Climatological Assessment of the Albertine Rift for Conservation Applications

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Executive Summary

From 2007-09, the Wildlife Conservation Society conducted the Albertine Rift Climate Change Assessment, an exploratory study funded by the John D. and Catherine T. MacArthur Foundation to develop understanding of potential impacts of anthropogenic climate change challenges on wildlife conservation in one of Africa's most biodiverse landscapes. The project objectives were to quantify conservative-to-extreme predictions of regional climate change across the Albertine Rift, to assess future impacts of climate change and estimate the future distribution of biodiversity in the Albertine Rift, and to develop our findings in partnership with the wider biodiversity conservation community. This white paper is the first of two that collectively present and describe the project results and findings. The companion study, ***Potential Climate Change Impacts in Conservation Landscapes of the Albertine Rift,*** presents findings on sophisticated environmental modeling performed for core areas of conservation focus in the Albertine Rift (Picton Phillipps and Seimon 2009).

Over the course of this project we found understanding of regional climatology for conservation applications to be poorly developed. This whitepaper consolidates information derived both from climatological analysis of observational data and climate modeling to build foundational knowledge for the benefit of the conservation community and other potential users. The purpose of this report is therefore to provide to conservation concerns and other potential users an observationally based assessment of Albertine Rift climatology and climatic change at scales most relevant to conservation and ecological applications.

Acknowledgements

The WCS Albertine Rift Climate Assessment was made possible by a grant from the John D. and Catherine T. MacArthur foundation. The authors also gratefully acknowledge the sustained support from the Africa Regional program of the WCS Global Conservation Program. In particular, without the hard work and dedication of a number of people, this project would not have been possible. From the MacArthur Foundation – our Program Officer Elizabeth Chadri. From WCS - Carolyn Gray, Sylvia Alexander, James Deutsch, Graeme Patterson, Monica Wrobel, Amy Pokempner and Jennifer Kennard.

In addition, the following people have made extremely significant contributions to the technical analysis conducted during the project:

Dr. Ruth Doherty for her expertise in Lund-Potsdam Jenna ecosystem modeling

Dr. Philip Thornton for his expertise in Global Climate Model downscaling and crop yield modeling

Dr. Andrew Plumptre, for organizing climatological data collection

Also a number of organizations and individuals contributed climatological data for analysis, which was invaluable for the climatological assessment.

Contents

1. Introduction

1a. The Albertine Rift – overview and significance

The Albertine Rift is the western branch of the Great Rift Valley of Africa It extends from the northern end of Lake Albert to the southern end of Lake Tanganyika, and encompasses lands flanking both sides of the rift and straddling several countries: The Democratic Republic of Congo, Uganda, Rwanda, Burundi, Tanzania and Zambia (Figure 1). It is a region of exceptional topographic and ecological complexity, encompassing the glacierized Rwenzori Mountains, the great lakes of the rift valley floor, and the continental ecotone of the Congo Rainforest and East African savannah biomes, among numerous other features.

The Albertine Rift is recognized to be one of the most important regions for the conservation of Africa's biodiversity. With many major protected areas currently established, it is home to many endemic species including the mountain gorilla and golden monkey, 42 species of birds, and many reptiles, amphibians, fish, invertebrates, and plants. It contains more vertebrate species than any other region on mainland Africa, and is home to some 40-50 million people, the large majority of whom are subsistence farmers (Plumptre et al., 2002, Plumptre et al., 2007).

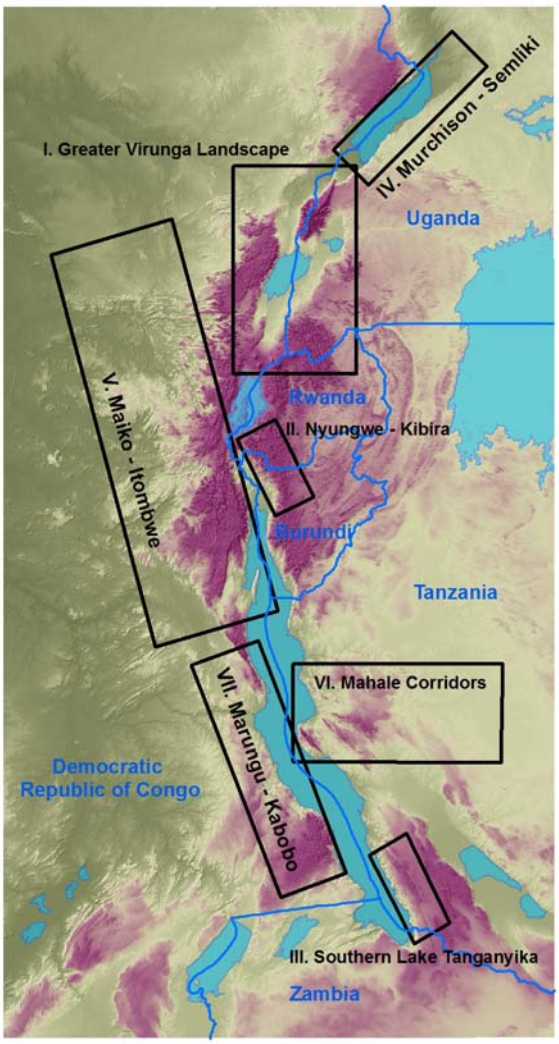

Figure 1: Relief map of the Albertine Rift region showing national boundaries and core biodiversity conservation landscapes examined in this study. Darkening maroon and green shades indicate increasing highland and decreasing lowland elevations, respectively. Major water bodies are shown in blue.

1b. Project purpose and outputs

In contexts of biodiversity conservation, climate is one of several inherited background states. As a geographic endowment, along with factors such as soil types, water availability, and geographic location climate exerts a strongly coercive influence on ecological system types and character, and likewise on human settlement patterns, health characteristics, livelihoods and economies, all of which impact biodiversity as well. Consequentially, long-term conservation success cannot be achieved without comprehension of present day climatic variability and climate changes ongoing and forthcoming.

Yet until very recently, climate change has largely been absent from consideration among priorities for biodiversity conservation in the Albertine Rift. As one of a series of measures aimed at addressing this shortcoming, in 2007 the John D. and Catherine T. MacArthur Foundation funded the Albertine Rift Climate Assessment, a two-year project by the Wildlife Conservation Society (WCS) to conduct an initial assessment of climate change and it potential impacts along the Albertine Rift corridor and within its key protected areas in particular. The project objectives were to quantify conservative-to-extreme predictions of regional climate change across the Albertine Rift, to assess future impacts of climate change and estimate the future distribution of biodiversity in the Albertine Rift, and to develop our findings in partnership with the wider biodiversity conservation community.

While our original project plan did not include an examination of climatology itself, following the initial review of the requirements for climate change analysis using Global Climate Change Models, it became increasingly apparent that a sound scientific understanding of contemporary climatology is an essential component for evaluating the potential impacts of climate change on biodiversity. We discovered, however, that such knowledge has never been properly established for the Albertine Rift. As a key objective of the project was to develop the baseline information to assist regional conservation managers in developing strategies for continuing successful biodiversity conservation efforts in the face of climate change, we decided to broaden the scope of the project to include this activity. The purpose of this report is therefore to provide to conservation concerns and other potential users an observationally based assessment of Albertine Rift climatology and climatic change at scales most relevant to conservation and ecological applications.

This whitepaper is the first of two that collectively present and describe the results and findings from the WCS Albertine Rift Climate Assessment. The companion study, ***Potential Climate Change Impacts in Conservation Landscapes of the Albertine Rift,*** presents findings on sophisticated environmental modeling performed for core areas of conservation focus in the Albertine Rift (Picton Phillipps and Seimon 2009). A third component of this project's output is an online archive of project output including data sets and analyses utilized in this report, outputs of downscaled climate and vegetation and crop modeling, all project documents including the companion study, and other materials. All items are freely available for download at the project website by registered users at: http://programs.wcs.org/Resources/Downloads/tabid/2801/Default.aspx

1c. Global climatic context of the Albertine Rift

Widespread recognition of the multifaceted threats represented by global climate change and its consequences to humanity, biodiversity and ecological systems has rather suddenly elevated tropical climatology from an obscure research topic to the forefront of numerous scientific agendas and international public policy discourse. Central to scientific investigation on climate change are ever more comprehensive and sophisticated environmental modeling efforts performed both according to organized protocols, such as the Intergovernmental Panel on Climate Change (IPCC)

multi-model framework utilized most recently in the Fourth Assessment Report (IPCC 2007), and also by a myriad of globally distributed organizations working more independently. Ultimately, these modeling efforts all require some form of baseline representation of the atmosphere developed through observational datasets. It follows that better model projections result from better observational inputs.

Among the world's continental landmasses, tropical Africa is by far the most underrepresented in term of systematic, quality controlled climate data. In some countries much of the available climatological data and understanding of regional climatology dates back to the colonial era of the early to mid 20th century. This void of reliable data has many causes and has been frequently lamented, but is now a cause for considerable concern in contexts of global climate change. The baseline data needed as inputs to ensure that models are launched with proper representation of actual conditions as a starting point, and which also serve as reference for assessing degrees of change shown in predictions, are for many regions of Africa largely unavailable. Instead, interpolation techniques must be applied between widely separated data points greatly smoothing out local climatic detail – the detail which determines many characteristics and particularities of local ecology. This insufficient representation is particularly problematic in mountains and other regions of complex topography, where both climatic and related ecological gradients are especially large.

This is largely the case for the Albertine Rift, where an extremely complex landscape configuration and widespread absence of verifiable point data resulting from sparse and poorly sustained climatological observations stand as obstacles to efforts to apply models for predicting climatic and ecological futures. Furthermore, contemporary understanding of Albertine Rift regional climatology conveyed in scientific literature contains notable knowledge gaps, if not fundamental misperceptions, regarding the regional climatic system. In particular, as will be demonstrated in this study, prevailing perspectives portrayed in scientific literature and elsewhere tend to oversimplify the precipitation hydrology, and thus fail to represent patterns that are likely of consequence to ecological systems and, it follows, among those most susceptible to perturbation under changing climatic regimes.

Such simplification is in part the product of expectations by climatologists and other users of climatological data that at seasonal time scales tropical precipitation occurrence is stochastic in terms of the frequency of rainstorms and the amount that falls from each storm. Guided by such expectations, rainfall observations taken at daily or hourly intervals is archived, analyzed and presented as monthly and annual aggregated totals and means. This process effectively smoothes out high frequency behavior before it can be analyzed, and in doing so removes a considerable part of the climatic detail of actual relevance to terrestrial biodiversity and many ecological processes. As an example from the Albertine Rift, a climatological assessment of Kibale National Park in Uganda based on multi-decadal observations, collected for ecological applications such as phenological studies, only considers climatological data at monthly and longer time scales (Struhsaker 1997, Chapman et al 2004). Even the most comprehensive treatment of regional climatology identified during the present study, *The Meteorology and Climate of Tropical Africa* (Leroux 2001), which contains a 40-page chapter on tropical African rainfall modalities, only considers monthly and longer time scales. While this is both widely used and conventional practice in climatology, the consolidation of raw climatological data into aggregated quantities represents innumerable missed opportunities to ecological studies and applications, among other things. The monthly data reveals the low-frequency characteristics only; more highly resolved information could more effectively elucidate both present-day relationships between climate and ecology, and enable stronger inference on likely impacts to ecological systems as a consequence of climate change forthcoming.

Therefore, to construct baseline analyses for comparison with climate change projections developed for the modeling component of this project effort was placed in obtaining original climate records at daily resolution along the Albertine Rift corridor, and particularly where observations have been systematically collected within protected areas.

2. General Climatology

2a. Synoptic Climatology

The climatic regimes of the Albertine Rift corridor are largely a consequence of its complex mountainous topography and a latitudinal domain that extends from the equatorial tropics in the north to the outer tropical belt in its southern extreme. Climatic seasonality along the north-south oriented rift corridor is largely dictated by the annual back and forth migration of the Inter-Tropical Convergence Zone (ITCZ), as can be seen at continental scale in Figure 2.

