Application of non-linear techniques for daily weather data reconstruction and downscaling coarse climate data for local predictions

Working Paper No. 21

CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS)

Roberto Quiroz, Adolfo Posadas, Christian Yarlequé, Haline Heidinger, Rubi Raymundo, Mariela Carbajal, Mariana Cruz, Jose Guerrero, Victor Mares, Elizabeth Silvestre, Charles Jones, Leila V. de Carvalho, Tufa Dinku

CLIMATE CHANGE
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Abstract

Downscaling techniques aim at resolving the scale discrepancy between climate change scenarios and the resolution demanded for impact assessments. Requirements for downscaled climate, to be useful for end users, include reliable representation of precipitation intensities, temporal and spatial variability, and physical parameters consistency. This report summarizes the results of the proof of concept phase in the development and testing of a novel data reconstruction method and a downscaling algorithm based on the multiplicative random cascade disaggregation method using rainfall signals at different spatial and temporal resolutions. The Wavelet Transformed-based Multi-Resolution Analysis (WT-MRA) was used for reconstructing the historical daily rainfall data needed as input for the downscaling methodology, using satellite-derived proxy data. Comparisons with presently used software showed that in all the cases; that is, the reconstructed, generated daily or downscaled daily data, the products developed outperformed the control test by either generating more accurate outcomes or by demanding significantly less parameterizing data.

Keywords

Cascade disaggregation; Downscaling; Multi-resolution; Wavelets

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Contents

Acronyms

CGIAR	Consultative Group on International Agricultural Research
GCMs	Global Climate Models
LARS-WG	Long Ashton Research Station Weather Generator
MF	Multifractal
MRA	Multi-Resolution Analysis
SPDSM	Statistical Physics Downscaling Model
TRMM	Tropical Rainfall Measuring Mission - NASA
WATER	Wavelet Transform for Estimating Rainfall software
WT	Wavelet Transform
WTMM	Wavelet Transform Modulus Maximum

Introduction

The present project aims at developing the proof of concept of a Statistical Physics Downscaling Model (SPDSM) based on multifractal (MF) cascade approaches. Rainfall estimation was selected as the target climate variable since this is the most chaotic signal and thus the most difficult one to model. We proposed using a combination of satellite-derived rainfall estimates for this proof of concept and to test the scale invariance of the signal in pixels ranging from ~1 to 500 kilometres.

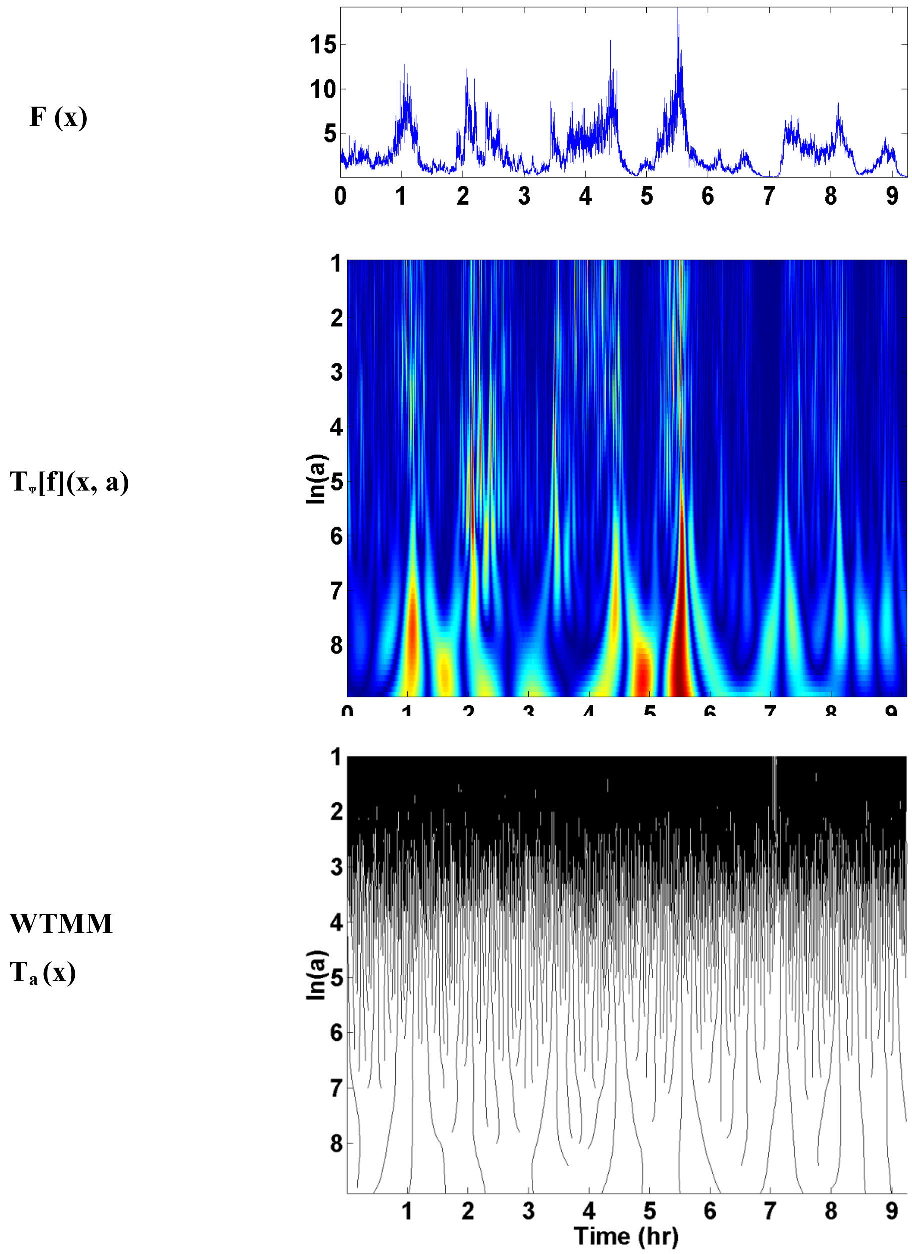
The development of climate downscaling tools is difficult in data-scarce environments, a condition found in most areas where CGIAR and CCAFS work. The first task must then be the completion of time series using the most reliable available methods. Therefore, the completion of daily rainfall time series at different spatial resolutions—to be used for estimating downscaling parameters and to build a daily weather generator—were the focus of Phase 1. Available daily rainfall data were collated for selected sites in Ethiopia, the Indo–Gangetic plains and the Andean plateau. Each weather station was duly characterized using conventional and innovative methods.

The workshop programmed to present and discuss results from Phase 1 and to discuss methodologies for Phase 2 was implemented.

Characterization of weather stations

Daily rainfall is the most complex climatic variable, due to the combination of high-frequency/low-magnitude and low-frequency/high-magnitude events. Rainfall is commonly described at low temporal resolution and through statistical parameters or dynamical equations supported by the classical theory. Notwithstanding the usefulness of such characterizations, these techniques omit key attributes that could be useful in characterizing spatial and temporal differences—for example, extreme events (singularities), scalability, and the like. The Wavelet Transform (WT) combined with the Multifractal (MF) methodology is a plausible option to assess the variability in high-resolution temporal rainfall signals and understand the conservative properties of the processes across temporal scales. By analyzing these events at several time scales, physical processes governing rainfall can be inferred. To guarantee an adequate description of the true multifractality of high temporal resolution signals, the Wavelet Transform Modulus Maximum (WTMM) was applied. The advantages of this methodology include (1) the removal of the non-stationarities that mask the true 'fluctuations' in the signal; (2) access to the whole range of singularities; (3) efficient and robust estimation of singularities by using the ridges of the maxima; and (4) direct estimation of the MF spectrum. Consequently, the ridges of the maxima connect the occurrence of rainfall events across scales (Figure 1) thus permitting the detection of changes—regardless of their size—in several time dimensions (hours, days, weeks, months, seasons, years). We hypothesize that this methodology can facilitate the analysis of rainfall differences in topo-climates and thus help develop hypotheses on how the physical parameters vary in topographically heterogeneous terrains. Another attractive feature is the possibility of linking local land properties with high-resolution climatic variables.

