Tyndall°Centre
for Climate Change Research

RAINFALL AND WATER RESOURCES VARIABILITY IN SUB-SAHARAN AFRICA DURING THE 20TH CENTURY

Declan Conway, Aurelie Persechino, Sandra Ardoin-Bardin,
Hamisai Hamandawana, Claudine Dieulin and Gil Mahe

July 2008

Tyndall Centre for Climate Change Research Working Paper 119

RAINFALL AND WATER RESOURCES VARIABILITY IN SUB-SAHARAN AFRICA DURING THE 20^{TH} CENTURY

Declan Conway[1, 2*], Aurelie Persechino[1], Sandra Ardoin-Bardin[3], Hamisai Hamandawana[4], Claudine Dieulin[3], Gil Mahe[3]

[1]School of Development Studies and [2]Tyndall Centre for Climate Change Research, University of East Anglia, Norwich, NR4 7TJ, United Kingdom
[3]UMR HydroSciences Montpellier, IRD, BP 64501, 34394 Montpellier cedex 5, France
[4]Department of Geography and Environmental Sciences, North West University, Republic of South Africa.

[*]Corresponding address and email:
School of Development Studies, University of East Anglia,
Norwich NR4 7TJ, United Kingdom.
d.conway@uea.ac.uk

Abstract*

River basin rainfall series and extensive river flow records are used to characterise and improve understanding of spatial and temporal variability in sub-Saharan African (SSA) water resources during the last century. Nine major international river basins (comprising ~32% of SSA's area), chosen primarily for their long good quality flow records are examined. A range of statistical descriptors highlight: substantial variability in rainfall and river flows (e.g. differences in rainfall [flows] of up to -14% [-51%] between 1931-60 and 1961-90 in West Africa); marked regional differences; and modest intra-regional differences. On decadal time scales sub-Saharan Africa exhibits drying across the Sahel after the early 1970s, relative stability punctuated by extreme wet years in East Africa, and periodic behaviour underlying high interannual variability in Southern Africa. Central Africa shows very modest decadal variability with some similarities to the Sahel in adjoining basins. No consistent signals in rainfall and river flows emerge across the whole of SSA.

Detailed analysis of rainfall-runoff relationships reveals varying behaviour including: strong but non-stationary relationships (particularly in West Africa), many basins with marked variations (temporal and spatial) in strength, weak almost random behaviour (particularly in Southern Africa), and very few strong, temporally stable relationships. 20-year running correlations between rainfall and river flow tend to be higher during periods of greater rainfall station density, however, there are cases where weak (strong) relationships exist even with reasonable (poor) station coverage. Non-stationary behaviour in West African rivers is associated with Sahel desiccation and primarily reflects the non-linear runoff response to rainfall, but may include some effects from changes in land cover. We conclude for SSA that robust identification and attribution of hydrological change is severely limited by data limitations, conflicting behaviour across basins/regions, low signal-to-noise ratios, sometimes weak rainfall-runoff relationships and limited quantification of the magnitude and potential effects of land use change and other anthropogenic influences. We identify a clear need to integrate better understanding of biophysical drivers of variability (e.g. ENSO, Sahelian desiccation) with actions to strengthen the capacity of African water managers to deal with climatic variability and extremes.

Tyndall Working Paper No. 119, July 2008. Please note that Tyndall working papers are "work in progress". Whilst they are commented on by Tyndallresearchers, they have not been subject to a full peer review. The accuracy of this work and the conclusions reached are the responsibility of theauthor(s) alone and not the Tyndall Centre.

---

[*] A version of this paper is in press as: Conway, D. Persechino, A., Ardoin-Bardin, S., Hamandawana, H., Dieulin, C. and Mahe, G. (2008) Rainfall and water resources variability in sub-Saharan Africa during the 20th century. Journal of Hydrometeorology.

1. INTRODUCTION

1.1 The significance of water resources variability in Africa

Rainfall and river flows in Africa display high levels of variability across a range of spatial and temporal scales with important consequences for the management of water resource systems. Studies by Sutcliffe and Knott (1987), Grove (1996), Laraque et al. (2001), Conway (2002), Ogutunde et al. (2006) and Hamandawana (2007) demonstrate that high levels of interannual variability exist in many African river basins. Throughout Africa this variability brings significant implications for society and causes widespread acute human suffering and economic damage (Conway and Hulme, 1996; Mahe and Olivry, 1999). Water scarcity is also a growing concern in many parts of semi-arid Africa (Falkenmark, 1991; van Jaarsveld and Chown, 2001; Hellmuth, et al., 2007). Examples of variability include prolonged periods of high lake levels and flows of rivers draining large parts of East and Central Africa (Conway, 2002), and multi-decade anomalies in river flow regimes in parts of West Africa, where long term mean yields of freshwater into the Atlantic Ocean fell by 17.6 per cent between 1951-1970 and 1971-1989 (Mahe and Olivry, 1999).