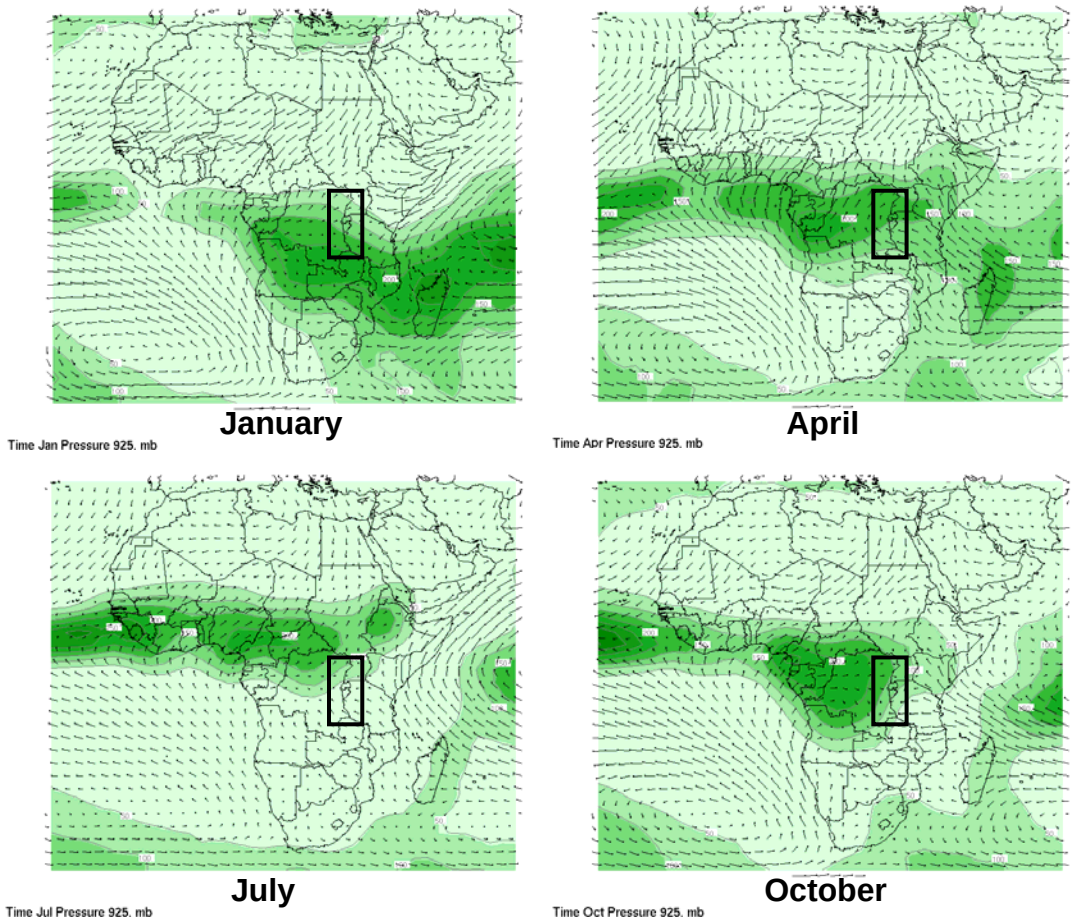

Figure 2: Continental scale depiction of moisture distributions over Africa according to monthly averages of rainfall rate (mm per day) derived from global analysis products. The Albertine Rift region is outlined by the black rectangle in each figure. The annual north and south migrations of the ITCZ, evident as the darker green shades over equatorial regions, bring the Short and Long Rains to the northern part of the rift region around October and April, respectively, while

southern parts of the domain experience a single long-duration wet season peaking around January when the ITCZ is at its southern zenith.
Source: International Research Institute for Climate and Society (IRI), New York

Thermal conditions are largely a function of elevation throughout the domain, with very little thermal seasonality experienced in terms of monthly mean temperatures. An exception is the southern part of the rift flanking Lake Tanganyika, where a marked dry season with reduced humidity and cloud cover in the austral winter months is associated with slightly lowered nocturnal minima. Climatic variability and seasonality in the Albertine Rift is therefore most evident in moisture variations, in cloudiness and precipitation occurrence.
At the more focused regional scale of the Albertine Rift, complexity becomes evident in climatic behavior and spatial patterns throughout the region. At these scales the influence of regional landforms, large lakes and vegetation on spatial distributions of climatic parameters become amply apparent, as can be discerned from a satellite's perspective on virtually any given day (see cover photo).

While the climatology of the Albertine Rift is largely dictated by the invariant seasonal cycles of annual solar migration, external climatic forcings also play a significant role in inter-annual climatic variability through linkages known as teleconnections. Year to year precipitation variability is most strongly influenced by the El Niño Southern Oscillation (ENSO) which, despite being focused in the eastern equatorial Pacific Ocean at a vast distance from the Albertine Rift, exerts considerable influence over rainfall occurrence in eastern Africa (Anyamba et al 2002, Gianini et al, 2008). The general pattern links warm ENSO (El Niño) events with regional rainfall surpluses and cold ENSO (La Niña) events with rainfall deficits; this pattern is inconsistent, however, since a more local factor, the Indian Ocean Dipole, must act in concert with ENSO in order to yield the expected rainfall anomalies (reference here). Other climatic teleconnections are recognized too. Inter-annual rainfall variability in the Greater Horn of Africa region including northern parts of the Albertine Rift has been shown to correlate remarkably well with surface pressure over the Indian subcontinent (Camberlin 1997); these factors in turn relate to the ENSO-Indian Ocean complex described above.

A current point of debate in scientific circles of relevance to this study concerns the relative roles played by internal versus external forcing factors in determining multidecadal trends in rainfall widely observed throughout tropical Africa, most notably the Sahelian region but also in eastern Africa extending to the Albertine Rift. Climate modeling studies find the trends to be externally dictated by seas surface temperature variations, whereas findings from regional modeling studies determine that internal forcing by anthropogenic land cover change within the continent itself largely explains the trend behavior (see, e.g. Gianini et al, 2008; Paeth et al 2009). Both factors are very likely at work, though understanding to what degree proportionally is of considerable importance in assessing climate model predictions and improving GCM representation of both forcings and responses.

3. Data

3a. Climatological records

To enable detailed site-specific assessments for this study, original climate observation records were sought from research groups and protected area managers throughout the Albertine Rift region. We were gratified to receive data series contributed by several respondents from inside and close to some of the most important protected areas of the Albertine Rift region. These records are mostly from observational periods of less than 30-years, which is the conventional time period

used to establish parameter normals for climatological applications. We therefore analyze data according to the mean values inherent in each data set, and assess anomalies and trends relative to these baselines.

There are also many issues concerning data consistency and quality, and most of the raw data files required considerable error checking and correction before being considered usable. The lack of standardization in instrumentation quality and in siting weather stations generally means that these records cannot be considered authoritative and comparable to the quality controlled data series compiled for the Global Hydro Climatological Network (GHCN) and other archives. They are, however, often the only direct measurements available within the protected areas that are this study's primary focus, so are used here as the principal climatological data base, though with various caveats necessarily applied. A priority for future work is the installation of appropriately sited research grade automatic weather stations at Albertine Rift sites. These will be situated in current data void regions and also at several sites where climate monitoring is already ongoing but with inadequate systems; both data streams should operate concurrently for at least one year in order to identify possible systematic bias and other errors that should become evident when data from the old and new systems are compared.

All climatological data was error-checked using a combination of subjective and objective pattern recognition methods. In some cases corrections could be applied (e.g. when overnight minimum temperature was considerably higher than the measured temperature recorded at the time of observation); in cases where the correct value could not be ascertained, the questionable data was deleted and left as blank. The resulting "cleaned-up" quality-controlled data files will be made available for download from the project website for those sites where permission to do so is granted by the parties providing the data.

For purposes of climatological analysis of observed parameters a "year" over much of the Albertine Rift is more meaningfully defined by a July-June hydrological year, rather than the January-December calendar year. Rainfall anomalies associated with ENSO are most strongly developed during the ENSO phase maxima, which typically peak in the December-March summer season of the northern Hemisphere. It is unfortunate that many studies assess tropical African annual rainfall according to January-December calendar years, since these will generally split the phase signals associated with ENSO between two different wet seasons, often corresponding to consecutive ENSO phases of opposite sign. In the cases presented below we use a combination of the two formats to clarify both the actual climatology and to enable straightforward comparison between observational data and model output prepared in the conventional format.

3b. Climate model output

The downscaled GCM predictions presented here are from multi-model output generated using the SRES A2 emissions scenario (IPCC 2007). Details on the models and methodologies utilized to generate these figures, and the rationale behind the choice to use the A2 scenario, are presented in the companion study (Picton Phillipps and Seimon, 2009).

4. Results

Three types of project results are presented in this section. In section 4a we present spatial interpolations of present-day monthly mean climatology across the Albertine Rift project domain for several key parameters. In section 4b we present analysis and discussions on climatological

patterns and trends revealed in actual observations recorded within key protected areas. These sites lie within several of the priority conservation sub-regions that form the focus of environmental modeling described in the companion report, and are identified in Figure 1. Finally, in section 4c we present spatially and temporally explicit downscaled GCM predictions for key climate parameters in the Albertine Rift for three different time steps during the 21st century.

4a. Mesoscale climatology as represented in model interpolations

Climatological representations of monthly mean distributions of key climatological parameters based on interpolations incorporating topography are informative for understanding spatial organization and seasonal behavior of the annual climate cycle. For the modeling component of this project and many others like it, observationally-based interpolated climatology products serve as the baseline for comparison with modeled climatic predictions. We used the University of East Anglia Climate Research Unit CRU TS2.1 interpolated baseline climate gridded data (Mitchell and Jones 2005) averaged over the period 1980-1999 to generate the plots of monthly men cloud cover, precipitation and temperature of the Albertine Rift project domain.

In a data sparse domain such as the Albertine Rift, the limited observational data utilized to generate the gridded products results in low confidence that location-specific climatology will be accurately represented. Nevertheless, these products are highly informative in conveying the spatial and temporal patterns of the annual climate cycle over the Albertine Rift as a whole, and to a lesser degree, at site-specific localities in a general sense as well. At more focused scales the representation of the gridded data to actual climatology diminishes considerably, and as such, actual *in situ* measurements become a necessity in order to ascertain actual conditions.

The interpolated data fields for each month of the year from the historic 1990 reference data are presented in Figures 3, 4 and 4 for Monthly Mean Cloud Cover, Precipitation Amount and Temperature, respectively. Despite the coarse resolution, which is inadequate to capture topographic detail other than the most major landforms, the plotted fields are informative for revealing spatial aspects of seasonal evolution and the locations of relative maxima and minima.