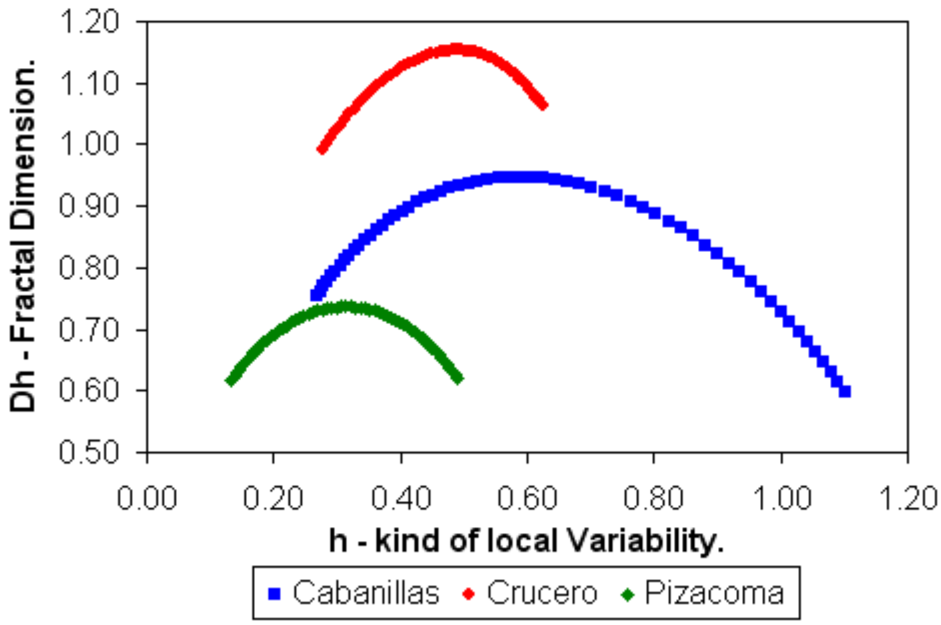
Figure 1. Graphical portray of a high temporal resolution rainfall signal, the wavelet transform and the ridges of the maxima.



Source: Venugopal et al., 2006

This work aims at (1) applying the WTMM-MF to characterize rainfall stations in different regions; (2) correlating the multifractal parameters with those of the climate; and (3) defining a “filter” matrix that represents the heterogeneity of rainfall in space. Several gauged stations from five countries were processed with the WTMM-MF technique and the results were discussed in the workshop. The objective was to see whether the technique could tell apart differences even in weather stations proximal to each other (see Figure 2). It seems that the methodology is sensitive to small changes and thus the user must be cautious about the interpretation. For instance, the data from two weather stations in Addis Ababa presented different spectra, albeit rather close. Similar differences were found elsewhere with apparent minor changes in the surroundings. These preliminary results, although encouraging, demand concerted efforts among disciplines to better explain differences and hopefully will contribute to the search for the understanding of physical parameters that characterize rainfall in micro-zones. Montecarlo experiments are planned to further our understanding and generalizing of this technique. A paper comparing classical and MF methods to characterize rainfall signals is expected in 2012.

Figure 2. Multifractal spectra of three contrasting rainfall signals in the high plateau, a region deemed as "homogeneous" rainfall-wise.

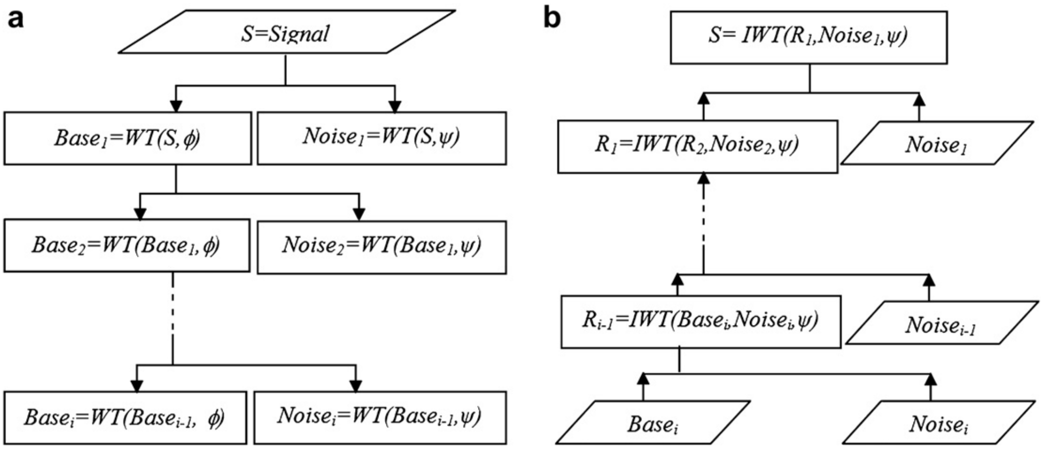


Completion of rainfall time series

Accurate rainfall data with sufficient spatial resolution are of key importance in assessing the impact of a changing climate on agriculture and other related economic activities. Unfortunately, gauged rainfall data in developing countries present several limitations. The spatial coverage is limited, particularly in terrains with high topographical heterogeneity, where a higher density of stations is required. Long-term (~ 30 years) rainfall time series, needed to assess land-atmosphere interactions, are seldom available and, when available, it is common to find a large amount of missing values. Remote sensing can provide spatial precipitation patterns and thus provide a proxy for quantitative assessments at spatial and temporal scales in regions where meteorological stations are scarce.

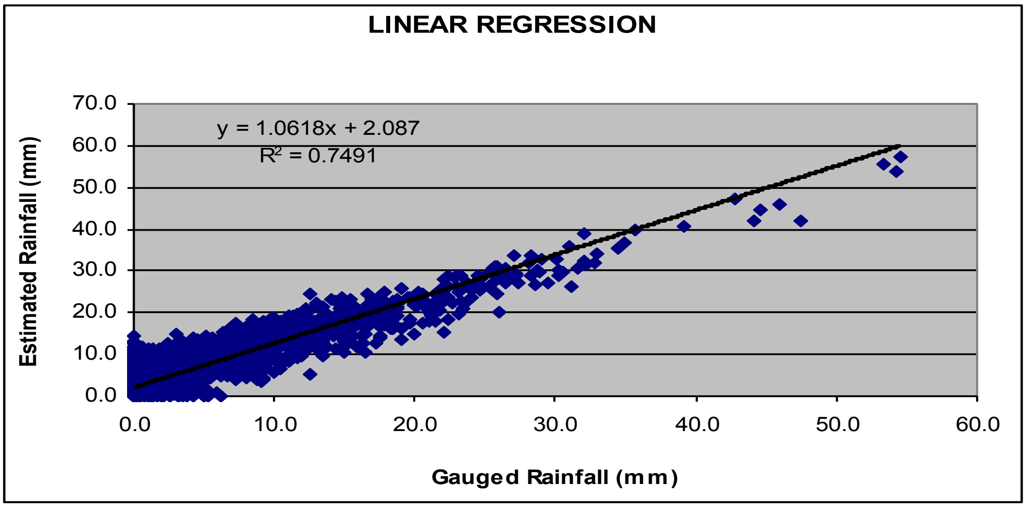
A WT-based Multi-Resolution Analysis (MRA) was implemented to combine remotely sensed data with the distinctive feature of local rainfall variability extracted from gauged measurements (Quiroz et al., 2011). This approach was programmed in the freeware Wavelet Transform for Estimating Rainfall (WATER), which can be used to run the applications described below (downloadable from http://inrm.cip.cgiar.org; go to download and then to simulation models). Multi-resolution analysis (Mallat and Zhong, 1992), as implied by its name, comprises the evaluation of the signal at different frequencies with different resolutions. The MRA allows the decomposition of a signal into various resolution levels, which retain the main features of the original signal. The filtering approach to multi-resolution WT is to form a series of half-band filters that divide a spectrum into a high-frequency band (retain information about the higher-frequency components) and a low-frequency band (contain information about lower-frequency components). It is formulated on a scaling function or low-pass filter (LP) and a wavelet function or high-pass filter (HP). These filters initially act on the entire signal band at the high frequencies (small-scale) filters and gradually reduce the signal band at each stage (see Figure 3). The algorithm extracts information from the process through the decomposition or scale up of both signals; and then uses it to reconstruct the signal with the initial high resolution through the inverse process. The reconstructed signal retains the statistical properties of the local rainfall variability, thus improving the quality of the remotely sensed data.

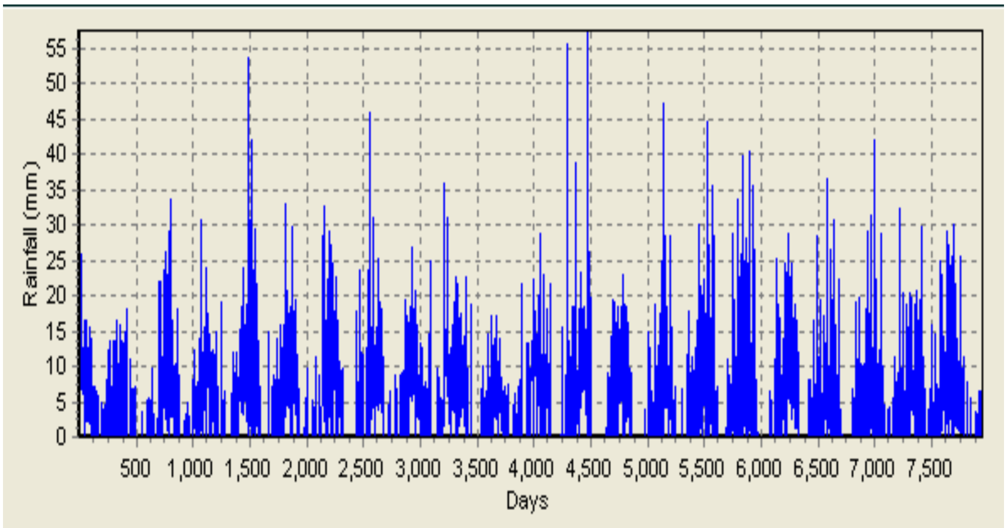
Figure 3. Multi-resolution analysis processes: a Decomposition or "up-scaling" process. b Reconstruction or "down-scaling" process. The algorithm and the mother wavelet (ψ) for both processes is the same; i = 0, 1, 2, is the finite process level [decomposition (a) and reconstruction (b)] which define the scale as $\lambda=2^i$ and φ is the scaling function associated to ψ.