Non-stationary behaviour in rainfall and river flows undermines traditional methods of water resource management. There are clear examples of the challenges posed by water resources variability in Africa: Lake Chad fisheries (Sarch and Allison, 2000); reservoir management on the Senegal River (Magistro, 2001); balancing supply and demand for Nile water in Egypt (Conway, 2005); irrigation management in Greater Ruaha River in Tanzania (Lankford and Beale, 2007), and hydropower generation in the Kafue (Sutcliffe and Knott, 1987) and Lake Victoria basins (Tate et al., 2004). Economic modelling of the economy-wide impacts of hydrological variability in Ethiopia demonstrates significant effects on projections, including lower rates of economic growth and increased poverty rates over a 12 year period (World Bank, 2006).

As anthropogenic climate change becomes increasingly manifest the prospect of shifts in flows and variability underscores the need for better understanding of the drivers of variability, rainfall-runoff interactions and their management context. It is likely that extreme events are going to be the greatest socio-economic challenge. Whilst sub-Saharan Africa (SSA) is generally associated with drought related impacts anecdotally there appears to be greater frequency and spatial extent of damaging floods, particularly in East Africa and Ethiopia (e.g. 2006 and 2007). Major floods, for example, have caused socio-economic disruption in Mozambique, 2000 (Christie and Hanlon, 2001) and East Africa, 1961, 1978 and 1997 (Conway, 2002), whilst smaller floods may be somewhat overlooked but locally significant, for example in Nigeria (Tarhule, 2005). In late 2006, early 2007, floods of unprecedented spatial extent (and timing) occurred across Somalia, Ethiopia and other parts of East Africa which is broadly in line with projections in the Intergovernmental Panel on Climate Change's (IPCC) Fourth Assessment Report for increases in autumn and winter rainfall (Christensen et al., 2007). From a scientific standpoint it is unfortunate that floods also disrupt and destroy valuable equipment and disrupt monitoring sites with implications for water resources management.

Efforts to reduce Africa's exposure and sensitivity to climate variability have to begin with analysis of recent events to identify barriers to their effective management. Success in this endeavour will be closely related to scientific and social capacity to anticipate climatic hazards, deliver effective support when they occur, and learn from these experiences. Improving capacity to do this in Africa is a pre-requisite for successful adaptation to climate change, however, in this paper we focus primarily on improving our understanding of the biophysical drivers of variability.

1.2 Drivers of water resources variability

The main driver of much of the observed variability in river flows is of course rainfall, particularly at the scale of large river basins (see Hulme et al. 2001 for African overview). Above average and sometimes extreme rainfall in East Africa tends to be associated with periodic circulation dipole events in the Indian Ocean and complex interaction with the El Niño-Southern Oscillation (ENSO), particularly during the short October-December rains (Saji et al., 1999; Webster et al., 1999). The large decline in many West African river flows is primarily related to the effects of the prolonged drying in the Sahel (late 1950s to late 1980s), with conditions still drier than during the humid 1950s (L'Hôte et al., 2002; Dai et al., 2004), though there are exceptions (Nicholson, 2005).

Nevertheless; in spite of the large influence of rainfall fluctuations on river flow variability, the response may be influenced by other factors such as changes in land use or land cover: For example, in the Sahel/West Africa (Mahe et al., 2005, Li et al., 2007 and Leblanc et al., in press) and Southern Africa (Troy et al., 2007; Woyessa et al., 2006; Lørup et al., 1998). Human abstractions and reservoir construction also play a role (Vörösmarty and Sahagian, 2000; Hamandawana et al., 2007a), along with land surface to atmosphere feedbacks (Savenije, 1996).