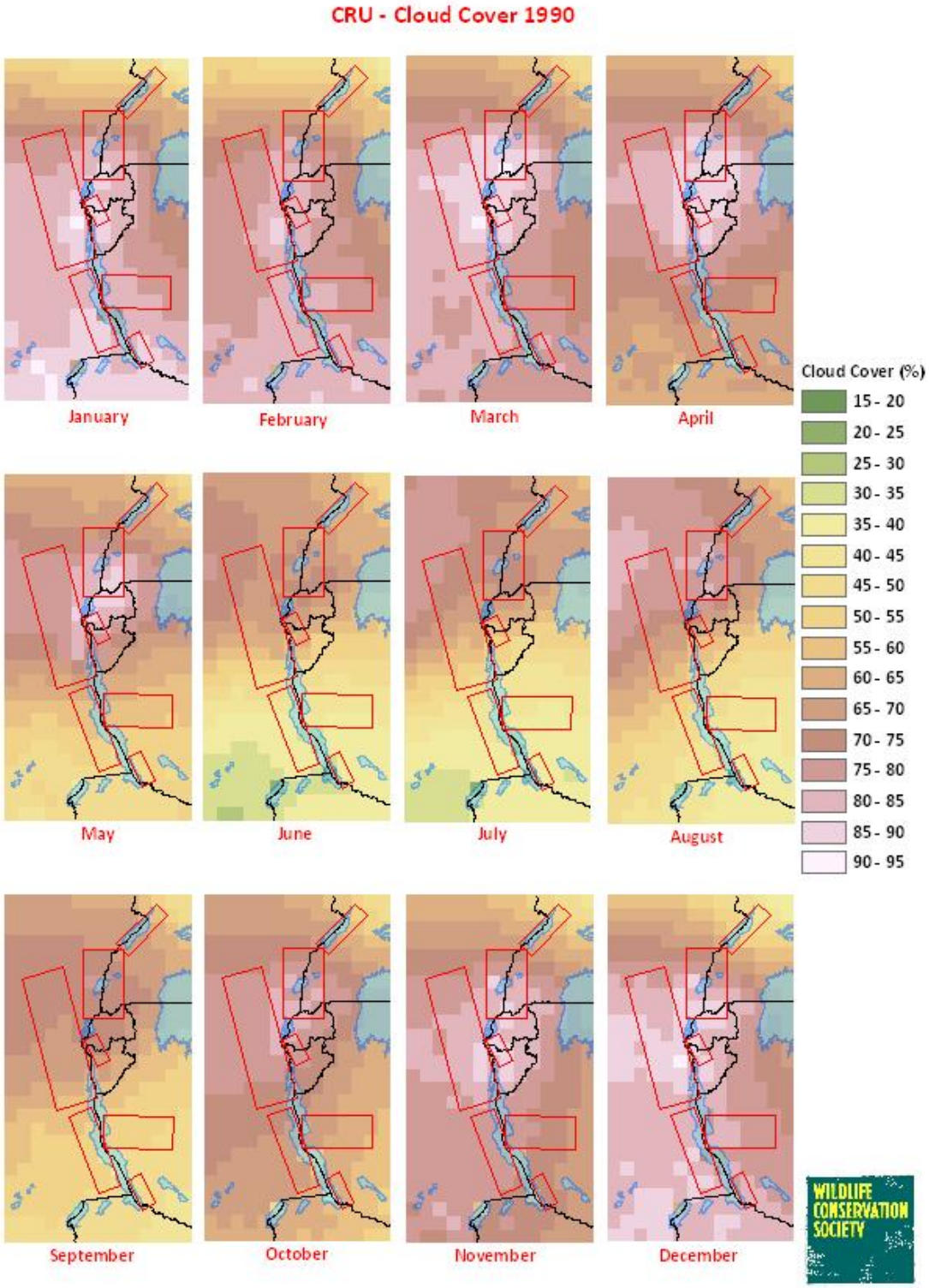

Figure 3: Climatological representation of monthly mean cloud over the Albertine Rift project domain based on 1980-1999 interpolated data. The ebb and flow of the rain-bearing Inter-tropical Convergence Zone (ITCZ) from its southern perigee in December-January to its northern apogee in July-August and subsequent return are readily apparent.

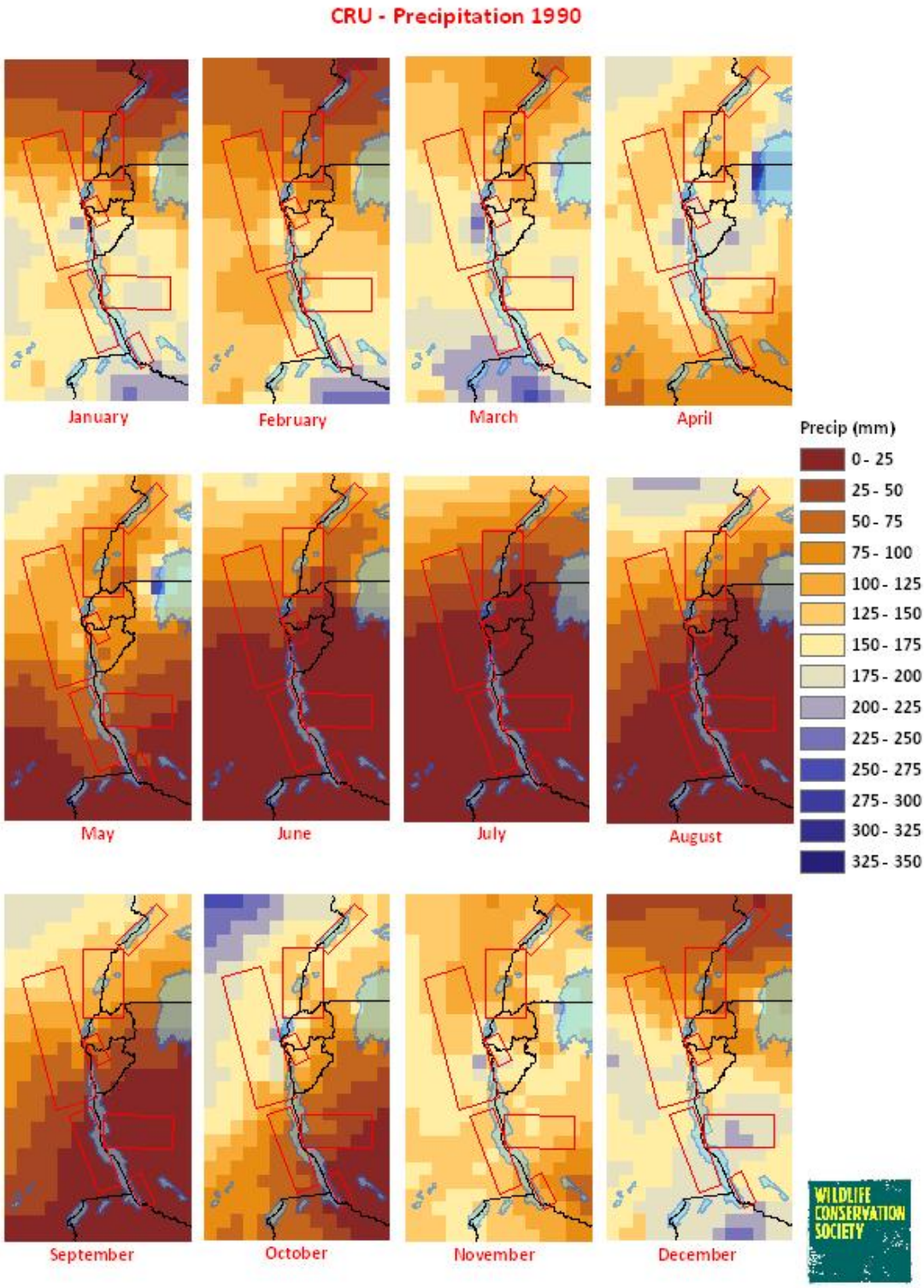

Figure 4: Climatological representation of monthly mean precipitation amount over the Albertine Rift project domain based on 1980-1999 interpolated data. Seasonal ITCZ migrations evident in cloud cover bring twin rainy seasons of relatively short duration to the central Albertine Rift each year, and longer, unimodal rainfall seasons to both the north and south.

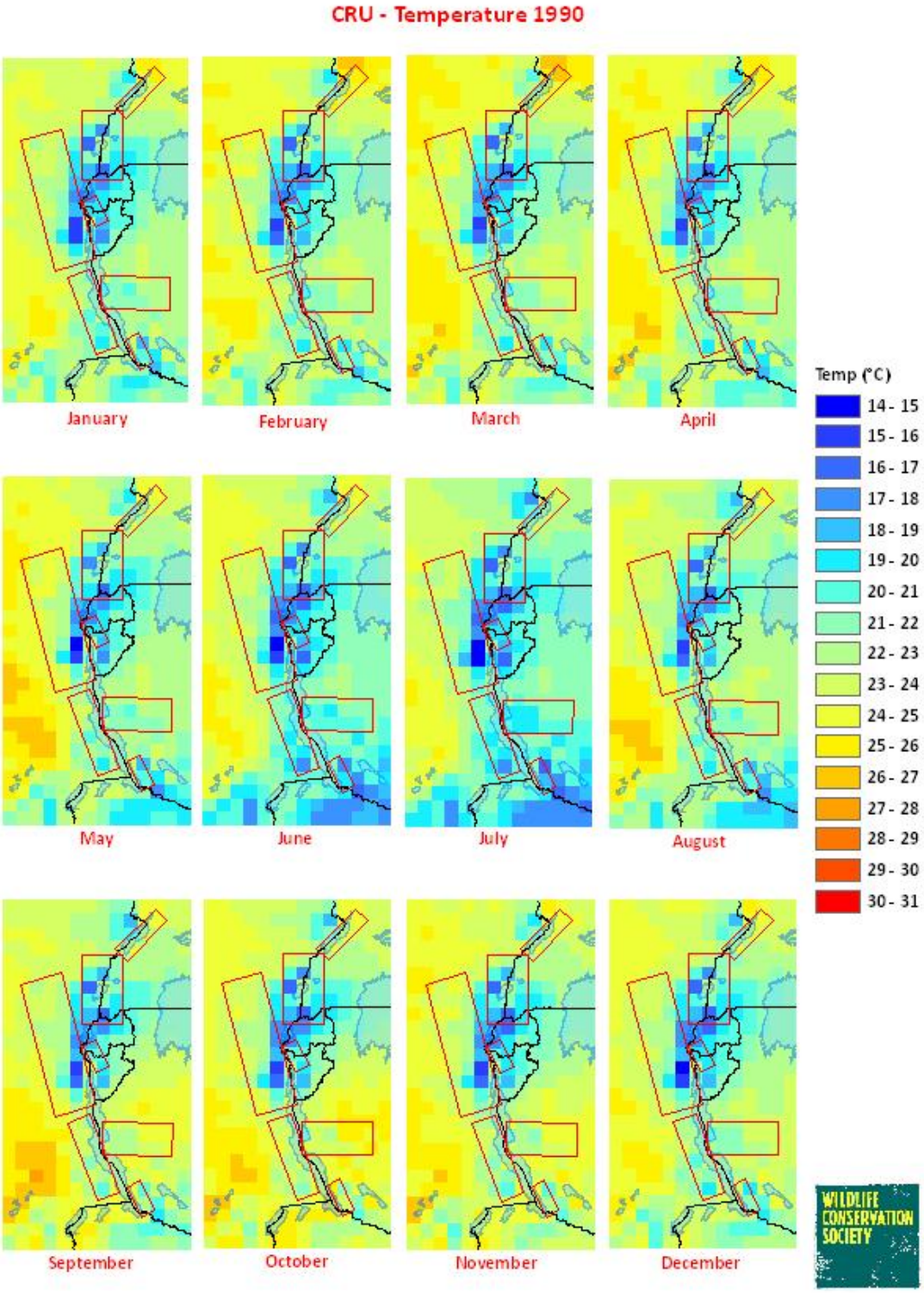

Figure 5: Climatological representation of monthly mean surface temperature over the Albertine Rift project domain based on 1980-1999 interpolated data. Spatial variation remains fixed in place over time, reflecting control of terrain elevation over temperature. Some thermal seasonality is evident in the austral winter across the southern part of the Albertine Rift domain.

4b. Sub-regional Assessments

Sub-region I: Greater Virunga Landscape

This Greater Virunga Landscape sub-region encompasses the most extreme range of landscapes in the Albertine Rift, ranging from the relatively arid lowlands plains on the valley floor to the glacierized heights of the Rwenzori a short distance away. By straddling the equator the sub-region is subject to the characteristic bimodal rainfall pattern of the central Albertine Rift domain. A classic representation of this is demonstrated from daily rainfall records displayed according to conventional aggregated into monthly means from Bwindi National Park in Uganda (Figure 6).

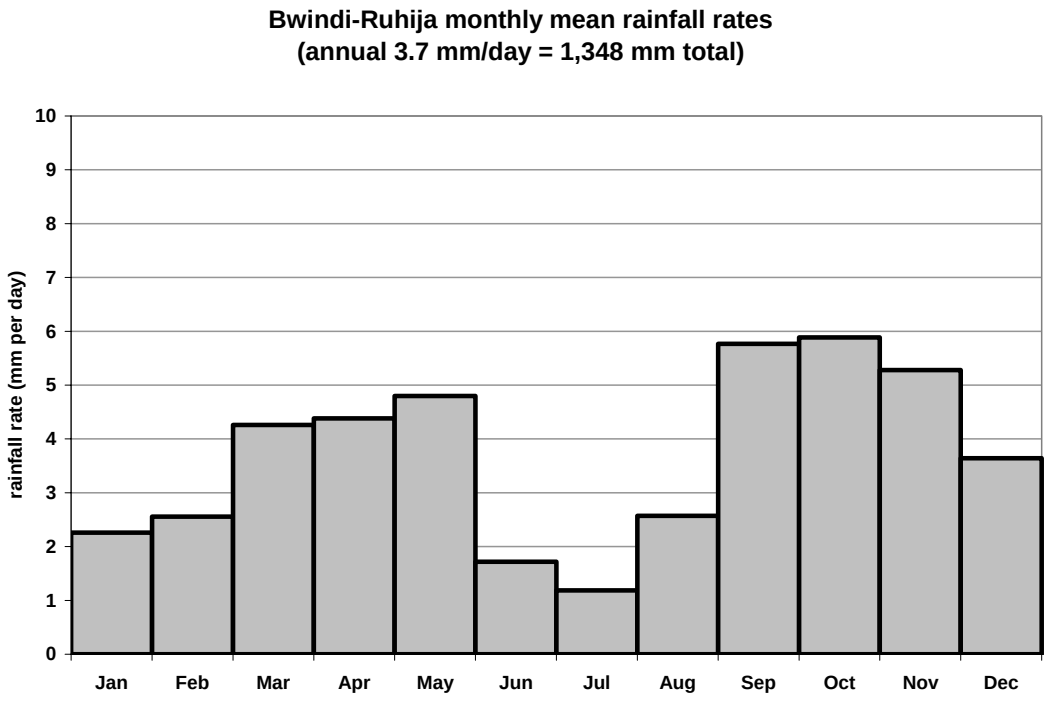

Figure 6: Conventional calendar-year pluviogram showing monthly mean rainfall rates (mm/day) based on data from 1990-2006 at Ruhija in the Bwindi Impenetrable Forest, Uganda

Analysis of the same data at daily resolution reveals startlingly different rainfall climatology suggesting far greater complexity is characteristic of the local climate system. The monthly averages from Bwindi clearly portray the annual bimodal seasonality in precipitation delivery, and suggest a relatively simple and well-defined hydrological system. In marked contrast, the sub-monthly patterns identify a remarkably robust intra-seasonal variability to precipitation, whereby both rainy seasons are revealed to be interrupted by intense maxima flanked by temporary minima (Figure 7). This in turn identifies the likelihood that there is far greater complexity to Albertine Rift regional climatology than can be represented in monthly statistics.