Three applications of the MRA methodology to rainfall signals for a specific geographical position are summarized: (1) rainfall data gap infilling based on an improved version of the procedure described by Carbajal et al., 2011; (2) daily rainfall estimation from Normalized Difference Vegetation Index (NDVI), based on Quiroz et al., 2011; and (3) TRMM correction, based on Heidinger et al., 2012. It was shown that the methodology produced good results in contrasting areas of the world (for example in the Ethiopian highlands, the Indo-Gangetic plains, Sao Paulo, Brazil, and the Andean plateau). The feasibility of generating long-term daily rainfall data was also demonstrated (see Figure. 4).

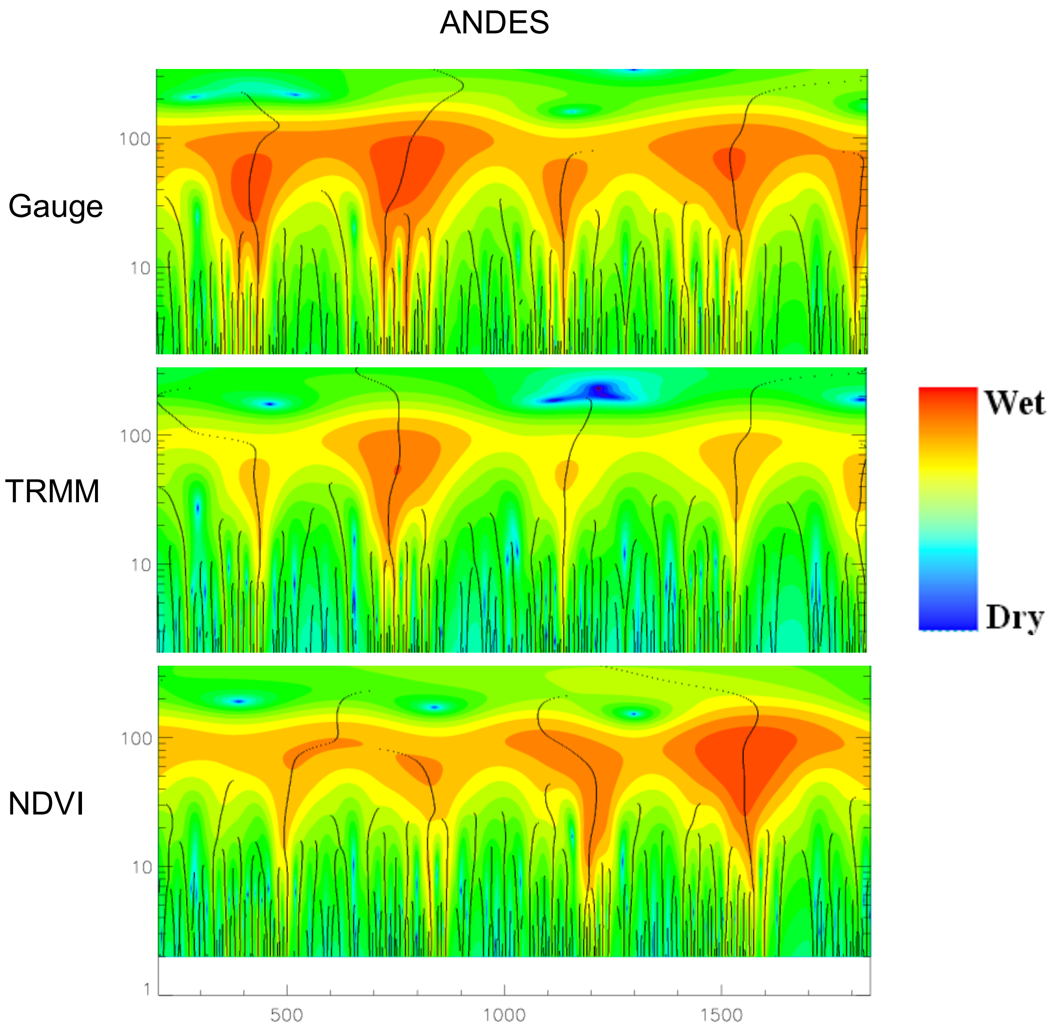
Figure 4. Thirty years daily rainfall reconstruction in the Andean plateau using NDVI with the MRA methodology.





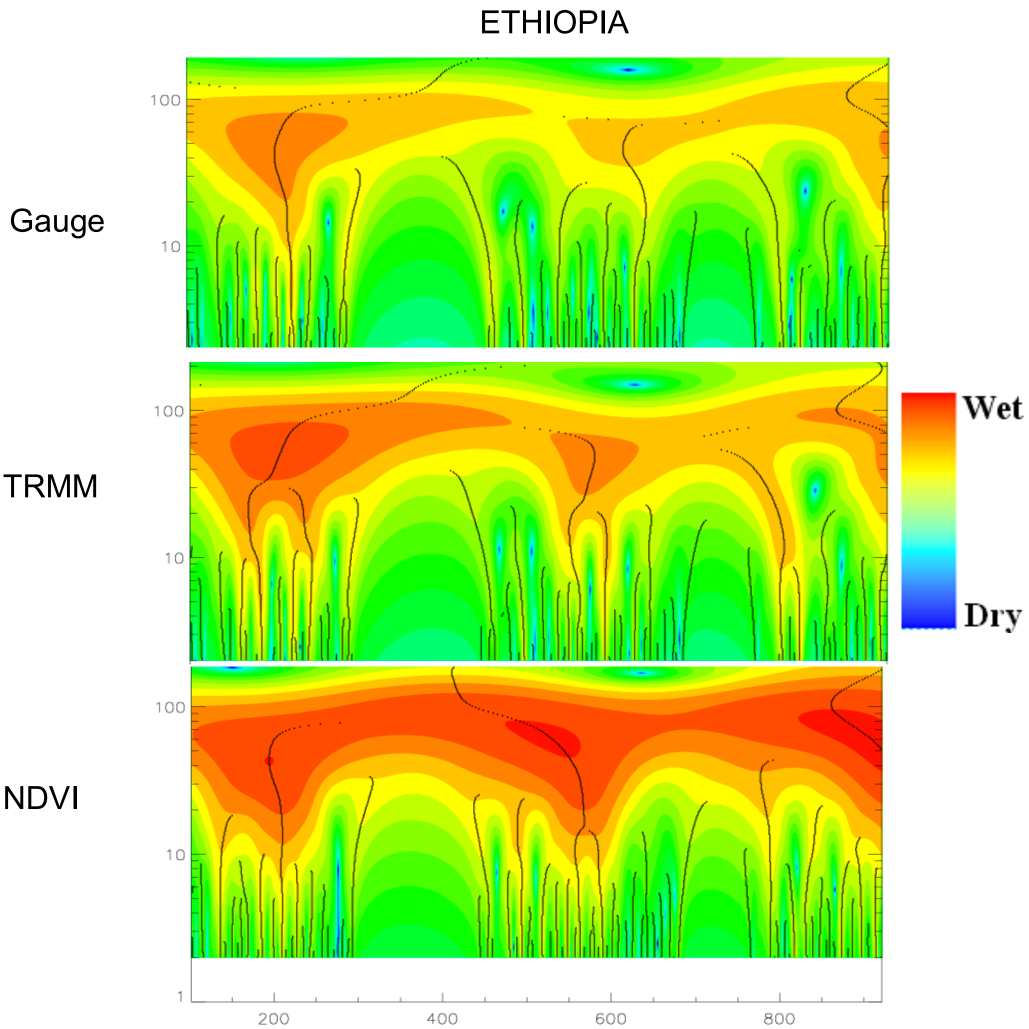
Daily rainfall generated with remotely sensed information was quite good, as judged by several metrics (e.g., probability density functions, bias, R^2, entropy difference). More details of the process are given in Quiroz et al., (2011). An additional test was implemented. Gauge and estimated data were analysed at different time domains using the WTMM (Figures 5–7). In these figures the Y-axis represents the time (days) on a log scale, where the memory of the process is visualized; while the X-axis corresponds to time in days on a normal scale. The graphs show five years of data.