Depending on the actual hydrological conditions, the effects of rainfall variability on the hydrologic response will generally translate into smooth and delayed responses in lake and wetland systems, while semiarid river basins often exhibit low runoff coefficients and high sensitivity to rainfall fluctuations (Nemec and Schaake, 1982; Li et al., 2005; McMahon, et al., in press). In addition, the nature of the land surface itself may increase the variability of river flow responses to rainfall fluctuations. Peel et al. (2001; 2004) examine differences in the temporal behaviour of rainfall and river flow between continents and show that variability of annual river flows is higher for temperate Australia, arid Southern Africa and temperate Southern Africa than for other continents with similar climatic zones. Along with rainfall variability they found that the distribution of evergreen and deciduous vegetation in temperate regions was a potential cause of greater river flow variability. Vörösmarty et al. (2005) found interesting features of African river systems by combining biophysical and social data sets to show that population distribution is strongly concentrated in regions exposed to high levels of interannual variability in rainfall and runoff.

1.3 Aims

Whilst lots of evidence exists for high interannual and decadal variability in rainfall and river flows in SSA there are few detailed studies of their spatial and temporal co-variability. Previous attempts to estimate runoff at this scale have been based on the limited data available through international bodies: none have undertaken detailed rainfall-runoff analysis at the basin and subbasin scale or taken a long historical perspective to incorporate natural variability over decadal and century timescales. Rather surprisingly, SSA provides one of the best opportunities globally to do this type of analysis, as many of the very large river basins possess long relatively natural river flow records. We combine extensive databases held by international and national agencies to build a comprehensive picture of hydrometeorological variability during the 20th century in large river basins comprising roughly 32 per cent of SSA's area. Our overarching aim is to contribute to the scientific understanding of variability in large water resource systems. First we characterise the spatial and temporal dimensions of rainfall and river flow co-variability across the region during the 20th century and second, we examine the characteristics and stability of rainfall-runoff relationships over time.

2. DATA SETS: IDENTIFYING RIVER BASINS AND REGIONS FOR THE ANALYSIS

2.1 Data Sources

We utilise river flow observations recorded over the period 1901-2002. These were mainly provided by IRD of Montpellier for the West and Central African regions and from a range of international and national sources for the East and Southern African regions. The data provided by IRD come primarily from the SIEREM database ("UMR HydroSciences" of Montpellier; Boyer et al., 2006; www.hydrosciences.fr/sierem). The SIEREM project gathers hydrological and climatic data collected by national networks, various international organizations and by research bodies i.e. FAO and IRD. Update of the data was carried out previously by IRD until 1980 (Ardoin-Bardin, 2004). Thereafter updates have been obtained within the framework of UNESCO's FRIEND-AOC project and cooperative undertakings with national agencies. Data for

East Africa come primarily from: Hurst (1933 and subsequent supplements) for rivers in the Nile Basin (Kagera, Lake Victoria outflows, Blue Nile, Equatorial Lakes, Sobat and Atbara rivers, see Conway and Hulme 1993; Sutcliffe and Parks, 1999); UNESCO (1995) for the Tana; and Hamandawana et al. (2005) for the Okavango. Other river flow series and some recent updates to the above series were obtained from respective national agencies.

For rainfall, we use the CRU TS 2.1 0.5° resolution time series for 1901-2001 from New et al. (2001) and updated in Mitchell and Jones (2005). River basin boundaries upstream of gauging stations were delineated using SRTM (Shuttle Radar Topography Mission) from NASA/ USGS as digital elevation model, and ESRI's Digital Chart of the World drainage files to delineate the catchments. Basin rainfall series were calculated as the average of all 0.5° CRU TS 2.1 grid boxes within the basin boundary. Detailed information on CRU TS 2.1 quality control and notes on data interpretation can be found in relevant publications, but we note here that Africa has generally poor spatial and temporal coverage of rainfall stations (Hulme, 1996; Nicholson, 1996) and this is true for the CRU TS 2.1 data, particularly before the 1930s and after about 1980. To explore the possible effects of changing station distribution on basin rainfall series and runoff relationships we use gridded time series of the number of stations within range of a grid box (Mitchell and Jones, 2005; www.cru.uea.ac.uk/~timm/grid/stns.html) and calculate a basin average series from all grid boxes in the basin. Range is defined as the correlation decay length (450km for rainfall) so that the series represent the average number of stations with data upon which the grid-boxes in the basin may draw to calculate rainfall anomalies. Because these series do not record the actual number of stations that have been used to generate rainfall values we concentrate on changes in their relative rather than their absolute number.