The exceptionally large-magnitude fluctuations in rainfall rate centered in early May and September are strongly evident in the daily and 7-day smoothed data, but entirely masked by averaging in the monthly means. Such signals might be of considerable importance in local ecology, yet would remain undetected using conventional climatological analysis as shown in Figure 6 above. Given the relatively short duration of the period considered, it is possible that these patterns are the products of statistical noise, rather than true climatological signals, and thus might smooth out given the expected stochasticity of tropical rainfall over longer time periods.

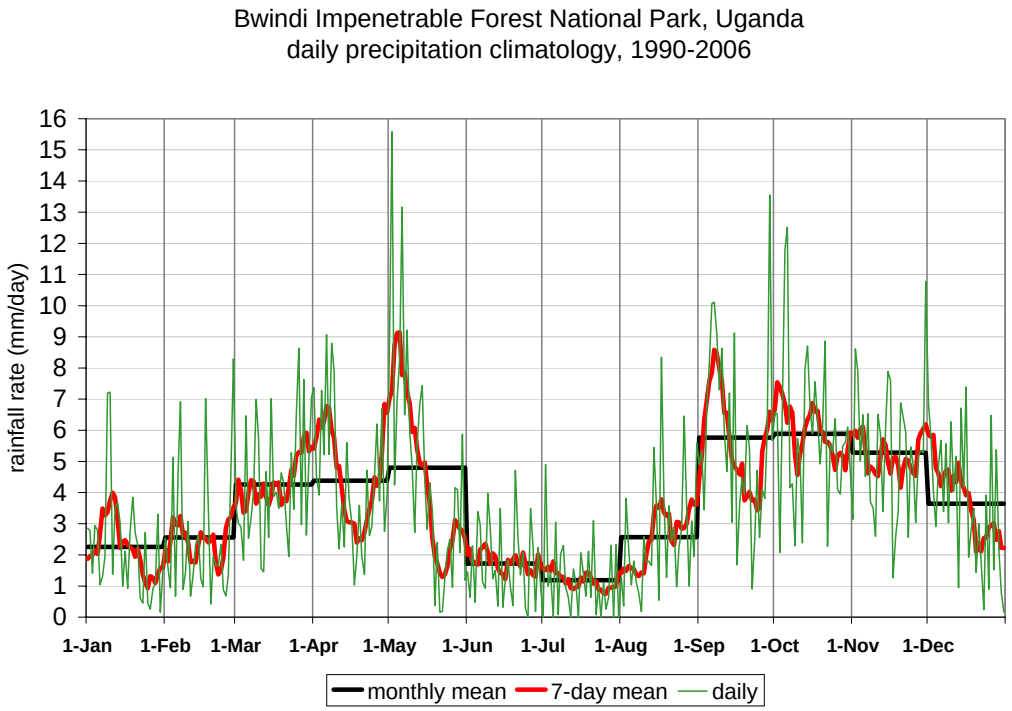

Figure 7: Pluviogram showing rainfall climatology for Bwindi at monthly and daily resolution for the period 1991-2006. The monthly data is the same as shown in Figure 6.

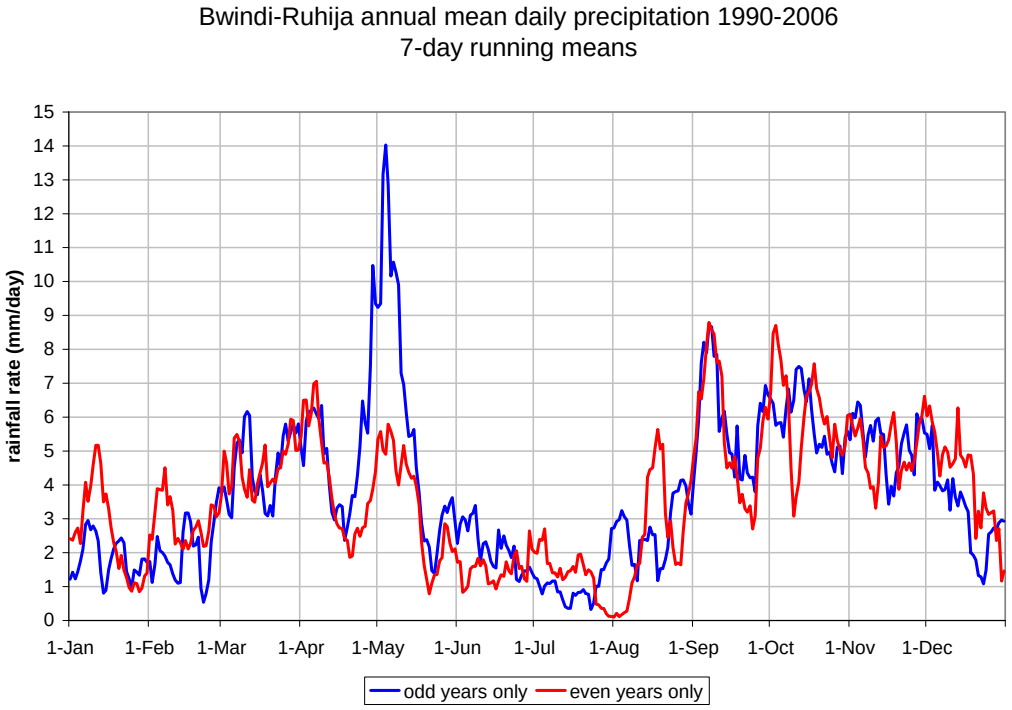

Figure 8: Bwindi 7-day running means of rainfall (mm/day) for the years 1990-2006 separated in odd and even years.

To examine this possibility, the rainfall data was divided into odd- and even-numbered years, as plotted in Figure 8. This showed that the anomalous signals were retained and synchronous in both data series, providing strong indication that the anomalous signals represent actual vs. accidental signals. Whereas the September peak is almost identical in both series, the early May maximum is greatly amplified in the odd year series.

Kibale National Park and vicinity

Also situated within the Greater Virunga Landscape sub-region, the Kibale region offers more than a century of climatological records available thus should offer one of the best opportunities for ascertaining long-term climatic trends and variability in the Albertine Rift. This region encompasses several of the most important protected areas of the Albertine Rift: Queen Elizabeth, Rwenzori, Kibale National Parks. Close to these is Fort Portal, where systematic climate monitoring was initiated by the British colonial government in 1903. Surprisingly however, analysis reveals rainfall trend signals that conflict with published reports, making coherent trends assessment problematic. A strong, multi-decadal increase in annual rainfall has been reported for the Kibale National Park-Fort Portal region based upon spliced data series (Struhsaker 2002, Chapman et al, 2005). We analyzed monthly records from Fort Portal and confirmed a slight increasing trend for the data period from 1903-71. However, a second data series from the Torokahuna Tea Estate that begins when the Fort Portal data ends shows declining rainfall for their period of record (1970-2008), as shown in Figure 9. This conflicts diametrically with the trends reported from Kibale National Park of strong increases in rainfall over the past several decades. Explaining these different signals is beyond the scope of the present analysis, but should be resolved to clarify whether regional patterns are indeed so disparate.

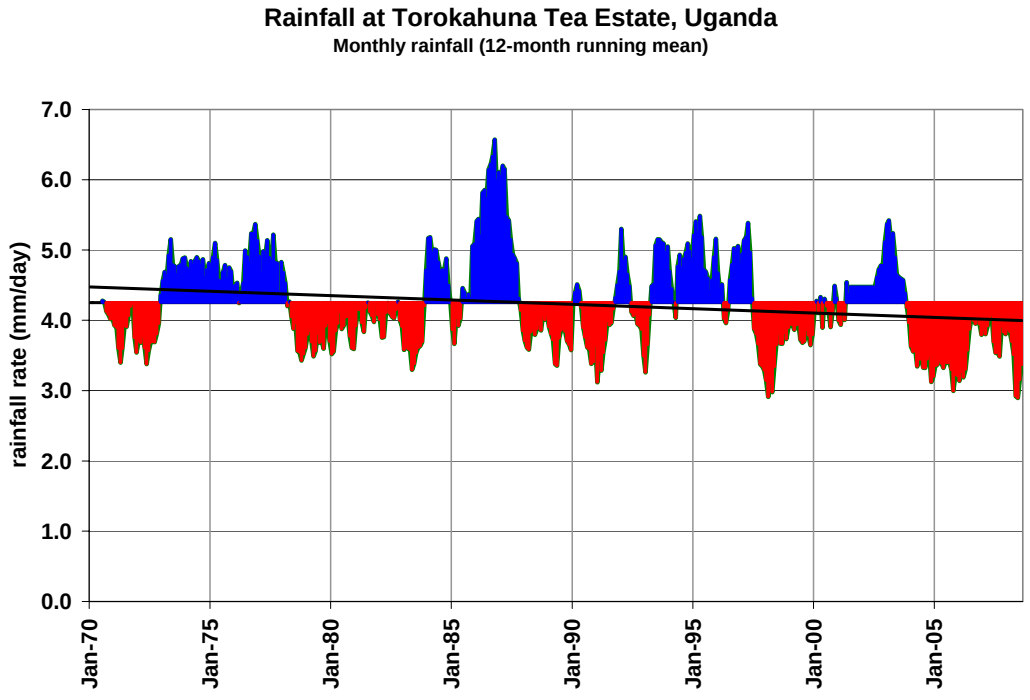

Figure 9: Inter-annual and multi-decadal trends in rainfall rate at Torokahuna Tea Estate near Kibale National Park, Uganda relative to the long-term mean based on monthly records from 1970-2008. Positive and negative rainfall anomalies are indicated by blue and red shading, respectively, while linear regression of the data is shown by the black trend line.

Sub-region II: Nyungwe, Rwanda

The Nyungwe National Park in the highlands of Rwanda occupies a central position along the Albertine Rift corridor. The discussion presented here is based upon climatological records from Uwinka inside the park covering the period 1996-2007. The period considered is too short to enable meaningful trend assessment, but generally high rainfall rates allow for an assessment of hydroclimatology suitable for comparison to downscaled climate model output. Recently, a research grade climate monitoring site was installed within the park for a carbon sequestration study, and a comprehensive climate monitoring protocol is additionally planned to being in 2010 as part of the Tropical Ecosystem and Monitoring (TEAM) initiative. Taken collectively, these resources will make Nyungwe a principal climate data collection and climate change assessment site for the future. Efforts should be made to uncover earlier records in and around the park.