Figure 5. Gauged and estimated rainfall for the high plateau of the Andes aggregated at different time domains to identify anomalies through the ridge of the maxima: gauge rainfall, corrected TRMM rainfall estimates, and reconstructed rainfall from NDVI.



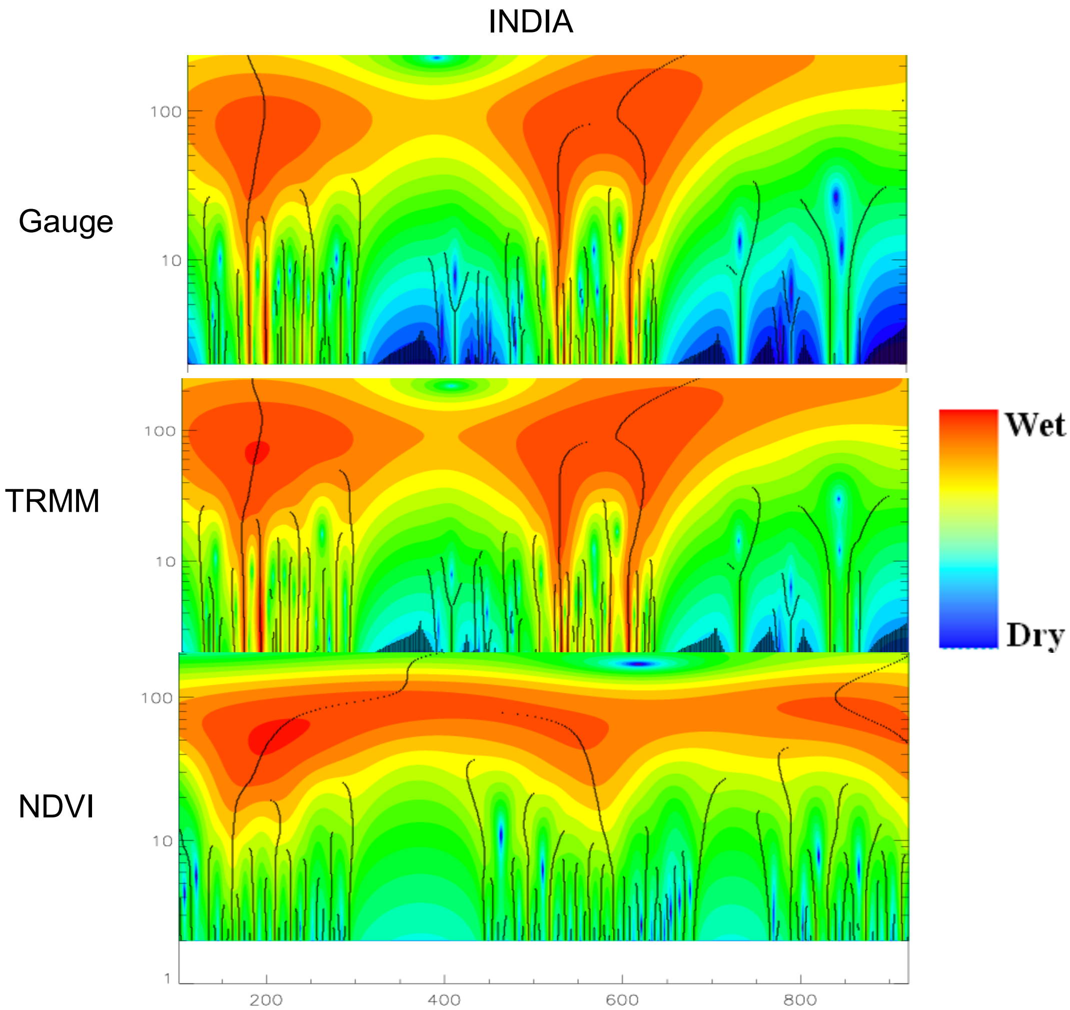
It is important to highlight several features in the graphs: (1) when the signal is analysed up to three weeks, the magnitude and the ridges of the maxima are similar in the three signals; (2) at least 100 d are needed to see the presence of intermediate to strong extreme events such as ENSO; and (3) as expected, TRMM provides more accurate rainfall estimates than NDVI. Nonetheless, NDVI seems to be a good option for reconstructing long-time rainfall series when no other proxies are available, and it might be the only option for reconstructing rainfall at high temporal-spatial resolutions in semi-arid areas.

Figure 6. Gauged and estimated rainfall for the high plateau of Ethiopia aggregated at different time domains to identify anomalies through the ridge of the maxima: gauge rainfall, corrected TRMM rainfall estimates, and reconstructed rainfall from NDVI.



The comments made for the Andean plateau are pertinent for the Ethiopian plateau. The numbers of years analysed were fewer, due to the lack of daily data, so some of the inferences made for the Andes are difficult to extrapolate. A larger number of weather stations and larger numbers of years are required. Notwithstanding, the methodology seems to work well under these conditions. We can argue that CCAFS can benefit from these methodologies to generate long-time series for East Africa.

Figure 7. Gauged and estimated rainfall for the Indo-Gangetic plains aggregated at different time domains to identify anomalies through the ridge of the maxima: gauge rainfall, corrected TRMM rainfall estimates, and reconstructed rainfall from NDVI.



In irrigated areas, NDVI estimates become unreliable since apparently the sporadic rain events during the dry period are not detected (dark blue spots).

The following graphs portray some of the preliminary results of NDVI-derived spatial rainfall estimates in three sites. Figure 8 shows a snapshot of the cumulative rainfall during the rainiest month in an ~ 60 x 60 kilometres sample area in each site. Figures 9–11 present the spatial distribution of extreme and intermediate rainfall events at ~ 1 kilometre resolution within the respective rainiest month in each site.

Figure 8. Snapshots of cumulative NDVI-derived rainfall during the rainiest month in an area of around 60 x 60 km in each site.

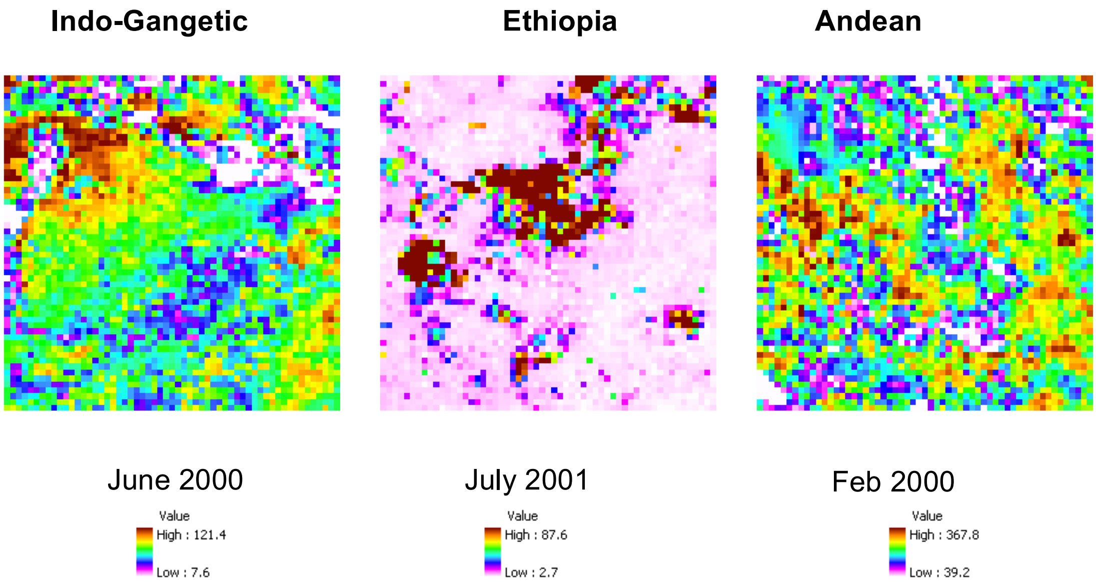


Figure 9. Snapshot of a spatial NDVI-derived rainfall distribution during three contrasting days within the rainiest month in the Indo-Gangetic plains

