Future change of temperature and precipitation extremes in South America as derived from the PRECIS regional climate modeling system

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Abstract

Using the PRECIS regional climate modeling system, this study analyzes the distribution of extremes of temperature and precipitation in South America in the recent past (1961-1990) and in a future (2071-2100) climate under the IPCC SRES A2 and B2 emissions scenarios. The results show that for the present climate the model simulates well the spatial distribution of extreme temperature and rainfall events when compared with observations, with temperature more realistic. The observations over the region are far from comprehensive which compromises the assessment of model quality. In the future the occurrence of warm nights is projected to be more frequent in the entire tropical South America, while the occurrence of cold night events is likely to decrease. Significant changes in rainfall extremes and dry spells are also projected. These include increased intensity of extreme precipitation events over most of Southeastern South America and western Amazonia consistent with projected increasing trends in total rainfall in these regions. In Northeast Brazil and eastern Amazonia, smaller or no changes are seen in projected rainfall intensity though significant changes are seen in the frequency of consecutive dry days. In all the future climate scenarios considered all parts of the region would experience significant and often different changes in rainfall and temperature extremes. These changes would have impacts in biodiversity, human health, water resources and may have to be considered in the implementation of adaptation measures to cope with climate change.

1. Introduction

Large departures from a mean climate state (hereafter 'extreme events') occur on scales ranging from days to millennia though in this paper we will focus short-term extreme events given their potential for significant impacts. Extreme events are also an integral aspect of climate variability, i.e. defining its envelope as well as being important contributors to the mean and other measures such as its standard deviation. This explains the difficultly in viewing short-term extreme events as a manifestation of either 'weather' or 'climate'. From a climatological point of view, short-term extremes are events whose probability of occurrence is conditioned by larger-scale, longer lasting patterns which dynamically favor or inhibit the short-term events.

One of the most important questions regarding short-term extreme events is whether their occurrence is increasing or decreasing over time; that is whether the shape of the distribution, which defines if these events occur more or less frequently, is changing significantly. Statistically this can be thought of as resulting from changes of the variable's mean and/or other parameters of its distribution or climatologically as a result of changes in the frequency and intensity of the associated weather events themselves and/or the occurrence of the large-scale patterns conditioning these events. Thus a sequential analysis of time series can determine the existence of trends without giving any information on the underlying causes (even in the absence of abrupt changes which may have contributed).

Extreme temperature (cold spells, heat waves) and hydrometeorological (rainfall, floods, dry spells) events affect South America in all seasons and their impacts vary according to the sector. Heavy or extreme precipitation events have important effects on society. Flash floods associated with intense, but often brief, rainfall events may be the most destructive of extreme events. Over many areas the frequency of heavy precipitation events has increased, consistent with warming, and widespread changes in extreme temperatures have been observed over the last 50 years (IPCC, 2007a). Cold days, cold nights and frost have become less frequent; while hot days, hot nights, and heat waves have become more frequent (Vincent et al. 2005, Haylock et al. 2006, Caesar et al. 2006). Such changes in extremes have impacts in human activities, biodiversity and natural ecosystems, water resources, economy and other sectors.

Climate scenarios rely upon the use of numerical models. The continuous evolution of these models over recent decades has been driven by a considerable increase in computational capacity, with supercomputer speeds increasing by roughly a factor of a million in the three decades from the 1970s to the present day. This computational progress has permitted a corresponding increase in model complexity (by including more and more components and processes), in the length of the simulations and in spatial resolution. The models used to evaluate future climate changes have therefore evolved over time. Global models have allowed for a better scientific understanding of anthropogenic global climate change and this led to commensurate developments of mitigation strategies. However, at the regional scale there remains an urgent need for relevant, targeted projections of the regional climate change. Furthermore, adaptation, as opposed to mitigation, is inherently a local and regional scale issue, and limited by the measure of confidence in the projected changes at these scales.