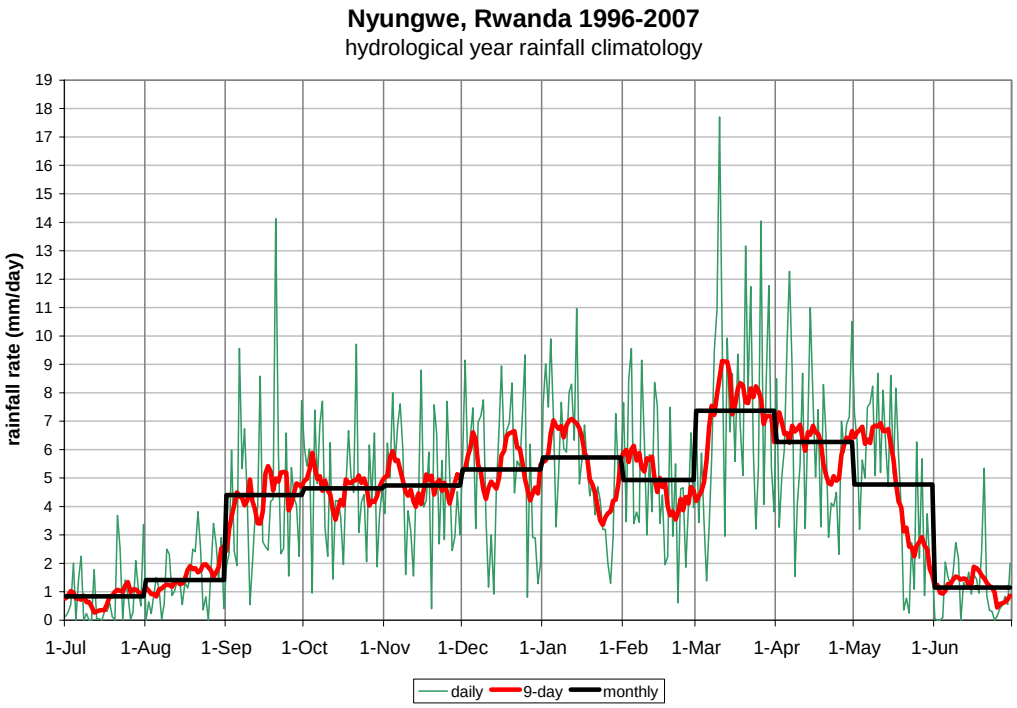

Figure 10: Rainfall climatology for the July-June hydrological year at Uwinka in Nyungwe National Park, Rwanda based on observations from 1996-2007.

Representing a blend of central and southern Albertine Rift climates, the July-June hydrological year at Nyungwe is characterized by a lengthy pluvial season of 8.5 months duration and dry season punctuated by intermittent rainfall (Figure 10). The wet season onset occurs abruptly around the first of September and dry season onset even more so, in the middle of May. Rainfall peaks in March, with rainfall rates of 8 mm/day sustained for much of the month. An interesting anomaly is evident from January through March when the increasingly wet tendency of the season is interrupted by two pronounced minima that precede the annual rainfall maximum. This likely reflects the nearby presence of a true dry season not far to the north such as shown from Bwindi in Uganda.

Daily maximum and minimum temperature data is also available from Nyungwe/Uwinka for 1996-2007. A high temporal resolution temperature climatology derived from this data show that the dry season features reduced maxima and minima, with annual minima for both recorded in July while

the sun is at zenith in the northern hemisphere. The rapid onset and cessation of the rainy season is only slightly reflected by perturbations in the thermal data (Figure 11).

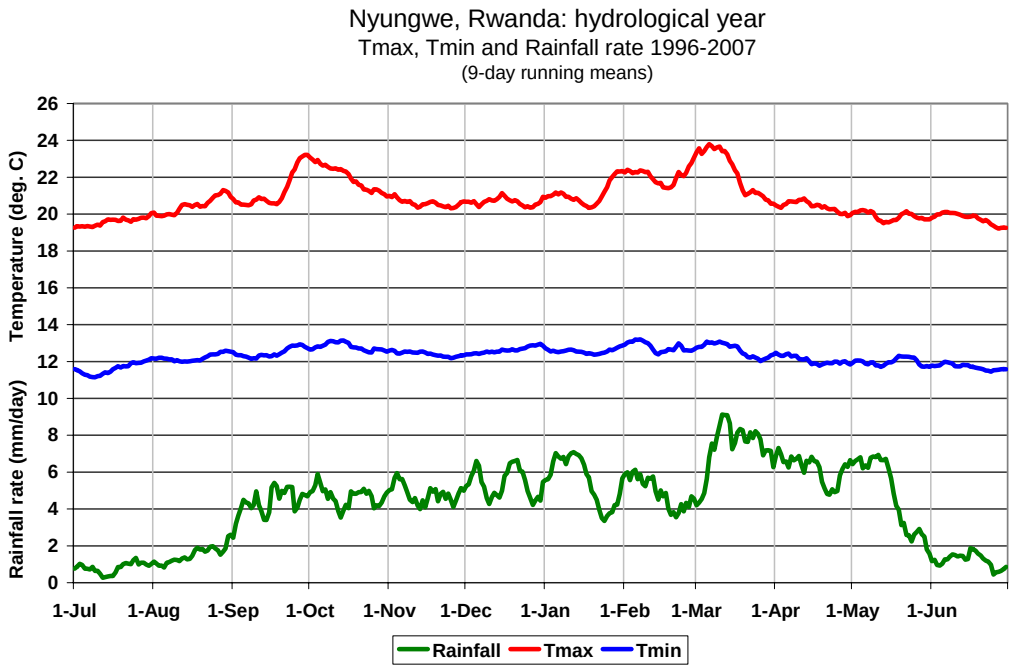

Figure 11: Climatogram displaying 9-day running means of maximum (Tmax) and minimum (Tmin) temperature and rainfall rate (mm/day) for Uwinka in Nyungwe National Park, Rwanda based on daily data collected from 1996-2007.

The most significant patterns are two pronounced multi-week positive departures in daytime temperature maxima that peak in late September and early March, respectively. These are striking for their relatively symmetry, their remarkable magnitude given the considerable elevation of the station, and for their occurrence during the highly pluvial months. These factors cast some doubt on the reliability of these observations. In a similar manner to the anomalous rainfall patterns discussed for the Bwindi case above, the daily data can be scrutinized to verify its reliability. Analysis of temperature shows that the anomalous thermal peaks correspond with wild swings in variance, which is only registered consistently around these times of year (Figure 12). We interpret this as evidence of twice annual interference on associated with the solar migration around the time of the equinoxes, bringing direct sunshine on or close to the thermometers. If true, this would represent systematic errors introduced by inappropriate siting of instrumentation. An image of the thermometer location taken in 2009 tends to support this assertion (Figure 13); on the other hand, a lesser positive anomaly in Tmax early in February correlates quite clearly with precipitation behavior at the time.

Fortunately, it should be a straightforward exercise to establish the reality of the diurnal temperature maxima behavior by correlating the Uwinka data when the new data stream from the carbon sequestration study site becomes available.

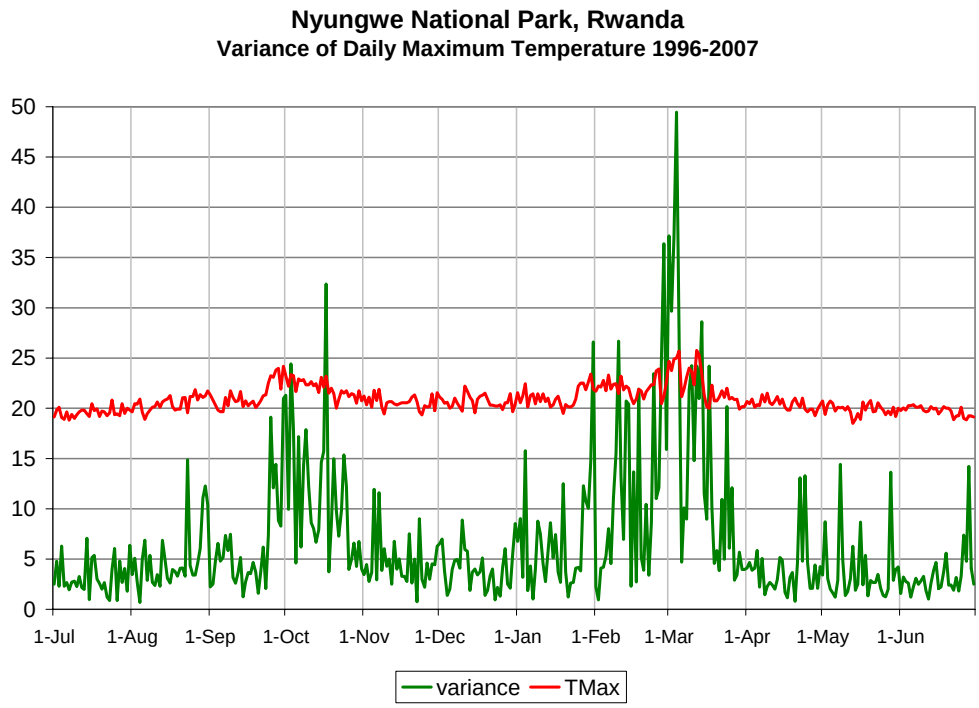

Figure 12: Nyungwe means of maximum temperature and variance of daily observations at Uwinka for 1996- 2007.

Figure 13: Climate observation sites at Uwinka in Nyungwe National Park, Rwanda. The thermometers are located on the window frame on the left side of the building, and therefore subject to interference including heating from solar absorption of the concrete floor and on the dark wall. (Photo: A. Plumptre)

Sub-region IV: Murchison-Budongo

This is the northernmost sub-region considered from the Albertine Rift domain, and is characterized by both extensive highlands flanking the rift valley and lowlands of the valley floor itself. The project obtained climate observations from two sites here, the lowland Semliki-Toro Wildlife Reserve and highland the Budongo Forest Reserve**.**

As with several other protected area data sets evaluated, the climate record from Semliki covers a short period only, though in this case there is the relative advantage of duplicate observations taken from two sites, helping to improve the representation. This is also needed in this case due to long lapses in sampling at one or both sites on several occasions. Despite these shortcomings with the data, a sufficient number of observations were available to reveal patterns suggesting highly defined, complex rainfall climatology might exist in this region (Figure 14). While additional years of data collection are required to validate this and refine the rainfall climatology, obvious similarities to the robust patterns already demonstrated from Bwindi of large magnitude, short-period maxima and minima and clearly evident and thus seem quite plausible.

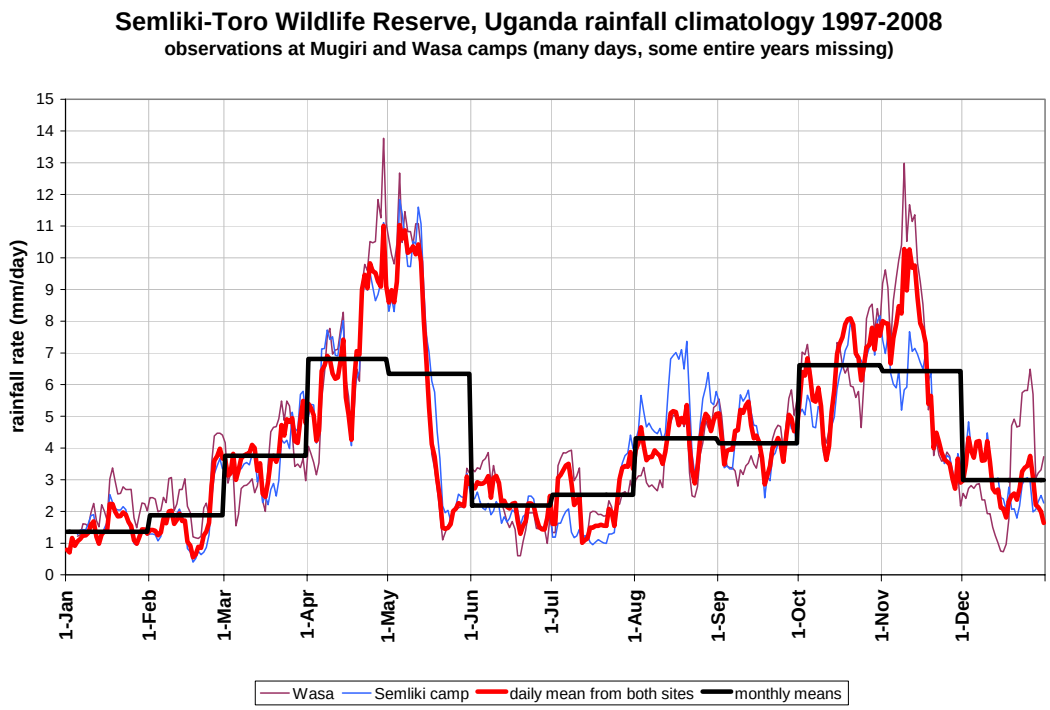

Figure 14: Rainfall climatology at Mugiri and Wasa in Semliki-Toro Wildlife Reserve, Uganda based on observations from 1996-2007.