2.2 River flow records in major African river basins

The study concerns SSA, divided for means of presentation and analysis into four regions; West, Central, East and Southern. Observations are used for 28 gauging stations in total, irregularly spaced between and within the regions (Figure 1). The period of record and details of river gauge and basin characteristics are summarised in Table 1. The river basins range in size from ~16,300 km² to ~3,475,000 km². We used three loosely applied criteria to select river basins for analysis as follows, in decreasing order of priority: availability of long verifiably good quality river flow record; large in area (>10,000 km²); and spatial coverage across SSA. In some cases we relaxed the criteria in order to maximise spatial coverage. In all cases at annual time scales the river flow records are for the most part unaffected by human influences in the form of upstream dams and major abstractions.

Figure 1 shows that in general the gauges represent the key upstream contributing areas of these large basins and in some cases combinations of upstream and downstream gauges (Niger and Ogooué). In all cases at annual time scales the river flow records are for the most part unaffected by human influences in the form of upstream dams and major abstractions. Since the construction of the Owen Falls dam in 1954, the outflows from Lake Victoria have been regulated to follow the natural relationship between lake level and outflows (an 'agreed curve', Tate et al., 2004). After a rise in the lake in the late 1990s, outflow departed from the agreed curve to alleviate flooding around Lake Kyoga downstream (Goulden, 2006; Sutcliffe and Petersen, 2007) but we only use data up to 1989. There is a major dam on the Senegal river, the Manantali dam, so we use reconstructed natural discharges for the downstream series at Bakel (Bader, 1990; Bader, 1992). The Niger river has some dams but these have only minor effects on the annual timescales used in this anlaysis. The discharge series of Senshi Halcrow is influenced by the Akosombo dam mainly during the first years of filling (1964-1967). Its interannual variability remains similar to that of neighbouring rivers but the monthly regime has been modified due to regulation and the total discharge has been reduced due to evaporation (Moniod et al., 1977).

