These models need to be better in representing local climate patterns and processes. The use of stochastic rainfall simulators, for instance, may eliminate the use of highly uncertain precipitation forecasts from GCMs (Fig. 3) (*Fowler et al.*, 2007). However, the implementation of such models in the tropical Andes and many other regions in the world is in its infancy, notwithstanding the large socio-economic consequences of climate change.

4 Conclusions

Uncertainties related to projections of future climate can have a profound effect on the planning of adaptation strategies. This study analyses the impact of uncertainties related to GCM projections on future changes of streamflow in the Paute river basin, Ecuador. Although uncertainties in the hydrological model and downscaling techniques are neglected, prediction ranges are very wide, and of the same magnitude as current discharges. This uncertainty should be taken into account when designing adaptation actions. Short-term strategies may aim towards improved resilience of water supply systems (*Dessai and Hulme*, 2007). However, improving climatic and hydrologic models as well as the development and implementation of downscaling methods is necessary to improve our understanding of potential future changes.

5 Acknowledgements

During part of the research, Buytaert was funded by an EU Marie Curie Intra-European Fellowship at Lancaster University. We also acknowledge the helpful comments of two anonymous reviewers.

References

Allen, M. R., and D. J. Frame (2008), Call off the quest, *Science*, *318*, 582–583.

Allen, M. R., and W. J. Ingram (2002), Constraints on future changes in climate and the hydrologic cycle, *Nature*, *419*, 224–232.

Allen, R. G., L. S. Pereira, D. Raes, and M. Smith (1998), *Crop evapotranspiration. Guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper 56*, 300 pp., FAO, Rome.

Andersen, H. E., B. Kronvang, S. E. Larsen, C. C. Hoffmann, T. S. Jensen, and E. K. Rasmussen (2006), Climate-change impacts on hydrology and nutrients in a Danish lowland river basin, *Science of the Total Environment*, *365*, 223–237.

Beven, K. J. (2001), *Rainfall-runoff modelling. The primer*, 360 pp., John Wiley and sons, Chichester.

Bradley, R. S., M. Vuille, H. F. Diaz, and W. Vergara (2006), Threats to water supplies in the tropical Andes, *Science*, *312*, 1755–1756.

Buytaert, W., R. Celleri, B. De Bièvre, R. Hofstede, F. Cisneros, G. Wyseure, and J. Deckers (2006), Human impact on the hydrology of the andean páramos, *Earth-Science Reviews*, *79*, 53–72.

Celleri, R., P. Willems, W. Buytaert, and J. Feyen (2007), Space-time variability of rainfall in the Paute river basin of South Ecuador, *Hydrological Processes*, *21*, 3316 – 3327.

Croke, B., and A. Jakeman (2004), A catchment moisture deficit module for the ihacres rainfall-runoff model, *Environmental Modelling & Software*, *19*, 1–5.

Dessai, S., and M. Hulme (2007), Assessing the robustness of adaptation decisions to climate change uncertainties: A case study on water resources management in the East of England, *Global Environmental Change*, *17*, 59–72.

Dibike, Y. B., and P. Coulibaly (2007), Validation of hydrological models for climate scenario simulation: the case of Saguenay watershed in Quebec, *Hydrological Processes*, *21*, 3123–3135.

Fowler, H. J., S. Blenkinsop, and C. Tebaldi (2007), Linking climate change modelling to impacts studies: recent advances in downscaling techniques for hydrological modelling, *International Journal of Climatology*, *27*, 1547–1578.

Giorgi, F., and X. Bi (2005), Updated regional precipitation and temperature changes for the 21 century from ensembles of recent aogcm simulations, *Geophysical Research Letters*, *32*, L21,715.

Huntington, T. G. (2006), Evidence for intensification of the global water cycle: Review and synthesis, *Journal of Hydrology*, *319*, 83–95.

Intergovernmental Panel on Climate Change (2007), *Climate Change 2007 - Impacts, Adaptation and Vulnerability*, Cambridge University Press, Cambridge.

Markoff, M. S., and A. C. Cullen (2008), Impact of climate change on pacific northwest hydropower, *Climatic Change*, *87*, 451–469.

Myers, N., R. A. Mittermeier, C. G. Mittermeier, G. A. B. da Fonseca, and J. Kent (2000), Biodiversity hotspots for conservation priorities, *Nature*, *403*, 853–858.

Pappenberger, F., and K. Beven (2006), Ignorance is bliss: or seven reasons not to use uncertainty analysis, *Water Resources Research*, *42*, W05,302.

Prudhomme, C., and H. Davies (2009), Assessing uncertainties in climate change impact analyses on the river flow regimes in the uk. part 1: baseline climate, *Climatic Change*, *93*, 177–195.

Salathé Jr, E. P., P. W. Mote, and M. W. Wiley (2007), Review of scenario selection and downscaling methods for the assessment of climate change impacts on hydrology in the United States pacific northwest, *International Journal of Climatology*, *27*, 1611–1621.

Stahl, K., R. D. Moore, J. M. Shea, D. Hutchinson, and A. J. Cannon (2008), Coupled modelling of glacier and streamflow response to future climate scenarios, *Water Resources Research*, *44*, W02,422.

Stainforth, D. A., T. E. Downing, R. W. A. Lopez, and M. New (2007), Issues in the interpretation of climate model ensembles to inform decisions, *Philosophical Transactions of the Royal Society A*, *365*, 2163–2177.

Vergara, W., A. M. Deeb, A. M. Valencia, R. S. Bradley, B. Francou, A. Zarzar, A. Grünwaldt, and S. M. Haeussling (2007), Economic impacts of rapid glacier retreat in the Andes, *EOS transactions AGU*, *88*, 261.

Wilby, R. L., and I. Harris (2006), A framework for assessing uncertainties in climate change impacts: Low-flow scenarios for the river Thames, UK, *Water Resources Research*, *42*, W04,419.