The rainfall climatology from Budongo, developed with more complete records over a longer period, likewise exhibits a strongly bimodal rainfall climatology as seen at Semliki with less amplified short-period behavior (Figure 15). An interesting exception to this is found at the annual pluvial peak in October, which is split in two by a pronounced minimum of about a week's duration. The significance and cause behind this phenomenon is unknown, but again indicates unexpected complexity in local climatic behavior. Of note is that this short term anomaly is entirely unrepresented in the monthly mean data.

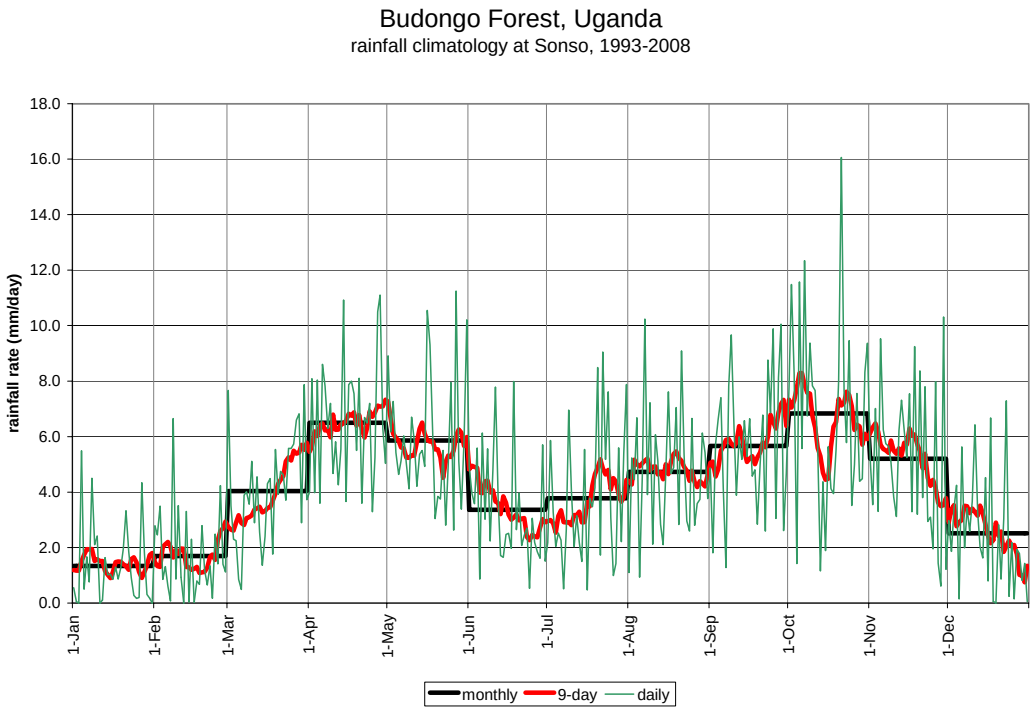

Figure 15: Rainfall climatology at Sonso in the Budongo Forest Reserve, Uganda based on observations from 1993-2008.

Sub-region VI: Mahale Corridors

The southernmost site with observational data available for climatological analysis is the Mahale National Park in southern Tanzania within the Mahale Corridor conservation landscape of the Albertine Rift. A high-quality data series of temperature and rainfall observations from Mahale from the period 1989-2009 is detailed here. As with Nyungwe in Rwanda, the southern location prescribes the use of the July-June hydrological year for better representation.

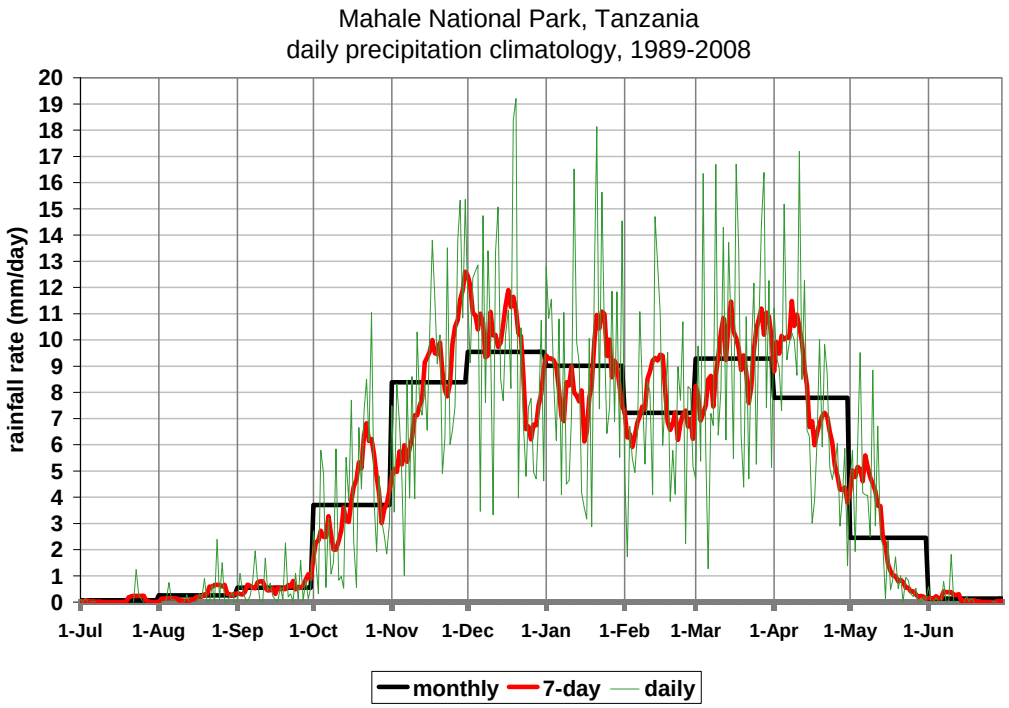

Figure 16: Hydrological year rainfall climatology showing monthly, 7-day and daily means recorded at Mahale for the period 1989-2008.

The hydrological year at Mahale is relatively unimodal, characterized by one long rainy season that begins in early October, followed by a shorter but significant dry season that begins abruptly in the middle of May and ends in early October (Figure 16). Wet season rainfall rates are high, with peaks above 10 mm/day during 3 multi-day periods between November and April. The highest rates occur early in the wet season, with 7-day running means reaching more than 12 mm/day around 1 December. The highest daily mean is an exceptional 19.2 mm/day on 20 December; this value would probably reduce closer to the mean given a period of measurements longer than 20 years. Of note, however, is that this peak is followed by a 10 day period of significantly reduced rainfall rates averaging close to 7 mm/day.

The Mahale precipitation data exhibits noteworthy inter-annual signals and trend behavior. Overall, the climate is very moist, whereby even the driest years have more than 1,000 mm of rain. The annual average is 4.85 mm per day, which is among the highest values recorded anywhere along the Albertine Rift. The patterns shown are noteworthy in displaying both pronounced inter-annual and decade-scale variability. The year to year variations are of high amplitude from 1993-2001, although the variability has become more moderate since then. Short period anomalies range from close to 50% above the mean (1997-1998) to about 33% below the mean in 1993 (Figure 17).

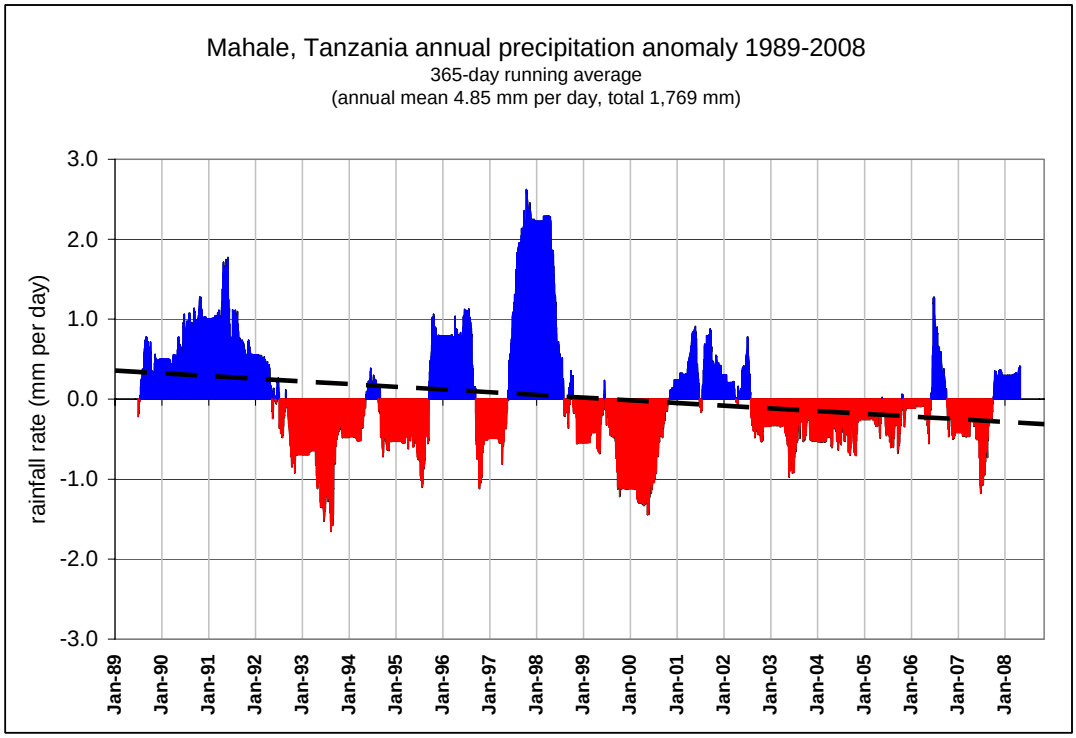

Figure 17: Daily rainfall departure from normal, where blue and red indicate above and below 1989-2008 annual mean values, respectively. The overall trend identified by linear regression is shown by the dashed line.

A consistent pattern reflecting ENSO variability is not apparent, although the extremely wet period in 1997-98 was experienced throughout eastern Africa, and is undoubtedly related to the extremely strong warm-ENSO event in the tropical Pacific Ocean at that time (Anyamba et al., 2002). This is the most anomalous hydrological year in the Mahale time series. The decadal variability is interesting, although the period of record is not long enough to make any clear determinations about its significance. The data suggests that wet and dry years tend to occur in short sequences. There is an overall tendency towards a drier climate, which matches projections for the future by many global climate models for southern Tanzania. The drying trend shown by the dashed line in the figure is occurring at a rate of -0.032 mm/day, equivalent to -11.68 mm per year. If this trend is sustained into the future, ecological consequences should quickly become apparent.

Splitting the hydrological year pluviogram into two equal-length periods suggests that during the past 20 years the rainy season has on average decreased in length by several weeks, and has significantly more rainfall occurring during the first peak of the wet season in November-December, and significantly less rain occurring in the third peak from mid-February through mid-April. These signals are quite clearly defined and are suggestive of a shift in distribution of rainfall during the hydrological year, as well as the overall reduction shown in the trend diagram above (Figure 18). However, the time period is too short to draw any conclusion regarding whether this represents true climate change versus cyclical behavior from decadal climatic variability.

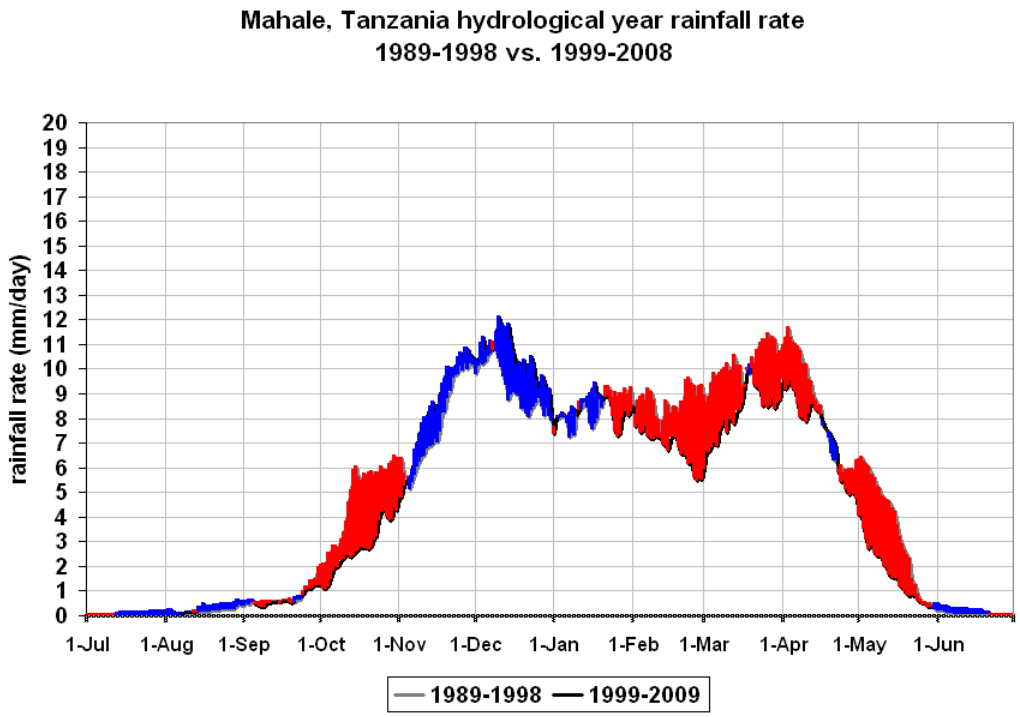

Figure 18: Hydrological year daily rainfall rate at Mahale smoothed by applying a 21-day running mean for the 10-year periods 1989-1998 and 1999-2008. The color shading indicates a shift from wetter to drier (red) and drier to wetter (blue) from the earlier to the latter period.