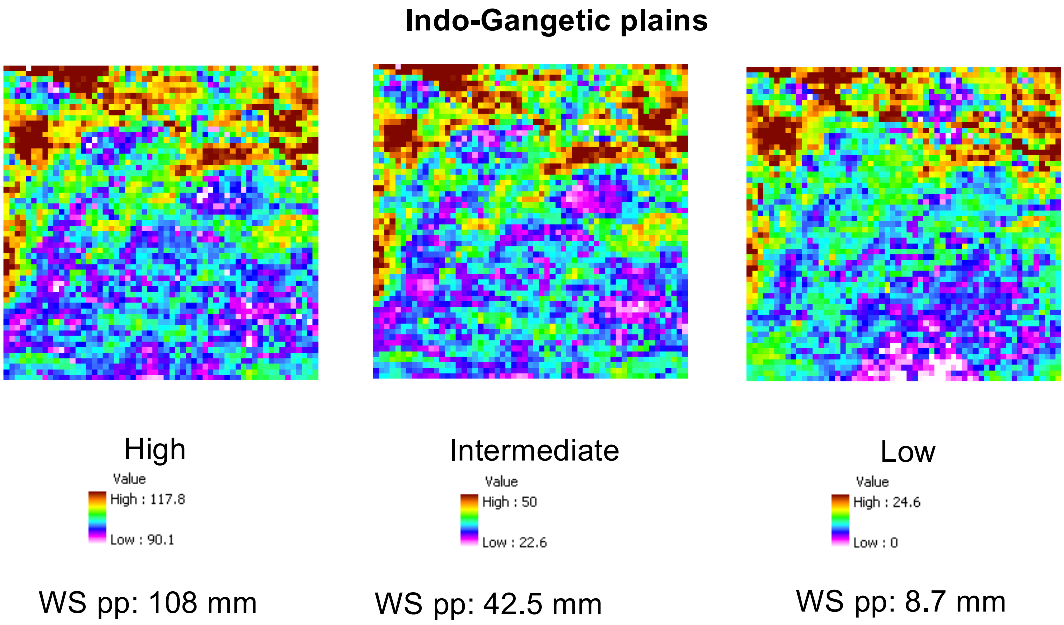


Figure 10. Snapshot of a spatial NDVI-derived rainfall distribution during three contrasting days within the rainiest month in Addis Ababa.

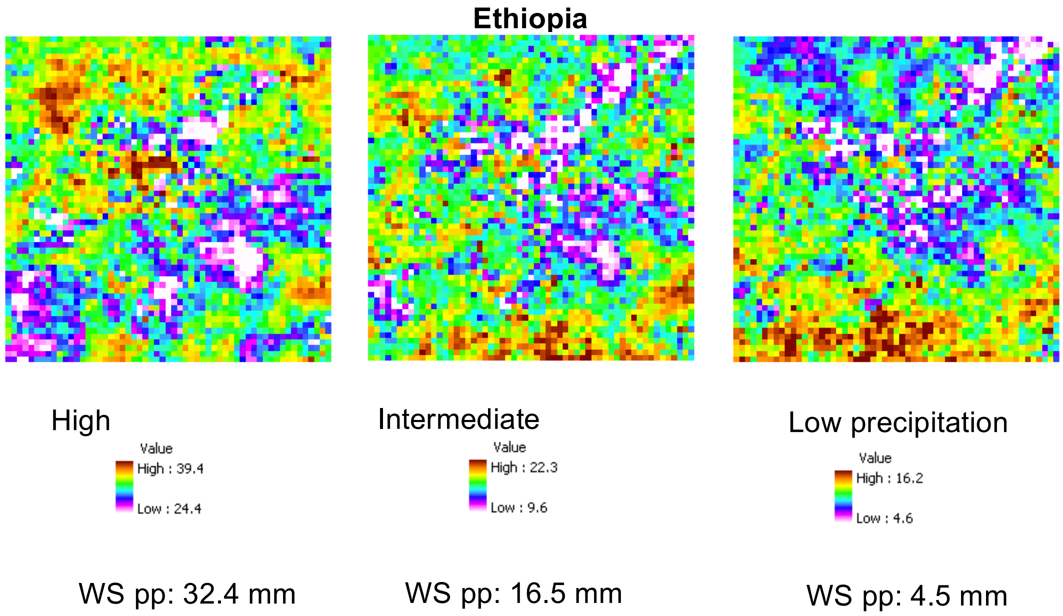
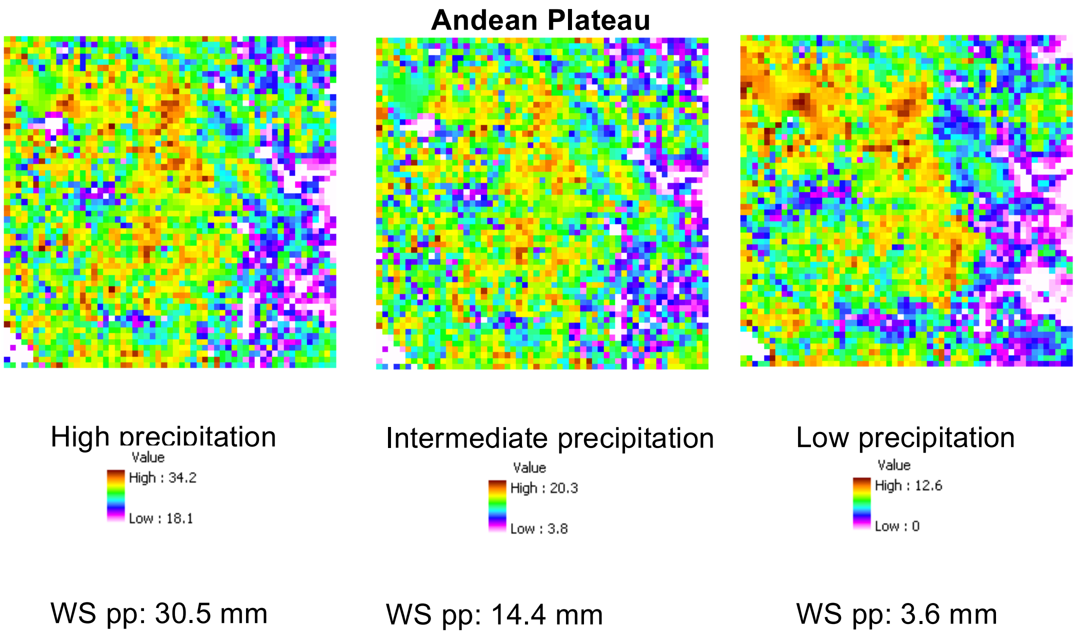
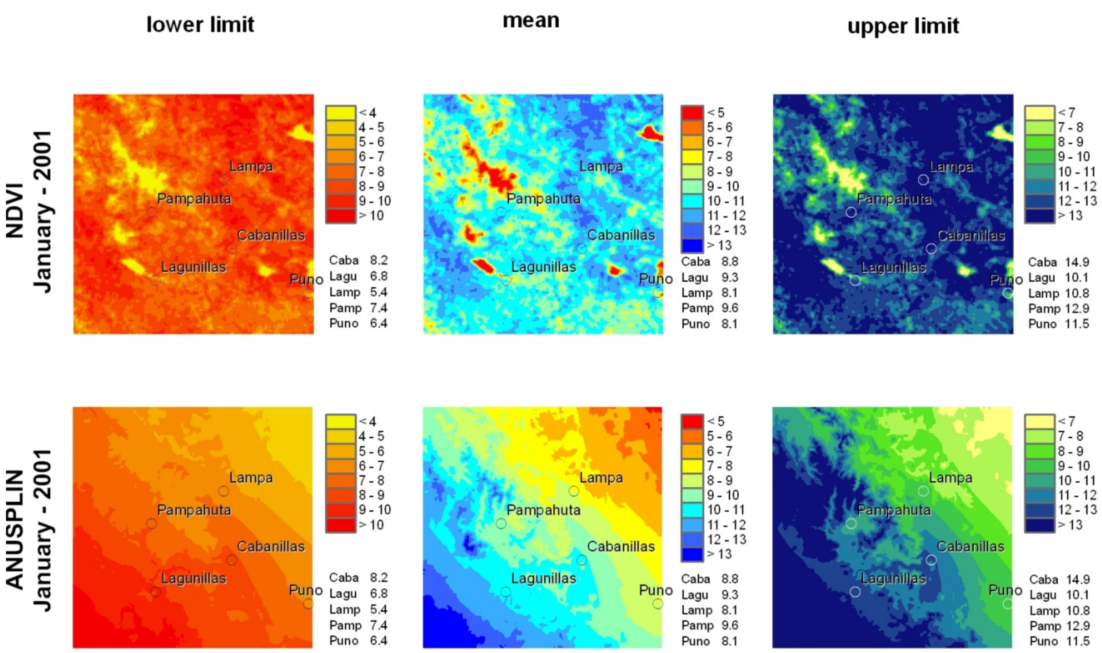


Figure 11. Snapshot of a spatial NDVI-derived rainfall distribution during three contrasting days within the rainiest month in the Andean Plateau.