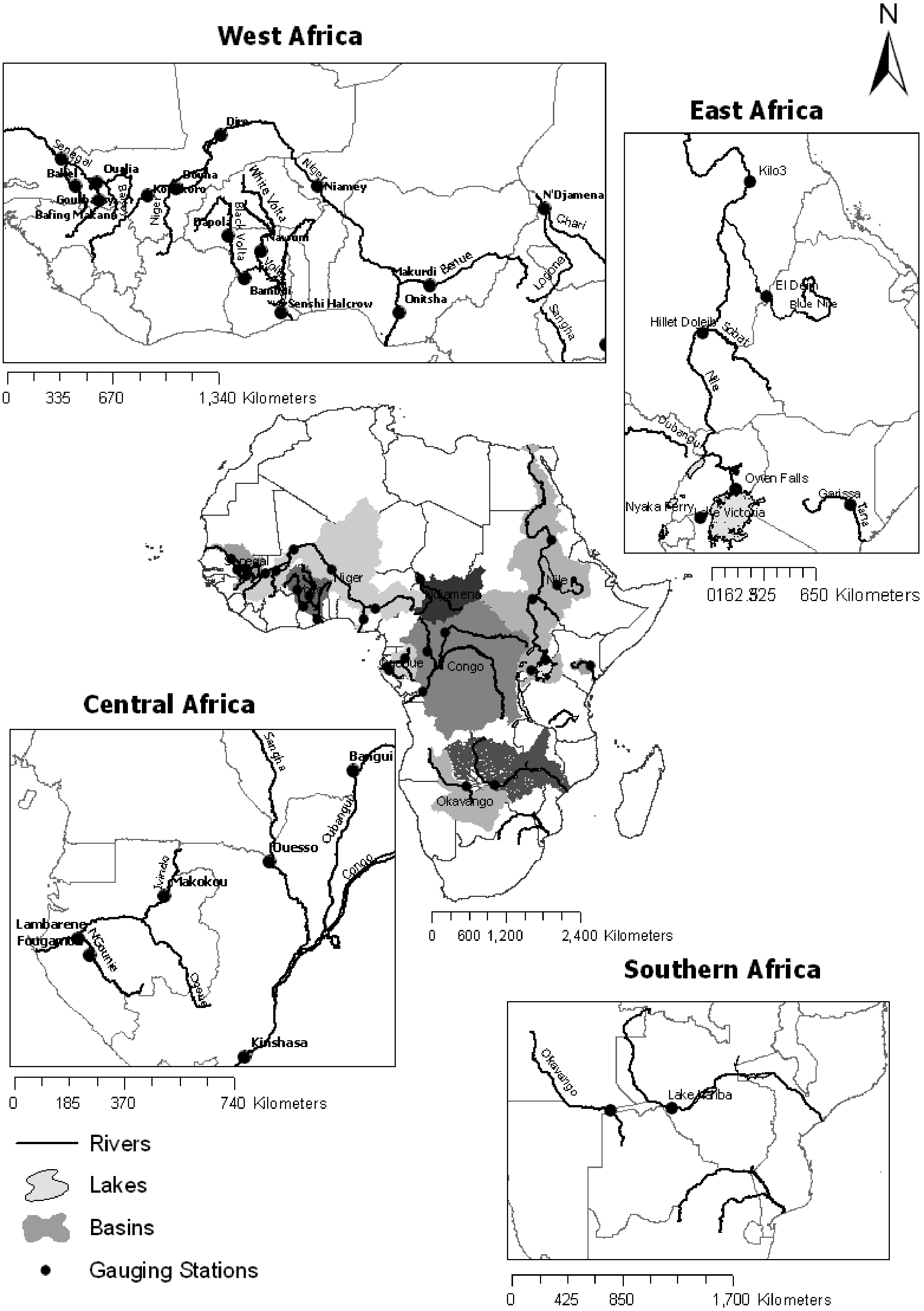


Figure 1: The main drainage basins analysed and location of the gauging stations (see Table 1 for details).

	Basin	Gauging Station	River	Lat. (ºN)	Long. (ºE)	Basin Area (km^2)	Period for River Flow Analysis
West Africa	**Niger**	**Koulikoro**	Niger	12.87	-7.55	120,332	1907-1999
		Douna	Niger	13.22	-5.9	101,226	1922-1997
		Dire	Niger	16.27	-3.38	341,066	1924-1998
		Niamey	Niger	13.39	2.18	631,381	1947-1996
		Makurdi	Benue	7.75	8.53	303,637	1955-1992
		Onitsha	Niger	6.18	6.77	1,388,334	1950-1987
	Sénégal	**Oualia**	Bakoy	13.6	-10.38	78,155	1904-1989
		Bakel	Senegal	14.9	-12.45	220,818	1904-2000
	Volta	**Dapola**	Black Volta	10.57	-2.92	86,559	1952-1994
		Senshi Halcrow	Volta	6.2	0.09	388,154	1936-1979
	Chari	**N'djamena**	Chari	12.12	15.03	601,984	1952-2000
Central Africa	**Congo**	**Bangui**	Oubangui	4.37	18.58	485,478	1936-1998
		Ouesso	Sangha	1.62	16.05	159,016	1948-1996
		Kinshasa	Congo	-4.30	15.30	3,475,000	1903-1996
	Ogooué	**Makokou**	Ivindo	0.57	12.86	48,912	1955-1983
		Fougamou	N'Gounie	-1.22	10.59	48,912	1954-1983
		Lambaréné	Ogooue	-0.71	10.23	205,418	1930-1989
East Africa	**Nile**	**Nyaka Ferry**	Kagera	-1.20	31.25	30,200	1940-1978
		Owen Falls	L. Victoria	0.43	33.23	258,000	1901-1989
		Owen Falls*	Equat. L.	0.43	33.23	293,000	1905-1982
		Hillet Doleib	Sobat	9.20	31.38	231,000	1905-1984
		Kilo 3	Atbara	17.68	34.02	188,200	1903-1982
		El Deim	Blue Nile	11.23	34.98	195,000	1912-2002
	Tana	**Garissa**	Tana	-0.45	39.70	42,220	1934-1975
S.Af.	**Zambezi**	**Victoria Falls**	Zambezi	-17.95	25.90	360,683	1907-1990
	Okavango	**Mohembo**	Okavango	-18.12	21.68	238,700	1933-1999

Table 1: General characteristics of the river basins included in the analysis (locations in Figure 1).
* Equatorial Lakes represents the difference between White Nile river flows measured at Owen Falls and downstream at Mongalla (see Conway and Hulme, 1993).