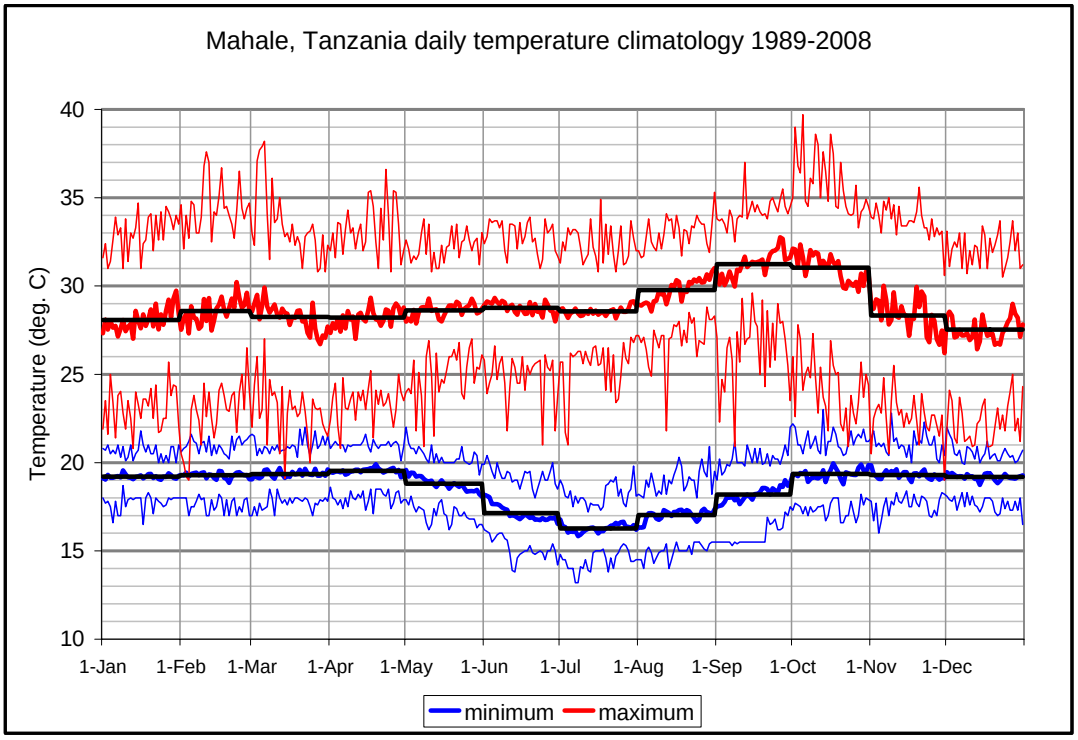

Figure 19: Climatology of daily mean and extreme temperature maxima and minima from Mahale observed for the period 1989-2008. Monthly representations of the means are provided for both maximum and minimum.

The annual cycle in maximum and minimum temperature at Mahale exhibits strong seasonality that is more typical of a subtropical location. Diurnal maxima peak ahead of the onset of the wet season following the September equinox as the sun cross to the Southern Hemisphere before cloud cover increases (Figure 19). Monthly mean values represent thermal minima behavior very well, but for diurnal maxima important short-period detail is lost through averaging. Pronounced short period departures are apparent in late March and September, attended by cool and warm conditions, respectively. The thermal maximum preceding the October wet season onset is likely to be highly significant to ecology and phenology, yet also highly prone to perturbation. An early or delayed onset of moisture import into the region heralding the start of the wet season would have major impacts on temperature at this time of year when, it follows, is the time of greatest hydrological stress following several largely rain-free months.

Time series of maximum and minimum temperature anomalies are highly informative when viewed side by side with a common scale. It becomes clearly evident that high and low temperature trends are largely independent of one another. Daily minimum temperature anomalies rarely exceed +1° or -1°C, and suggest a warming trend since 1989 although two colder than normal years in 2006 and 2008 interrupt this trend at the end of the record. Daily maximum temperature anomalies exhibit far greater variability from their mean values than the minima; this likely reflects a strong dependence on rainfall and cloud cover variability, whereby cloud-free days register much warmer than days with extensive cloud cover. This could be verified with daily observations of solar radiation at the climate station site.

An objective for further work should be to understand the regional controls of cloud cover in the Mahale region. The maxima also display strong year-to-year continuity with alternating periods of positive and negative anomalies being maintained for several years in a row. It is important to note that the amplitude of maximum temperature variability (7°C, from +4° to -3° degrees) in terms of departures from the 20-year daily means exceeds all but the most severe projections of temperature change resulting from greenhouse gas-induced warming in global climate models. This suggests that the observing site might be amplifying maxima on days with strong sunshine. Should this indeed be the case, from a climatological perspective this would be an observational error that would render maximum temperature data invalid. However, from an ecological perspective it might still be of value since the observations might actually offer an indication of incident radiation as well as temperature. A simple method to test this would be to have a second thermometer located close by in a fully shaded location to enable a comparison of temperature maxima on sunny and cloudy days.

4c. Albertine Rift region climate prediction

In this section we present composite plots of climate parameter changes for the Albertine Rift project domain as developed from downscaled GCM output for this project. These are displayed as monthly mean change relative to the baseline conditions displayed Figures 3-5 from section 4a.

Several steps were required to generate the climate model products utilized in this study. Output from low resolution GCM multi-model global ensembles were extracted for the Albertine Rift region for the period 1990 – 2090. The data extracted were the monthly means calculated from the raw GCM output data for 10 years either side of the year of interest. These datasets were used as input to a statistical downscaling procedure which produced a set of medium resolution climate model data for the same period with a spatial resolution of approximately 50 km. These datasets were used in their raw state to provide predictions of climate in the Albertine Rift at 2030, 2060 & 2090. The 20-year monthly means were developed to eliminate single year anomalies that may occur in model simulations. For example, the value that is provided in the data for January temperature for the year 2060 is actually the mean value of temperature in January for all the years between 2050 and 2069. As such, parameters values for a given year were calculated over the following periods shown in parentheses: for 1990 (1980–1999); for 2010 (2020-2039); for 2060 (2050-2069) and for 2090 (2080–2099).

When evaluating the GCM-derived products, it is important to consider the many caveats associated with the use of this GCM depictions of the future, among which are that:

- GCM accuracy and representation are uncertain and of coarse resolution
- GCMs are far from consistent in depicting common climatic outcomes
- Emissions scenarios are mere guesses of unknowable future anthropogenic forcings
- Non-greenhouse gas climate forcings, especially those related to anthropogenic land cover modification, are significantly underrepresented in GCMs (e.g. Paeth et al 2009)

Therefore, in presenting the climate modeling content and its often compelling, at times alarming, predictions, we also need to convey a high degree of caution regarding use of the information. This and related issues are elaborated further in the companion study.

Summary statistics of the three parameters assessed averaged over the project domain are presented below in Table 1.

		1990	**2030**	**2060**	**2090**	
Mean annual temperature	*Max*	26.0	27.0	28.1	29.7	°C
	Mean	**22.7**	**23.6**	**24.7**	**26.3**	
	Min	15.0	16.0	17.1	18.7	
Mean annual precipitation	*Max*	1887	1900	1968	2098	mm
	Mean	**1199**	**1233**	**1287**	**1406**	
	Min	821	875	938	1057	
Mean annual cloud cover	*Max*	82.6	82.4	81.7	81.9	%
	Mean	**67.2**	**67.4**	**66.9**	**67.1**	
	Min	42.4	43.2	43.2	43.4	

Table 1: Domain-averaged statistics for the project time steps.

Precipitation

In the A2 model simulations, precipitation changes are both highly significant and spatially heterogeneous across large parts of the Albertine Rift domain during the course of the 21st century (Figure 21). At regional scales two patterns of change stand out. The first is an overall increase in net annual precipitation. Relative to the 1990 baseline, rainfall increases by 3%, 7% and 17% in 2030, 2060 and 2090, respectively. The second pattern is temporal redistribution in the annual fraction of rainfall associated with the twin wet seasons that characterized rainfall over much of the Albertine Rift. The model output indicates that the largest increases in rainfall amount will occur from mid-century onward, when a large increase in the magnitude of November-December rainfall will occur while little net change is evident in the March April period.

Redistribution in annual rainfall concordant with this pattern is already apparent at Mahale on Lake Tanganyika, though whether this represents early establishment of the pattern depicted in the model output or simply climatic variability cannot yet be ascertained.

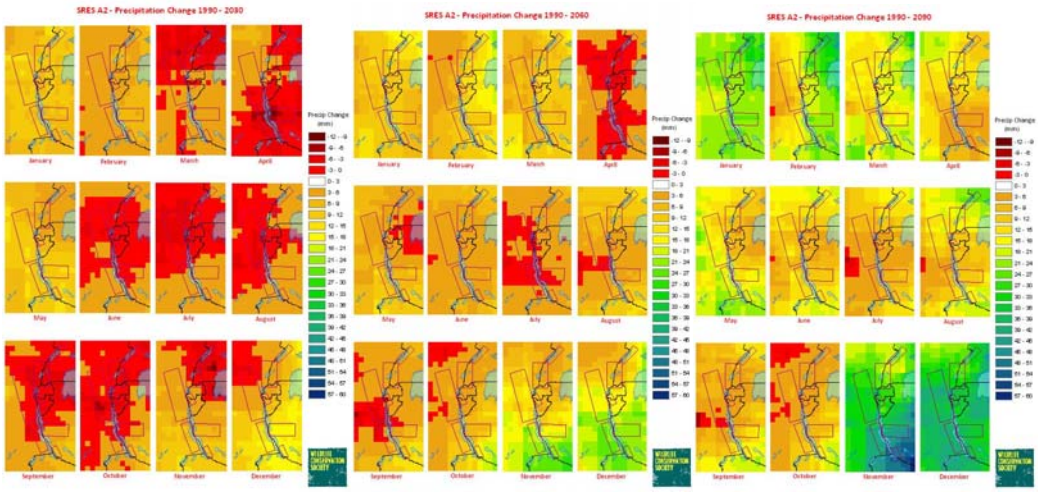

Figure 21: Downscaled GCM predictions of monthly mean cloud cover change over the Albertine Rift project domain for the benchmark years 2030 (left) 2060 (center and 2090 (right)

Cloud Cover

In the A2 model simulations, net cloud cover across the Albertine Rift domain remains almost invariant around 67% for all years assessed, but spatial changes nonetheless are significant and increase markedly during the course of the century as internal redistribution of cloudiness patterns develop (Figure 22). Monthly cloud cover changes mostly fall within the range of +/- 2% in 2030 relative to the 1990 baseline, though with some spatial coherence indicating slight moistening in the south and drying in the north. More significant changes become apparent by 2060, when cloud cover reduction of 3-5% in April and May are widespread in the north, suggesting that the wet season termination will tend to occur earlier in the season over time. By 2090 cloud cover during the April wet season peak is reduced region wide, indicative of the trend towards a drier season evident in precipitation amount too. A large departure relative to the present is also depicted for 2090 in the months of November and December throughout the southeastern part of the domain. Here, cloud cover increases significantly, by more than 5%, in association with greatly increased rainfall, yet these factors nonetheless fail to dampen the magnitude of thermal increase which is still more than 3°C above the 1990 baseline.