When spatial climate is required, most users recur to interpolation techniques. Anusplin is one of the widespread techniques used for climate interpolation. This interpolation technique was used in the Altiplano (Figure 12). When a large number (n=19) of weather stations were used for daily rainfall, Anusplin provided good interpolations, as tested by cross-validations. If the number of weather stations used in the interpolation process was below 10, the interpolation values were meaningless. In geospatial reconstruction of daily rainfall, using the WT-based MRA described by Quiroz et al., 2011, the quality of the generated data was similar to those generated by Anusplin using 19 weather stations (Figure 12). On average R^2 were ~0.4 and > 0.6; MSE ~10 and ~3; and Bias <1 (both methods) for Anusplin and NDVI-reconstructions, respectively. The big difference was that for the tested area, only one weather station was required for the NDVI-based reconstruction. For data-scarce environments, the common denominator in CCAFS areas, these are encouraging results.

Figure 12. Snapshots of daily rainfall: top panels - mean and CI limits for NDVI-based reconstructions; bottom panels - mean and CI limits for Anusplin interpolations.



Weather Generator

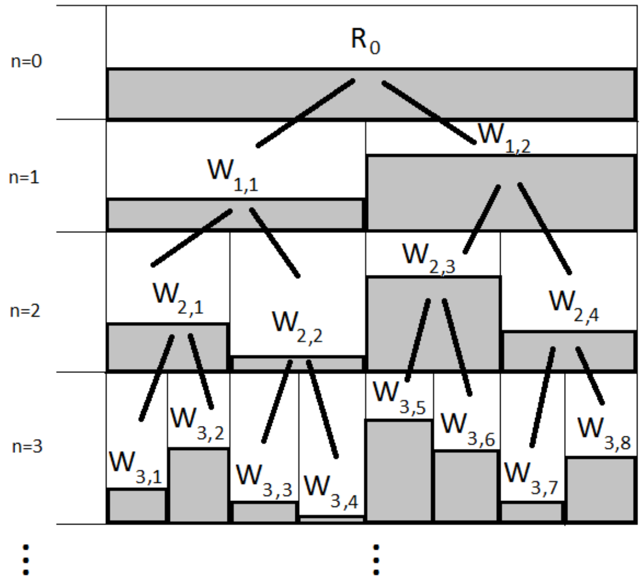
The literature on weather generators is extensive and these tools are of widespread application in climate and agricultural research. Most of the models used today are based on Markov chains but they demand long-time series for their parameterization. Several intrinsic features of rainfall such as the heterogeneity of the events in short periods of time, the anisotropy, stationary properties, and the long-time memory are seldom addressed by classical statistical methods, particularly when less than 30 years of rainfall events are available. When singularities or extreme events such as ENSO are present in the time series, the simulation of a combination of normal and extreme events is quite cumbersome. New interest in local stochastic weather simulation has arisen as a result of climate change studies. At present, output from global climate models (GCMs) is of insufficient spatial and temporal resolution and reliability to be used directly in impact models. A stochastic weather generator, however, can serve as a computationally inexpensive tool to produce multiple-year climate change scenarios at the daily time scale which incorporate changes in both mean climate and in climate variability (Semenov & Barrow, 1997).

Our group is searching for more robust alternatives. We briefly describe here the beta-version of the generator (For the time being called CIP-CCAFS-WG) produced with CCAFS funding. A downscaling algorithm based on the multiplicative random cascade disaggregation method was developed. The multiplicative cascade models are differentiated among themselves by the generator W and the procedure utilized to estimate the parameters of the distribution being modelled. The most common distributions include: Log-Normal, Log-Poisson, and Levy; and the parameters are obtained using statistical or multifractal techniques (Deidda, 2000; Molnar and Burlando, 2005; Over and Gupta, 1994; Schertzer and Lovejoy, 1987; and, Tessier et al., 1996). Therefore, the selection of W is based on the process being modelled. We tested most of the generators described in the literature and observed that the uniform distribution worked better for describing daily rainfall in different regions of the world.

Our cascade process starts from monthly data (it can start at higher temporal aggregations) as depicted in Figure 13:

- Level 0 in the cascade (n=0) corresponds to monthly precipitation (R) in time t; i.e. $R_0(t)=R_0$.
- The rainfall at the second level (n=1) is estimated by splitting the initial value R_0 into two after applying the random distributional weight W as: $R_{1,1}=R_0W_{1,1}$ and $R_{1,2}=R_0W_{1,2}$.
- The cascading process continues and can be denoted as: $R_n(t,i) = R_0(t)\prod_j^n W_{j,i}$, for $i=1,2,\ldots,b^n$; where b=2 indicates the number of divisions in each decomposition

Figure 13. Multiplicative cascade process in several cascade levels of decomposition, n.



To assess the quality of the WG, we searched for robust and widely used software, and tested the results against the Long Ashton Research Station Weather Generator (LARS-WG). LARS-WG is a stochastic weather generator for simulating time-series of daily weather based on modifications of the generator initially described in Racsko et al. (1991). For the generation of precipitation data, LARS-WG applies semi-empirical distributions of the occurrence of wet and dry series (a wet day has precipitation > 0.0mm). In turn, the precipitation value is simulated utilizing semi-empirical precipitation distribution for the specific month (Semenov and Barrow, 2002). According to Semenov et al. (1998), LARS-WG performs better or similar to other weather generators based on the Markov chain approach (i.e. WGEN). For the generation of weather data using LARS-WG, observed daily precipitation data of weather stations were used in model calibration. Although a single year of observed data can be used to generate synthetic data in LARS-WG, it is recommended to use at least 20-30 years of observed data (Semenov and Barrow, 2002).

Figures 14–16 and Table 1 show a comparative assessment of both weather generators described above against gauged data for three sites in the Americas. For this comparison the correction for dry days described by Quiroz et al., 2011 was not implemented (this will be implemented in the user's version to be programmed in C++). In spite of the systematic error introduced by the lack of the dry days' corrections, the quality of generated data through both procedures is quite good. Notwithstanding, the numbers of years with daily rainfall data required to parameterize the CIP-CCAFS-WG is much smaller than for the LARS-WG.

Figure 14. Empirical Cumulative Density function and rainfall signals in the Highlands of Peru: a) gauged data; b) Generated with LARS-WG; and, c) Generated with CIP-CCAFS-WG from 1998 to 2005.

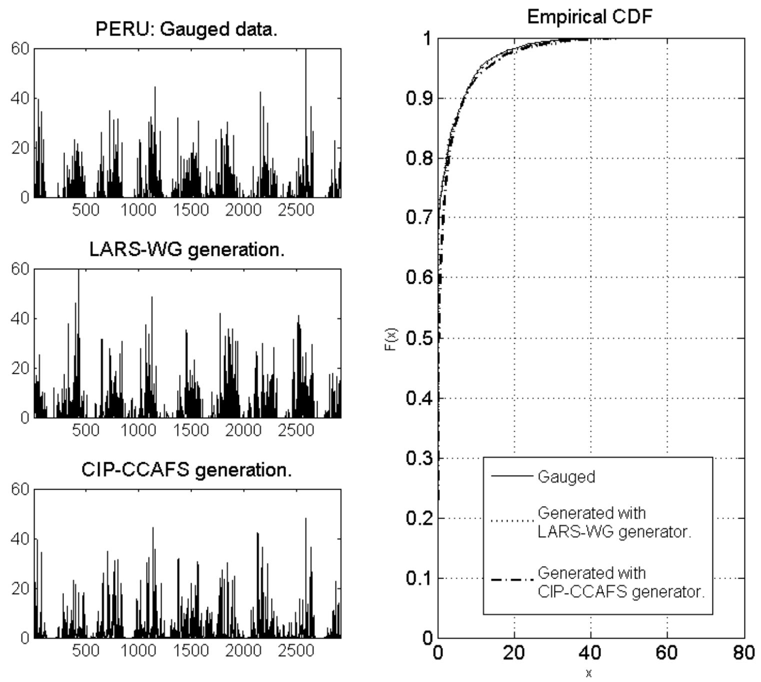


Figure 15. Empirical Cumulative Density function and rainfall signals in Sao Paulo, Brazil: a) Gauged data; b) Generated with LARS-WG; and, c) Generated with CIP-CCAFS-WG from 1998 to 2005.

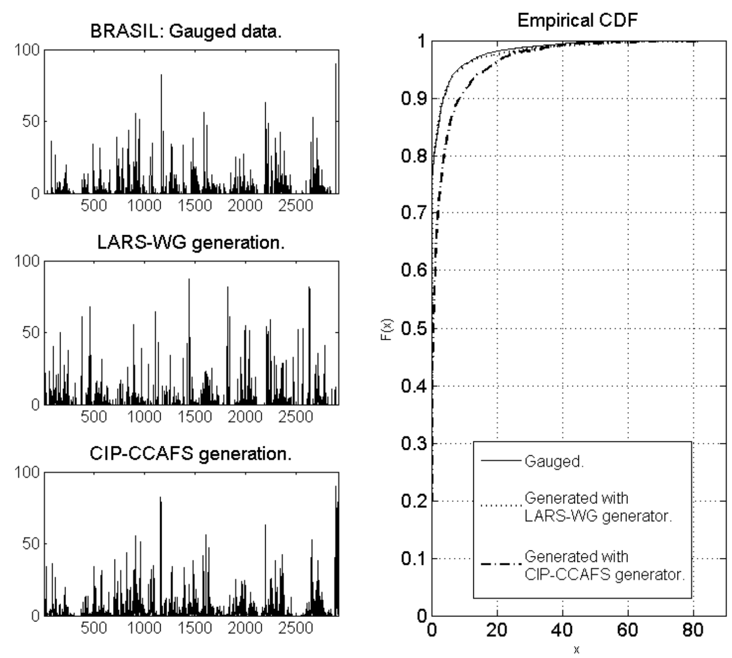


Figure 16. Empirical Cumulative Density function and rainfall signals in, Colorado USA: a) Gauged data; b) Generated with LARS-WG; and, c) Generated with CIP-CCAFS-WG from 1998 to 2005.