Therefore, it is at regional scales that credible information of probable climate change is most urgently needed to facilitate the development of appropriate adaptation strategies. Without appropriate regional projections of climate change, it is arguable whether regional adaptation strategies can be developed or implemented, other than on a "no regrets, best practice" basis (IPCC 2007a, b).

Within the impacts and adaptation community there is a growing move toward integrated assessment, wherein regional climate change projections form a principal factor for decision support systems aimed at reducing vulnerability. At present the regional projections are perhaps the weakest link in this process and the bulk of information readily available for policy and resource managers is largely derived from Global Climate Models (GCMs). Due to their coarse resolution, these models have limited skill in accurately simulating local scale climates especially the key variable of precipitation. GCM data are commonly mapped as continuous fields, and with different model skill and climate predictability. This may result in climate forecasts (at seasonal level) and in climate change projections which have little value for local application in impacts and vulnerability studies.

In view of the pressing need for regional projections, much effort has been expended in recent years on developing regional projections through diverse methodologies (Wilby and Wigley, 1997), and significant advances made to downscale the GCM skilful scale to the regional and local scales, either through high resolution dynamical modelling, or via empirical cross scale functions. However, to date, much of the work remains at the level of methodological development. Climate change projections that are tailored to the needs of the impacts community, and which demonstrate convergence of the projections across different forcing GCMs, are only now beginning to become more available.

In this study we focus on the application of the Regional Climate Models (RCM), the main dynamical downscaling technique. RCMs represent an effective method of adding fine-scale detail to simulated patterns of climate variability and change as they resolve better the local land-surface properties such as orography, coasts and vegetation and the internal regional climate variability through their better resolution of atmospheric dynamics and processes. Dynamical downscaling in South America has been developed for better understanding of the physical processes in the atmosphere, as well as in weather and climate forecasting (Seluchi and Chou, 2001; Nicolini et al., 2002; Chou et al., 2002; Seth and Rojas, 2003; Misra et al., 2003; Chou et al., 2004). The "added value" provided by the regionalization techniques depend on the spatial and temporal scales of interest, as well as on the variables concerned and on the climate statistics required.

Despite the concerns raise above about their resolution, initial analysis of the effect of climate change in extremes has been carried out using GCMs (e.g. Zwiers and Kharin, 1998; Emori et al., 2005, Kitkev et al. 2003, Hegerl et al. 2004). Tebaldi et al. (2006) has documented changes in extremes worldwide using the mean of 16 GCMs assessed in the IPCC AR4 under the A1B SRES scenario for 2080-2099. In South America the projections show tendencies for increasing extremes in temperatures in the entire continent, while rainfall extremes show a more regional variability, with increase in the frequency and intensity of extremes on subtropical South America and negative trends in some sections of tropical and subtropical South America.

The issue of the spatial resolution in scenarios must be put in the context of other uncertainties of climate change. Studies and analyses of climate change impact and adaptation assessments recognize that there are a number of sources of uncertainty in such studies which contribute to uncertainty in the final assessment. The importance of high resolution climate scenarios for impacts and adaptation studies remains to be thoroughly explored in South America. High resolution scenarios developed from regional climate model results have been obtained in various parts of the world: China (Zhang et al 2006), Europe (Christensen and Christensen 2003, Frei et al. 2006) and in South America (Nunez et al. 2006, Marengo and Ambrizzi 2006, Ambrizzi et al. 2007, Marengo et al. 2007).

In Europe and North America several national and international projects have used RCMs to help quantify better regional climate change and provide regional climate scenarios for assessing climate change impacts and vulnerability. This include the UK Climate Impacts Programme (Hulme et al., 2002), the European Project PRUDENCE (Christensen et al. 2006) in the North American project NARCCAP (Mearns et al. 2004). These have all followed a standard experimental design of using one or more GCMs to drive various regional models from meteorological services and research institutions in the regions to provide dynamically downscaled regional climate projections. Typically, a present day (e.g. 1960-1990) and a future climate (2070-2100) time slices are simulated to calculate changes in relevant climatic variables.