Interestingly, West and East Africa are well served by long river flow series primarily due to French, English and Anglo-Egyptian interests in water resources development from the 'scramble for Africa' (circa 1880s) to independence (1960s onwards). Since independence, West and Central African countries have tended to receive greater support for coordinated data collection (particularly through ORSTOM, now IRD). In the Nile basin, Egyptian and Sudanese interests have maintained long hydrological records, although conflict in southern Sudan has undermined these efforts since 1983. There are only a few large international river basins in East Africa that drain to the Indian Ocean as the region is dominated by the complex internal hydrology of the Rift Valley Lakes system. Long reliable lake level records exist for many of these lakes and have been described in detail by Nicholson (1998; 1999). Southern Africa has few long duration records for its larger river basins, partly because the effects of human influence (dams and abstractions) very early on in the Limpopo and Orange Rivers has restricted compilation of such records. Our coverage is therefore limited to the Zambezi (measured at Livingstone) and Okavango Rivers. We also analysed the Olifants, a major tributary of the Limpopo, but decided the flow record was too difficult to naturalise. Finally, the Horn of Africa, Ethiopia and Somalia, are poorly represented because of limited data availability, especially in eastern and southern Ethiopia where some very large river basins (e.g. Omo, Wabe Shebelle) remain sparsely instrumented and under-studied.

3. METHODS OF ANALYSIS

We characterise rainfall and runoff for different periods; World Meteorological Organization normals (1901-30; 1931-60; 1961-90) and periods before and after notable breakpoints identified using statistical tests. Means, coefficients of variation (CV) and selected indicators of trend (based on linear regression) and temporal variability are presented. Breakpoints in time series are identified using Khronostat 1.0 software (1998) for non parametric tests and segmentation tests, including Hubert's segmentation, Pettitt, Lee and Heghinian and Buishand tests (Lubes-Niel et al., 1998). The relationship between rainfall and river flow is examined using plots of 20-year moving average correlations. Annual rainfall-runoff plots are used to identify shifts and spatial differences in relationships. The runoff coefficient represents the ratio (expressed as a percentage) of rainfall to runoff, that is, the fraction of total rainfall that becomes river flow.

4. RAINFALL AND RIVER FLOW VARIABILITY

4.1 Long-term conditions

Table 2 shows descriptive statistics for rainfall and river flows based on the 1961-90 WMO period along with per cent differences from the previous 30-year periods where data are available. The West African rivers are mainly strongly seasonal and humid with fairly modest interannual rainfall variability. In all cases river flows show much greater CVs due mainly to the heterogeneity and non-linear response of runoff to changes in rainfall and especially to variations in rainfall intensity. Groundwater interactions also contribute: variability of groundwater levels is linked to cumulative rainfall anomalies, and can affect runoff over prolonged periods, independently of the rainfall anomaly of a specific year (Mahe et al., 2000). Runoff coefficients are fairly low and show considerable variation, ranging from around 4-27 per cent. The period is marked by the large negative trend in rainfall and river flows which occurs in all the West African rivers and has been widely documented (Janicot, 1992; Paturel et al., 1997, 1998; Mahe and Olivry, 1999; Mahe et al., 2001; Leduc et al., 2001; Le Barbé, and Label, 1997). Time series show this event is characterised by a shift rather than a trend. Proportionally the shift is much greater in river flows (-13 to -51 per cent) than rainfall (-7 to -14 per cent). West Africa shows strong intra-regional homogeneity with all rivers studied exhibiting broadly similar temporal behaviour. Changes in rainfall and runoff between 1901-30 and 1931-60 (not shown) are modest, rainfall ranges from -2 to 8 per cent and river flow from -1 to 2 per cent (only five rivers have data for both periods).

Central Africa is dominated by the Congo River and its major tributary the Bangui. Conditions are humid with annual rainfall over 1500mm with modest seasonality. Rainfall and river flows are fairly stable from year to year and annual means show little variation between 1931-60 and 1961-90, except for the decrease in flows of the Bangui.