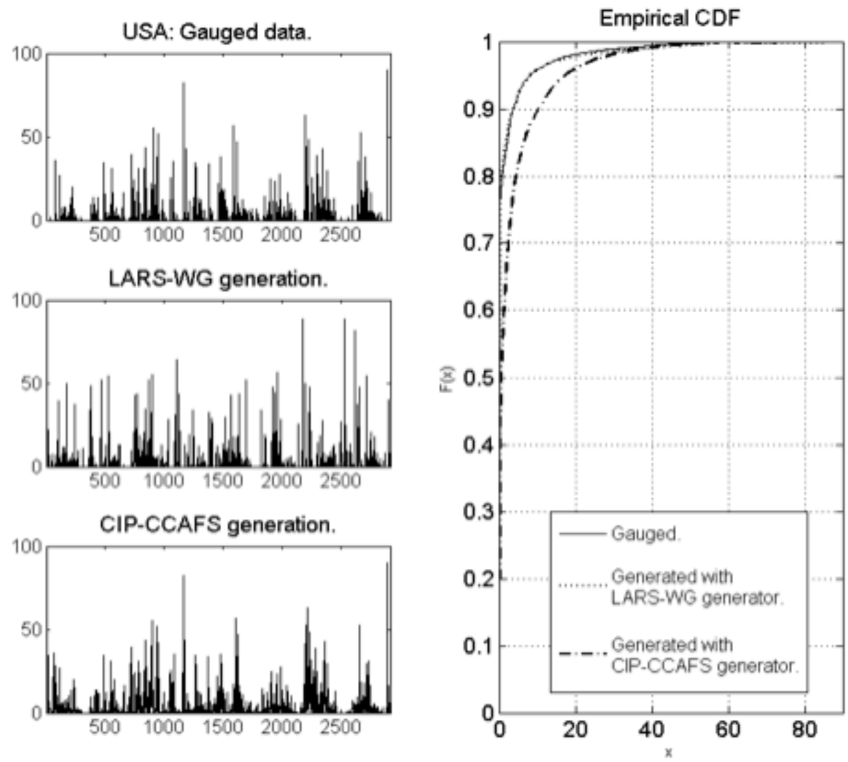


Table 1. Different metrics used to assess generated daily rainfall.

Station	R^2 of monthly Gauged data vs. monthly LARS-WG	Bias with LARS	MAE with LARS	Entropy difference % with LARS	RMSE with LARS	R^2 of monthly Gauged data vs. monthly CIP-CCAFS	Bias with CIP-CCAFS	MAE with CIP-CCAFS	Entropy difference % with CIP-CCAFS	RMSE with CIP-CCAFS
USA	0.04	0.94	2.93	5.61	8.7	0.73	0.45	4.02	90.09	8.9
BRASIL	0.09	0.89	2.98	2.87	8.92	0.25	0.48	4.01	90.08	9.33
PERU	0.48	0.95	3.03	0.84	6.74	0.32	0.80	3.18	83.29	6.58

The SPDSM multifractal cascade algorithm: Proof of concept

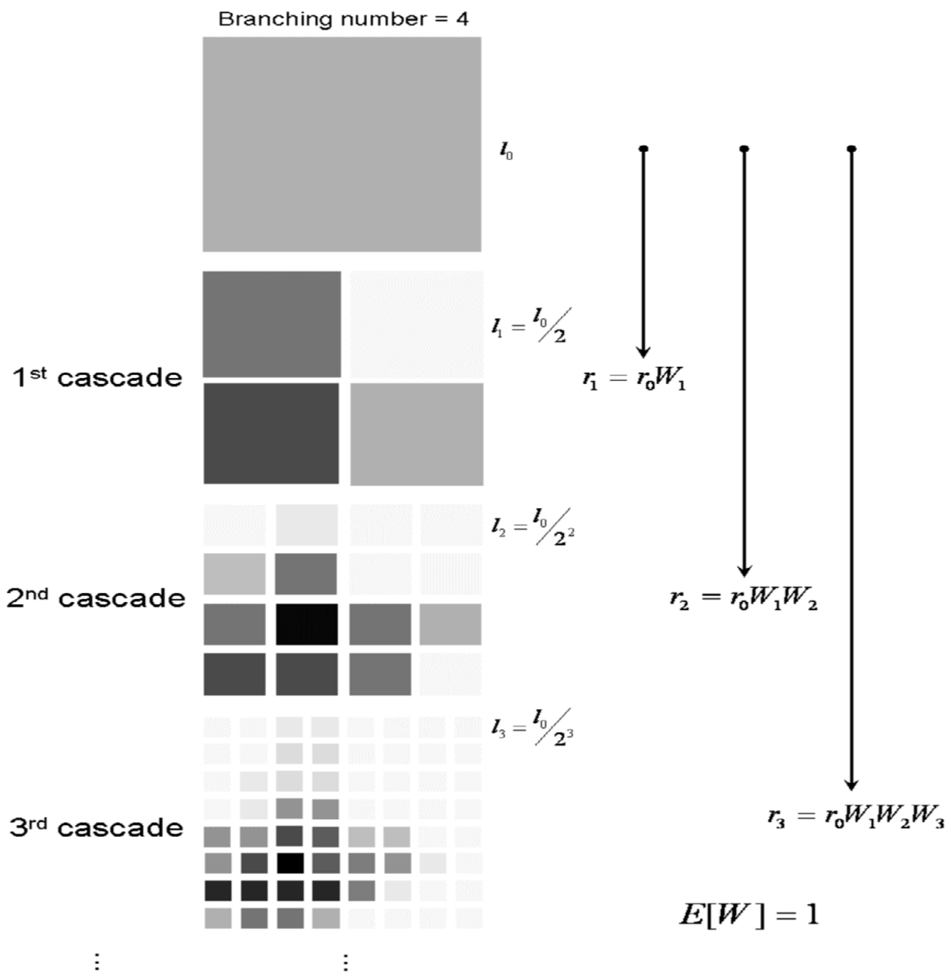
General Circulation Models suggest that rising concentrations of greenhouse gases will have significant implications for climate at global and regional scales. Less certain is the extent to which meteorological processes at individual sites will be affected. So-called “downscaling” techniques are used to bridge the spatial and temporal resolution gaps between what climate modellers are currently able to provide and what local impact assessments require.

How food production and security will be affected by climate change is one of the most important challenges facing regional-scale predictions. Regional scale precipitation and temperature simulations are absolutely crucial in order to understand how global changes impact livelihoods. Precipitation and temperature downscaling improve the coarse resolution and poor local representation of global climate models and help end users to assess the likely impacts of climate change through the generation of more realistic scenarios. Among the requirements for downscaled climate to be useful for end users are the following: (1) a reliable representation of intensities (precipitation in this example); (2) a sound assessment of the variability in time and space; and (3) physical parameters consistency. The quality of the results should be independent of region and season. Notwithstanding, there are gaps and uncertainties arising from sparse data; a short list follows: representation of extreme summer precipitation, sub-daily precipitation, and full precipitation fields on fine scales; capturing changes in small-scale processes and their feedback on large scales; and errors inherited from the driving global climate model.

The aim of this work is to develop climate downscaling tools that can suit the need of the end users cited above. The CCAFS project aimed at conducting a proof of concept for the downscaling methodology using precipitation as the test variable. Notwithstanding, the methodology is expected to be generic for any climate variable.