A similar initiative has been recently implemented in South America, CREAS (*Regional Climate Change Scenarios for South America* – Marengo and Ambrizzi 2006, Marengo et al. 2007). It aims to provide high resolution climate change scenarios in South America for raising awareness among government and policy makers in assessing climate change impact, vulnerability and in designing adaptation measures. CREAS runs three regional models nested in HadAM3P (a GCM used in PRUDENCE): Eta for Climate Change Studies –Eta CCS-(Pisnitchenko and Tarasova 2007), RegCM3 (Ambrizzi et al. 2007) and HadRM3P (Jones et al., 2004, Marengo and Ambrizzi 2006). CREAS will explore issues such as: the challenge of using regional climate projections to develop plausible scenarios for future changes at daily time scales for extreme events; an assessment of current methods of scenario development for regions where data is available; assessments of vulnerability in regions and key sectors in South America.

The focus of this study is HadRM3P, the RCM within PRECIS which has been used to develop regional climate change scenarios worldwide (e.g. Xu et al. 2006b, Rupa Kumar et al., 2006) including studying extremes (Zhang et al., 2007). In this paper we assess the performance of HadRM3P in simulating present extreme climate events by comparing simulated trends over the period 1961-1990 with those observed. HadRM3P projected changes in extremes under the two climate change scenarios. HadRM3P simulations of the climate of the period 2071–2100 under the IPCC SRES (Special Report on Emissions Scenarios, Nakicenovic et al., 2000) A2-high emission and B2-low emission scenarios are then compared with the 1961-1990 simulation to assess how extremes will changes under these two climate change scenarios. The HadRM3P simulations have been driven with boundary conditions from HadAM3P (the GCM on which the CREAS simulations are based) and are run at 50 km resolution. We also make a preliminary qualitative assessment of possible impacts and vulnerability of some key sectors in South America (water resources, biodiversity, and human health) due to changes in climate extremes.

2. Methodology

PRECIS (Providing Regional Climates for Impacts Studies) is a regional climate modelling system developed by the Hadley Centre allowing the RCM it incorporates, HadRM3P, to be run over any area of the globe (see Jones et al. 2004 which also includes a detailed description of HadRM3P). HadRM3P has 19 vertical levels and a choice of two horizontal resolutions, 50 km as used in this study (and the standard resolution for larger areas) and 25 km for smaller areas and when higher resolution is particularly important. Lateral boundary conditions for HadRM3P are available from a range of model and observationally based sources and in this study are obtained from the global atmospheric GCM, HadAM3P. The horizontal resolution of HadAM3P is 1.25° latitude by 1.875° longitude and the model formulation is the same as HadRM3P, an experimental setup which promotes consistency of the high resolution climate change projections from the RCM with those from the global model.

The experimental design of the driving HadAM3P experiment is described by Rowell (2005) and is summarised as follows. The HadAM3P 1961-1990 simulation is forced by observed sea-surface temperatures and sea-ice (SSTs) from the HadISST1 dataset (Rayner et al., 2003). For the future period, 2071-2100, HadAM3P is forced by SSTs which are formed from observed SSTs with the addition of mean changes and trends calculated a global coupled model projection. The coupled integration was performed with HadCM3 (Gordon et al., 2000) whose atmospheric component, HadAM3 (Pope et al., 1999), is the basis for HadAM3P (Jones et al., 2007). The same SSTs were used as the lower boundary condition for the HadRM3P simulations. Matching the SST forcing the HadAM3P and HadRM3P simulations for the period 1961-90 (present climate) incorporated observed GHG concentrations and SO_2 emissions and for the period 2071-2100 incorporated GHG concentrations and SO_2 emissions taken from the SRES A2 and B2 emissions scenarios.