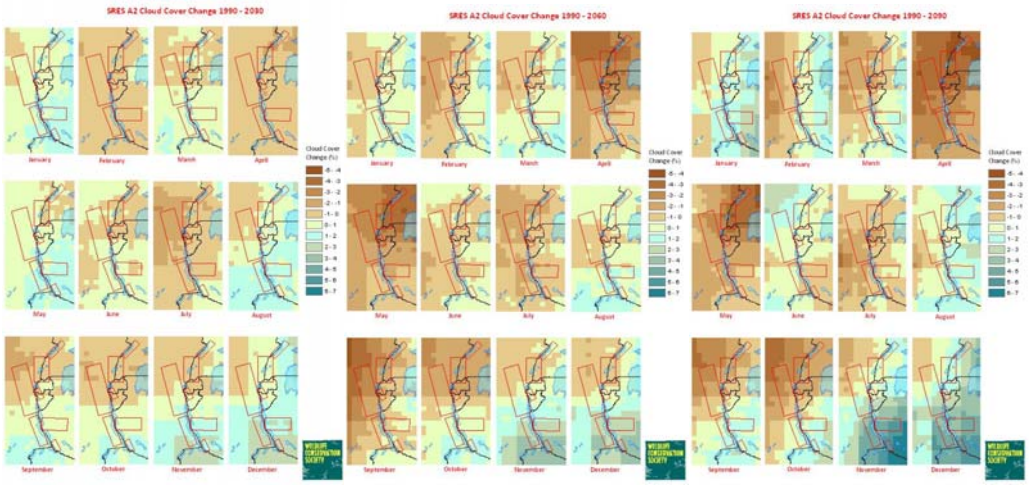

Figure 22: Downscaled GCM predictions of monthly mean cloud cover change over the Albertine Rift project domain for the benchmark years 2030 (left) 2060 (center and 2090 (right)

Temperature

In the A2 model simulations, temperature increases are significant and occur at an accelerating pace across the Albertine Rift domain during the course of the 21st century. It is noteworthy that temperature extrema in the mapped domain increase at the same rate as the domain-averaged mean (Figure 23). This identifies unambiguously that no locales will remain unaffected by strong and sustained warming relative to current conditions.

Given that temperature change as a function of elevation in tropical atmospheres average 5-6°C per km, the net region-wide thermal increase of 3.6°C under the A2 scenario translates to a very large upward displacement of 600-720 meters.

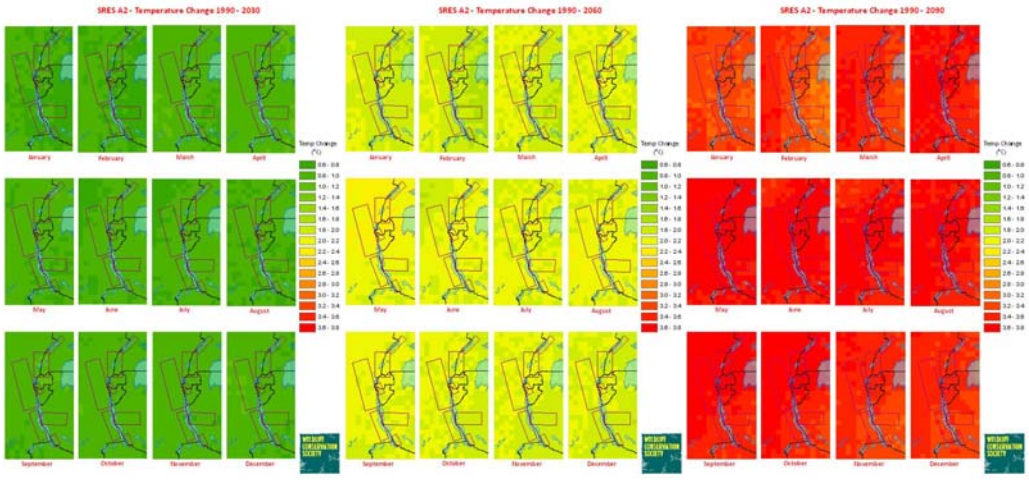

Figure 23: Downscaled GCM predictions of monthly mean temperature over the Albertine Rift project domain for the benchmark years 2030 (left) 2060 (center and 2090 (right)

5. Discussion

A comprehensive understanding of Albertine Rift climatology increases the potential for proactive versus reactive conservation management responses to threats and opportunities borne by climate change. Modeling approaches and capabilities are powerful tools, and as such are having the inevitable consequence of shaping how we view and understand climate change impacts and threats. In such depictions of the future, climate is often conceptually conflated into temperature and hydrological changes alone; other factors are only considered when specific objectives or concerns are tied to them. In contrast, improved understanding of present day climatology can improve comprehension of climate changes ongoing and those projected for the future. Fundamental to this is appreciation that important unknown and unrecognized elements of contemporary climate exist in the Albertine Rift as for almost any geographic context in tropical Africa, and that such factors might prove to be of major significance and most prone to perturbation as a consequence of anthropogenically forced climate change.

With the high degree of conservation and development attention focused on both wildlife and people in the Albertine Rift, it is surprising to find that understanding of the area's climatology is still largely undeveloped. When considered at all, climatic variability is assessed in terms of deficits or surpluses of net precipitation over monthly, seasonal or annual basis. Given the assumed simplicity of the equatorial climate system, little value is expected to be derived from assessing climatology at more focused time scales. However, as shown in this study when rainfall data is analyzed at daily time scales, robust and distinct climatological patterns become apparent, the knowledge of which could be of potential utility to a multitude of interests were they more widely known. The full ecological significance of these patterns in the Albertine Rift remains to be determined. But their identification here is also an invitation to reconsider climate change in contexts of far shorter-term and more spatially constrained phenomena than generally considered. For example, could climate models be studied for more meaningful guidance on durational changes in the annual wet and dry seasons, the timing and quantity aspects of rainfall maxima and minima, and identification and trend detection in short-period recurrent phenomena, such as the rainfall patterns demonstrated here from Bwindi, Nyungwe, Mahale, Semliki and Budongo? These are not merely concerns over minor details: such questions address climatic factors that strongly influence a wide variety of environmental and socioeconomic outcomes.

Having foresight of such climatic changes could become integral in conservation and development strategies for the region. At present, however, due in part to the format of the model output available, climate prediction are still mostly presented as changes in aggregated quantities; e.g. across Region X climate models depict reductions in rainfall of 20% by year Y. While such conventions are maintained in the this study and its companion report on environmental modeling, we have also made efforts to diversify the suite of parameters evaluated and provide detail on seasonality to monthly resolution, all of which makes the GCM output utilized far more ecologically relevant (see Picton Phillips and Seimon 2009). The "area under the curve" summary statistics are prevalent in climatological assessments and predictions alike, though it becomes a challenge to translate any single parameter value into ecological outcomes. But what potential users of this information are likely to be more concerned with is the *shape* of the curve and its *placement* along the calendar timeline, as well as the *net* quantity, hence the efforts made in this project's modeling component to examine monthly as well as annually aggregated model output data.

The model projections we have generated for Albertine Rift are already highly informative in this regard, yet still relatively crude compared to what might be possible if climatology at daily resolution could be meaningfully predicted for the future. It is possible that modeling has already

progressed to a point whereby regional climate models can reproduce such climatological detail in output generated for contemporary climate if assessed at daily resolution. If so, it would be of great interest to examine the temporal evolution of such characteristics into the model's depictions of the future for the Albertine Rift. In a marginal rain-fed agricultural landscape, a shift by several weeks in the start and/or end date of the rainy season, and the timing of its pluvial peak, might prompt a shift in the choice of cultivars planted by farmers or cross a threshold favoring pastoralism over cultivation. In a moist tropical forest these patterns might shift the phenology for flowering and fruiting of forest species that are food sources for primates, birds and many other taxa. Such changes hold high potential to introduce a host of cascading effects such as changes to the timing of visitation by migrant species and increasing asynchronies among symbiont species.

Observationally based climate change assessment

Therefore, there exists considerable potential for site-specific climatological assessments to rectify incomplete or simplistic understanding of climate within Albertine Rift conservation and other sustainable development and conservation contexts. This would in turn yield corollary improvements in stakeholder capacity to anticipate and plan for climate change in truly meaningful ways. Interests concerned with conservation management, research and planning more generally could examine the basis for current knowledge of a locale's climatology by addressing the following:

1. Determine if the local climatological context been developed from site-specific assessments or from generalizations based upon broader scale studies. If assessments are available, were they perfunctory studies or conducted with diligence?
2. Evaluate the data used in these determinations. Sometimes this will amount to asking if actual climatological data was used in the determinations at all.
3. When possible, inquire of those with local knowledge of the particularities of the climate from their perspective, and consider how well this information matches that discussed in published reports and analyses.

Then, to improve the level of understanding and improve prospects for proactive adaptive management, the following actions might be considered:

1. Searching for climatological data from the region of interest, both from conventional climate archives (e.g. http://www.ncdc.noaa.gov/oa/climate/ghcn-monthly/index.php; http://iridl.ldeo.columbia.edu/), but also from local observational sites and networks.
2. Prioritize analysis of daily observations over summary statistics derived from daily records.
3. Include a climatologist or other specialist with requisite experience in working with "raw" climatological data.
4. After error checking, perform climatological analysis designed to address ecological and conservation-focused questions.
5. Generate and evaluate climate model output designed to address the same ecological questions.
6. Develop planning scenarios for climate change informed by well developed, site-specific understanding of the relationship between contemporary climatology and ecology that incorporate climate model products as guidance, rather than as specific forecasts of changes to come.

6. Future Work

Analysis

In terms of regional ecology and phenology, and therefore for conservation as well, the intra-seasonal precipitation patterns identified in this study are likely of considerable significance, yet this information is effectively lost when only the monthly means are considered. Such patterns may also present targets for representation by climate models, both for validation of past and present climate behavior, and also as means of diagnosing change in projections of the future. Analysis on observational data sets should therefore be expanded and extended to point-specific global and regional climate model output, which could be examined for inference on climatic behavior such as:

- Modal behavior - at what specific times of year do intra-seasonal maxima and minima in precipitation amount occur, and what is the inter-annual distribution of these modes in terms of timing and amplitude?
- Intra-seasonal patterns - do high-amplitude, short-term variations in daily precipitation rate occur on a regular basis at specific times each year? The existence of such behavior might identify climatological triggers of phenological patterns.
- Precipitation intensity - how does the fraction of heavy versus light precipitation amount vary through time?
- Dry season duration - can the specific number of days be determined for each dry season to ascertain trends over time?
- Trends - can changes over time be identified for the patterns above?

Such levels of detail require temporal resolution in the data – and in climate modeling output – more precise than monthly increments. Therefore, for the baseline analysis that will serve for comparison to future climate change scenarios, effort must be placed in obtaining long-term daily precipitation measurements along the Albertine Rift corridor, and especially where climate station data has been collected within protected areas.

Monitoring

Climate monitoring in Albertine Rift protected areas, where available, is presently performed inconsistently, often with sub-standard instrumentation and lacking the systematic methodologies and instrument calibration that make inter-site data comparison possible. Even at research sites where efforts have been made to utilize digital sensors, economic considerations have led researchers to utilize lower-cost instrumentation with short life-spans, resulting in truncated or discontinuous data series.

With support being provided by the John D. and Catherine T. MacArthur Foundation, from 2010-12 WCS will begin to address this by installing research quality automated weather stations at principal long-term research sites within Albertine Rift protected areas as well as on high mountains, where we will also initiate concurrent long-term vegetation monitoring. Wherever possible, instrumentation will be co-located with existing monitoring equipment to establish continuity with existing records; both systems should run concurrently for at least one year to establish parameter relationships between new and old records. Protected areas where we intend to implement systematic climate monitoring include: Murchison Falls National Park, Uganda; Queen Elizabeth National Park, Uganda; Rwenzori National Park, Uganda, Virunga National Park, DR Congo; Volcanoes National Park, Rwanda; Kahuzi Biega National Park, Congo; Mahale Mountains National Park, Tanzania; and Itombwe Massif, Congo. Complementary high-quality climate data collection directed by WCS is now scheduled to begin at four other sites to be instrumented as part of Tropical Ecosystem and Monitoring (TEAM) network at Bwindi Impenetrable Forest and Kibale National Parks, Uganda, Ituri Forest, DR Congo, and Nyungwe National Park, Rwanda), and will thus become part of the climate monitoring network.

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