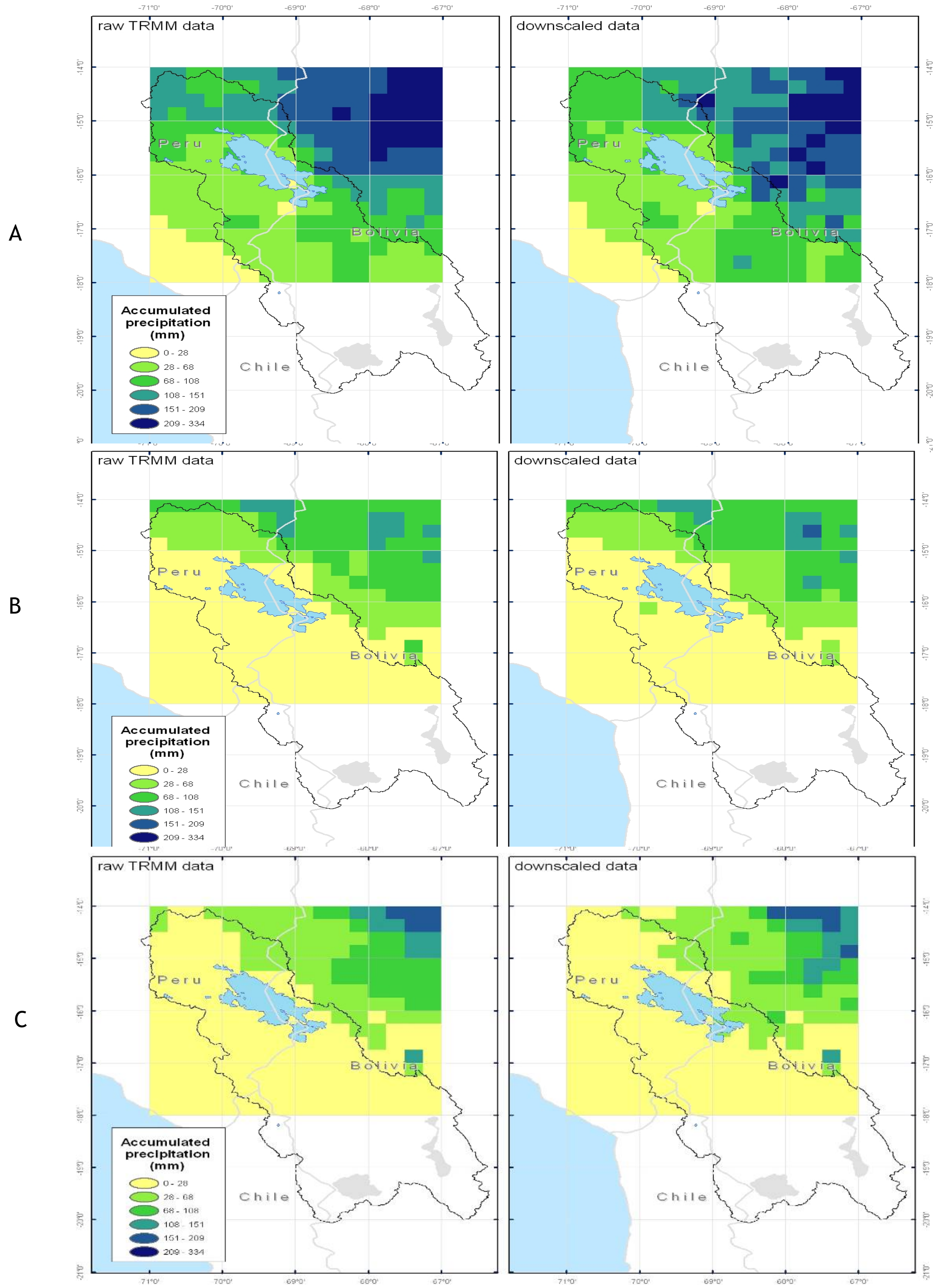
A downscaling algorithm based on the multiplicative random cascade disaggregation method was developed. The principal objectives were to (1) generate a multi-scaling random cascade disaggregation model that represents the precipitation as a Lognormal distribution, using a multifractal technique; (2) use the Mandelbrot-Kahane-Peyriere function to characterize the process (Fig. 17); and (3) apply the model to simulate rainfall distribution in an Andean area (Peru-Bolivia) with high topographical and rainfall heterogeneities.

Figure 17. Schematic representation of the intermittent random cascade method. Model - r_0 is the initial (uniform) rainfall value over the square with side length l_0 (or average value); r_i is the offspring rainfall value over a cell with side length l_i; and W is the log-normal random generator obtained through the multifractal characterization.



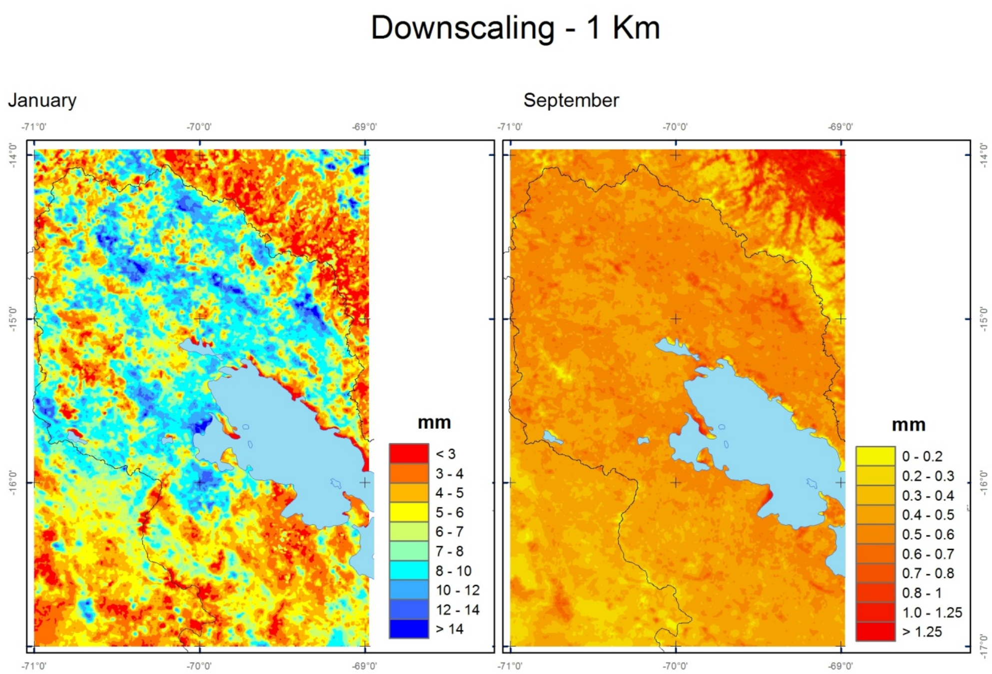
This algorithm was tested and calibrated using TRMM precipitation data to generate the downscaling parameters. Daily TRMM 3B42 v6 data for the period 1998–2007 were obtained from TRMM Online Visualization and Analysis. Monthly rainfall snapshots were created by accumulating daily estimates. February, April, and August 2003 were used to represent the wettest, an intermediate, and the driest month in the high plateau and surroundings, respectively. A square area of 16 x 16 TRMM pixels (~ 430 x 430 km)—spanning an altitude gradient from around 2,000 to 6,500 masl and a rainfall gradient from ~ 400–3,000 mm y^{-1} was selected. A rainfall ensemble over the entire square was downscaled—using the random cascade disaggregation model—to the individual pixels. Figure 18 portrays realizations of the downscaling for the three snapshots mentioned above.

Figure 18. Measured TRMM rainfall versus downscaled: A. February—wettest month; B. April—intermediate; and C. August—driest month.



Cascading down the rainfall events below the ~ 28 km resolution (TRMM pixel size) requires geospatial measurements of the events at the lowest desirable spatial resolution. For this proof of concept the probabilistic generator was parameterized using ~1 km layers generated through interpolation and NDVI-derived data, as shown above. Anusplin interpolation has the limitation that a large number of weather stations are demanded to have good quality interpolated data. NDVI-derived data is suitable in areas with rainfall below 1200 mm per rainy season. Another limitation for using NDVI-derived data is the presence of clouds, which could potentially introduce bias in the process. An example of the rainfall downscaled to ~ 1 km is provided in Figure 19. Snapshots corresponding to average daily rainfall during the highest and lowest rainy decads in the year are portrayed. The values are contained within the 95 % confidence interval of interpolated surfaces (A section of the area is shown in Figure 12). The beta version of the algorithm is ready. CCAFS has just approved the acquisition of a high performance computer where the software will be programmed and run. We invite CCAFS colleagues to contact us to test the suitability of the model in other target regions of the program.

Figure 19. Downscaled average daily rainfall for the mid decad in the months with highest and lowest rainfall in the Altiplano of Peru.



Conclusion

Several non-linear techniques were tested using rainfall signals as a test case. The WT-MRA was used to reconstruct daily rainfall with remotely sensed data as proxies. A multiplicative random cascade disaggregation method was tested for constructing a downscaling model based on statistical physics. Although preliminary, the obtained results seem to be as accurate as existing reconstruction or downscaling techniques. The difference—estimated through linear and non-linear metrics—seems to be capacity of the non-linear approaches tested to model rainfall signals, in space and time, with a reduced demand for data to parameterize the models. CIP–CCAFS is constructing a user–friendly SPDSM containing improved versions of the methods discussed in this document.

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