The validation of the simulated extremes for the present (1961-90) was made using temperature and precipitation records of 104 stations in South America, mostly concentrated in South America south of 6 ^{0}S. Trends have been computed the over the 30 years at every station, following Alexander et al. (2006). This density of stations is clearly completely inadequate to gain a truly regional picture of changing extremes and thus will provide for only a limited portrayal of observed changes and the model's ability to capture these. Thus it is obvious that we need to fill the remaining data gaps especially over the regions of northern and tropical South America (Figure 1).

The indices used to calculate short term extreme climate events were defined by Frich et al (2002). These indices sample the tail of a reference period distribution and have been calculated for 1961-90 present and 2071-2100 future, for both scenarios A2 and B2. From a total of 27 indices we calculated:

-*Very cold nights* (TN10): The percentage of time in a year when daily minimum temperature is below the 10th percentile of the 1961–90 daily temperature distribution,

-*Very warm nights* (TN90): The percentage of time in a year when daily minimum temperature is above the 90th percentile of the 1961–90 daily temperature distribution,

-*Consecutive dry days* (CDD): The annual maximum number of consecutive days when daily precipitation was less than 1 mm,

-*Maximum 5-day precipitation* (R5XDay): The annual maximum consecutive 5-day precipitation total that could led to flooding,

- *Extreme rainfall* (R95P): The annual total PRCP when precipitation is above the 95th percentile of the 1961–90 daily precipitation distribution,

- *Wet days* (R10): The number of days in a year with precipitation above 10 mm,

These indices do not represent extremely rare events, for which the computation of significant trends could be a priori hampered by the small sample sizes. Trends have been estimated by fitting a straight line to the data. The statistical significance of such a trend is determined by conducting a Student's t-test.

4. Validation of trends extreme climate indices for present climate

The observed and simulated spatial distribution of trends for the six extremes indices are shown in Figure 1, panels A-F respectively. Generally, the temperature-based indicators have trends which are consistent with the observed average regional warming. The observed TN10 (cold nights) and TN90 (warm nights) indices suggest respectively negative and positive trends. There are two exceptions which appear to have some regional consistency and are increasing trends in cold nights in northern Peru and Ecuador and in Paraguay. Observations show positive trends in all three indices of extreme rainfall in southeastern South America and the western coast of Peru and Ecuador, while southern Chile shows negative trends. The maximum consecutive dry day length shows a negative trend in southern stations and in South East Brazil and generally strong positive trends elsewhere.

The PRECIS simulated trends are displayed in Figure 1 panels G-L. They match well the patterns of negative trends in the cold nights in Southeastern South America, while the simulations for the warm night indices show the positive trends while the model underestimates the positive tendencies. In regions with no observational coverage the PRECIS simulations show also negative cold night trends and positive warm night trends, both in Northeast Brazil and in the Amazon Basin. The observed positive trends in TN10P noted above are not captured by the model and this coincides with regions of large observed increases in consecutive dry days also not simulated. Significant increases in dry days would imply significant reductions in cloudy days which could be responsible for the increases in cold nights though more detailed analysis would be required to confirm this.

The positive trends in TN90 simulated over Venezuela by the model are consistent with the positive trends observed by Alexander et al. (2006) and Caesar et al. (2006). The changes in temperature indices reflect an increasing trend in both maximum and minimum temperatures, which are consistent with the results of Marengo and Camargo (2007) for southern Brazil and Rusticucci and Barrucand (2004) in Northern Argentina.

The broad spatial pattern of observed trends in R10mm is well simulated by the model, with positive trends in large regions of Southeastern South America and negative trends around 40 S in Chile. The simulated trends in western Amazonia are consistent with those observed in stations on that region. The trends of RX5day and R95P are consistent between observations and simulations in northern Argentina, Uruguay and parts of Paraguay where they are generally increasing. In southern Brazil these indices have positive trends in the model simulations which is consistent with the few stations south of 20°S but inconsistent with those two stations between 15°-20°S. The simulated positive rainfall extreme trends in Northeastern Brazil and in southern Brazil-Northern Argentina are also detected in the observational studies on rainfall extremes by Groismann et al. (2005) and Rusticucci and Barrucand (2001), respectively. Over Chile again negative trends observed are captured by the PRECIS simulations.

The CDD maps shows that the model reproduces well the negative trends in central Argentina and west central Brazil south of 15S, and in the model the negative trends extend to Northeast Brazil. The observations show positive trends in Uruguay and in the boundary region between Argentina-Paraguay-Brazil while the model does not show any trend. Extreme northern Amazonia and Venezuela show positive trends in simulated CDD that are consistent with positive CDD trends observed in that region by Alexander et al. (2006).

In a qualitatively comparison of present day extreme indices simulated by the IPCC AR4 GCMs for the XX Century from Tebaldi et al (2007) and simulations with PRECIS, perhaps the best agreement is found for TN90 and the worst for CDD. The R10 simulations show similar distributions between the patterns from both GCMs and PRECIS, with positive trends in southeastern Brazil and western Amazonia and negative trends in northern South America and southern Chile.

5. PRECIS derived future changes in extremes

In general the temperature-based indicator changes (Figure 2 panels A, B, G, H) are consistent with the expected warmer future climate, with negative trends in cold nights and positive trends in warm nights. The trends are larger for A2 especially in tropical South America and the Andean regions while the trends are smaller south of 20 ^{o}S. Under the B2 scenario there are no significant changes in warm nights south of 20 ^{o}S and in some eastern tropical areas and even for a small area in Argentina under the A2 scenario. These projected trends seem to be a continuation of the generally negative and positive observed trends. The projected positive trends in TN90 from the PRECIS simulations are also consistent with the positive and statistically significant TN90 trends detected in the global IPCC AR4 multimodel simulation, especially in the region extending from Bolivia to Central Brazil in the A1B scenario from Tebaldi et al. (2006).

An expected consequence of global warming is an intensification of the hydrological cycle. In very broad terms this would be expected to increase the frequency and intensity of extreme rainfall events and also dry spells (IPCC 2007a, b) though significant regional and local deviations from this picture are likely (Christensen et al., 2007). In the climate response to global warming projected by PRECIS the changes in occurrence of R95P, RX5day and R10mm (Figure 2 panels, D, E, J, K) suggest increases in the frequency and intensity of extreme rainfall events in western Amazonia, the northern coast of Peru and Ecuador and in southeastern South America. The patterns are similar for the two emissions scenarios and in the A2 changes are larger in western Amazonia and southern Brazil. Negative trends are projected for northern South America and the eastern Amazonia- Northeast Brazil region, and again are larger in the A2 scenario. The projected trends in Southeastern South America show basically a continuation and intensification of the positive rainfall extreme trends detected during the second half of the XX Century.

On the other hand, the CDD index shows an increasing trend in the region extending from eastern Amazonia to Northeast Brazil which is inconsistent with the model trend in the control simulations (and the few stations with available data consistent with this). In the A2 scenario this extends into the northern South American coast (which is consistent with the model control trends) and into southeastern Brazil in the A2 scenario until the end of the XXI Century. Significant trends are also projected under the A2 scenario for Bolivia which are consistent with those observed.

Previous analyses of PRECIS projections for South America for 2071-2100 (Marengo et al. 2007, Ambrizzi et al. 2007) have shown reductions of total rainfall in eastern Amazonia and Northeast Brazil regions between on the order of 5-20%, as well small increases of rainfall in southeen Brazil and northern Argentina that can reach 5-10%, relative to the 1961-90 under the A2 and B2 scenarios. In the context of trends in extrenes, the results here imply that this rainfall reduction in eastern Amazonia and Northeast Brazil would be seen initially through an increase in CDD trends under a more moderate emissions scenario and then through further increases in CDD trends accompanied by reductions in heavy precipitation events. These results also imply that the increase of rainfall in southern Brazil and northern Argentina would be due an increase in the frequency of some intense rainfall in the future. The most marked increases in extreme rainfall are projected for western Amazonia implying increased flood risk here.

6. Implications for impacts and vulnerability in some key regions and sectors

The observed extreme rainfall trends in Southeastern South America, some of which are also simulated by PRECIS control run, are very relevant. Extreme rainfall events have affected large cities such as Sao Paulo, Rio de Janeiro and Buenos Aires resulting in an increase in flooding events during the last 50 years (Marengo et al. 2007). If these changes continue in the future as projected here by PRECIS then this would results in huge economical losses due to increase risk of floods.

Looking over a larger area, a recent study by Baettig et al. (2007) indicates that tropical South America, specifically Amazonia and Northeast Brazil, are very vulnerable to climate change by the end of the XXI Century. Two internal reports derived from the CREAS project (Ambrizzi et al. 2007, Marengo et al. 2007, available from www.cptec.inpe.br/mudancas_climaticas) show that in Amazonia by the end of the XXI Century air temperatures may increase between 3-4 ^{o}C and rainfall may reduce by 5-20% as compared to the present. In Northeast Brazil these changes can vary from 1-4^{o}C of warming with rainfall reductions of between 10-15%. These results are for the B2 emissions scenario, and for A2 the possibility of even larger changes is indicated (reaching up to 8^{o}C and 40% drier in both eastern Amazonia and Northeast Brazil). Such changes in average climate are very likely to have major impacts in the biodiversity, water resources and management, agriculture and human health. As demonstrated above, these changes will be seen in part through a range of different changes in extremes and a full description of all these changes are required to provide a comprehensive assessment of their impact.

Taking the example of biodiversity, simulations of biomes for the future (Salazar et al. 2007) have suggested that in the A2 scenario, natural ecosystems such as the tropical rain forest and the “caatinga” (natural vegetation in Northeast Brazil) would be affected and possibly replaced by savanna and semi-desert type vegetation, respectively. Because of the reduction in extreme rainfall accompanied by an increase in the tendency for consecutive dry spells until 2100, Eastern Amazonia would experience a loss of the tropical rain forest to the savanna type vegetation “cerrado” that is currently present in west central Brazil. The resilience of many ecosystems is likely to be exceeded this century by this unprecedented combination of extreme climate events and associated disturbances.

Although many early impacts of climate change can be effectively addressed through adaptation, the options for successful adaptation diminish and the associated costs increase with increasing climate change. Also, in this region the vulnerability to drought demonstrates that in this case the short term mitigation measures that have been implemented have not been successful suggesting adaptation would be more difficult to implement even under limited climate changes.

Lastly, for tropical South America, future vulnerability depends not only on climate change but also on development, and these two vulnerable regions face multiple stresses that affect their exposure and sensitivity as well as their capacity to adapt. Limitations and data gaps especially in tropical South America prevent more complete attribution of the causes of observed changes in climate extremes and therefore, and also the assessment of climate extreme responses to anthropogenic warming. Nevertheless, there is consistency between observed and projected changes in this and several studies and the spatial agreement between significant regional warming.

6. Conclusions

Simulations using the Hadley Centre's regional climate modeling system PRECIS of South American climate of the recent past and two possible future climates have been analyzed to provide guidance on how climate extremes may change over the region. Validation of the simulated climate of 1961-90 shows that the pattern of temperature extremes is similar between model and observations in Southeastern South America. Cold and warm nights validate well except for the former over Paraguay and the Northern

Peru/Ecuador region. Possibly linked to this are strong observed trends in these regions in the maximum dry spell length which the model also does not simulate. The lack of rainfall implied by increased dry spell length will probably be associated with reduced cloudiness leading to increased longwave cooling at nights and thus more cold nights. Maximum dry day trends in other regions (mostly negative) are simulated by PRECIS as are most of the heavy and extreme precipitation trends analyzed. The validation reported here is far from comprehensive due to the small number of stations available which in particular results in an almost complete lack of reliable information in tropical South America.

Changes in these extreme indices were analyzed for projections of the climate of 2071-2100 under the IPCC SRES A2 and B2 emissions scenarios. Cold and warm night trends are respectively negative and positive as expected with the response larger in tropical regions and under the A2 scenario. South of 20°S and in some eastern tropical areas there are no significant changes projected under the B2 emissions scenario. Tropical warm night trends are consistent with analyses of the multi-model ensemble assessed in the IPCC AR4.

Projected changes in the precipitation indices are more complex. Changes in annual rainfall resulting from the top 5% of daily precipitation events, the maximum 5 day rainfall total and the number of days with heavy precipitation (greater than 10mm) all show increases in western Amazonia, the northern coast of Peru and Ecuador and in southeastern South America. Negative trends are projected for northern South America and the eastern Amazonia-Northeast Brazil region. All these trends are larger under the A2 scenario. The projected trends in Southeastern South America continue and intensify those observed during the second half of the XX Century. Projected dry spell length increases over eastern Amazonia-Northeast Brazil and Bolivia though only are only significant in some area, more under the A2 emissions. Only the Bolivian changes are consistent with those observed.

A major objective of analyzing PRECIS simulations of extreme climate events under past and possible future emissions is to provide projections of future regional extreme climate events that could be used in impact studies in South American countries. For example, the projected increases in extreme rainfall for western Amazonia (the clearest hydrological cycle signal analyzed) imply increased flood risk there. Similar changes over southeastern regions also imply significant increases in economic losses in the major cities there. Over Eastern Amazonia the projected changes in dry spell length and the associated changes in average rainfall would lead to significant changes in the natural vegetation and thus impacts on ecosystems and biodiversity.

Climate change is expected to modify the frequency, intensity and duration of extreme events in many regions (Christensen et al., 2007). It is impossible to attribute single extreme events directly to anthropogenic climate change because of the probabilistic nature of these events. There is always a chance that any given event may be a result of natural climate variability, even if an event of such magnitude has never been recorded. Therefore, it is necessary to use models to augment observations in attempting to understand the changing likelihood of extremes under climate change scenarios, e.g. through calculating the enhanced risk of an extreme attributable to climate change as in Stott et al., (2004) for the heat wave in Europe in summer of 2003. If models can be shown to simulate the observed variability of extremes, then they can be used with a degree of confidence to provide reliable estimates of extremes within a given climate change scenario.

Future work will include the use of other regional models for the downscaling of the HadAM3P future scenarios and the downscaling of other GCMs to provide estimates of likely ranges of future climate changes. Another crucial area of future work is to improve access to data from and increase the observational network in tropical South America so the model can be validated for these regions. This well help in understanding the reasons for observed changes in climate extremes and in improving confidence in projected changes.

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Figures:

Figure 1. Observed and simulated trends of extreme climate indices for 1961-90. The trend is assumed as linear and represents the values of 1990 minus 1961. Panels a-f represent observations and panel g-l represent HadRM3 (PRECIS) simulations. (A) TN10 in %/30 years; (B) TN90 in %/30 years; (C) CDD in days/30 years, (D) R95P in mm/30 years, (E) RX5Days in mm/30 years, (F) R10 days/30 years. Color scale is shown on the lower side of the simulated indices maps. Black line delimitates areas where the linear trend is statistically significant at 5% level using the Student t-test.

Figure 2. Projected trends of extreme climate indices for 2071-2100 relative do 1961-90. Panels a-f show projections for the B2 scenario, and panels g-l show projections for the A2 scenario. (A) TN10 in %/30 years; (B) TN90 in %/30 years; (C) CDD in days/30 years, (D) R95P in mm/30 years, (E) RX5Days in mm/30 years, (F) R10 days/30 years. Color scale is shown on the lower side of each panel, and the black line delimitates areas where the linear trend is statistically significant at 5% level using the Student t-test.