East and Southern Africa show greater heterogeneity, within and between regions. Rainfall across the East African basins ranges from 582-1222mm and interannual variability tends to be highest in the drier basins, higher than in West African basins with equivalent annual rainfall. River flows are generally less variable than in West Africa, with the exception of the Atbara. Rainfall and river flows in all basins show decreasing trends from 1961-90. Runoff coefficients range considerably, from 3-63 per cent, due to the effects of high evaporative demand and transmission losses (Atbara), transmission losses (Sobat, Sudd swamps) and lake evaporation (Lake Victoria). Changes between 1931-60 and 1961-90 are mixed, with three basins showing modest decreases in rainfall, three almost no change and two modest to large increases. These trends are associated with some very large river flow responses, not easily explained by the rainfall changes and are explored in more detail in section 5. The two Southern African rivers possess slightly different climatic conditions, the upper Zambezi is humid seasonal and the Okavango is closer to semi-arid seasonal, both have modest interannual rainfall and river flow variability and quite low runoff coefficients. Mean rainfall between 1931-60 and 1961-90 is fairly stable, as is river flow in the Zambezi, whilst in the Okavango it recorded a 14 per cent increase.

Gauge location	**1931-1960**					**1961-1990**					**% change**	
	Rainfall (mm)	CV (%)	River Flow (m^3s^{-1})	CV (%)	RC (%)	Rainfall (mm)	CV (%)	River Flow (m^3s^{-1})	CV (%)	RC (%)	Rainfall	River Flow
WEST AFRICA												
Koulikoro	**1619**	7	**1529**	20	25	**1436**	10	**1213**	33	22	**-11**	**-21**
Douna	**1230**	10	**-**	-	-	**1066**	14	**332**	64	9	**-13**	**-51**
Dire	**1170**	8	**1101**	20	9	**1020**	12	**870**	29	8	**-13**	**-21**
Niamey	**807**	9	**-**	-	-	**693**	13	**804**	29	6	**-14**	**-20**
Makurdi	**1268**	8	**-**	-	-	**1175**	11	**3152**	31	27	**-7**	**-**
Onitsha	**992**	8	**-**	-	-	**898**	11	**5580**	22	14	**-10**	**-**
Bakel	**953**	12	**764**	32	11	**808**	17	**549**	48	9	**-15**	**-41**
Oualia	**927**	12	**170**	34	7	**793**	16	**116**	68	5	**-14**	**-34**
Senshi Hal.	**1080**	8	**1204**	38	9	**992**	12	**1044**	68	8	**-8**	**-13**
Dapola	**963**	9	**-**	-	-	**836**	15	**89**	46	4	**-13**	**-**
N'Djamena	**1047**	8	**-**	-	-	**942**	12	**892**	42	5	**-10**	**-**
CENTRAL AFRICA												
Kinshasa	**1567**	4	**40584**	6	24	**1567**	6	**42418**	13	25	**0**	**+5**
Ouesso	**1537**	9	**-**	-	-	**1550**	7	**1571**	17	20	**+1**	**-**
Bangui	**1555**	10	**4265**	11	18	**1517**	8	**3740**	28	16	**-2**	**-12**
Lambarene	**1762**	9	**4761**	16	42	**1764**	9	**4587**	13	40	**0**	**-4**
Makokou	**1597**	10	**-**	-	-	**1616**	9	**-**	-	-	**+1**	**-**
Fougamou	**1839**	15	**-**	-		**1862**	16	**712**	19	39	**+1**	**-**
EAST AFRICA												
Nyaka Ferry.	**1058**	9	**412**	18	42	**1084**	9	**662**	21	63	**+2**	**+61**
Owen Falls	**1129**	12	**672**	15	7	**1222**	12	**1190**	17	12	**+8**	**+77**
Owen Falls*	**1147**	9	**105**	67	1	**1167**	12	**372**	21	3	**+2**	**+254**
Hillet Doleib	**1039**	11	**408**	14	5	**974**	21	**448**	21	6	**-6**	**+10**
El Deim	**1070**	10	**1626**	13	25	**1010**	10	**1454**	20	23	**-6**	**-11**
Kilo3	**644**	22	**390**	26	10	**582**	21	**294**	36	8	**-10**	**-25**
Garissa	**615**	19	**131**	41	16	**706**	26	**-**	-	-	**+15**	**-**
SOUTHERN AFRICA												
Victoria F.	**860**	17	**1171**	33	12	**857**	15	**1183**	38	12	**0**	**+1**
Mohembo	**777**	20	**763**	23	13	**743**	17	**869**	22	16	**-4**	**+14**

Table 2: Long term conditions, 1961-1990, rainfall and river flows: Annual mean, coefficient of variation (CV), runoff coefficient (RC) and percentage change in rainfall and river flow between 1931-1960 and 1961-1990. See Table 1 and Figure 1 for locations. * Owen Falls represents the Equatorial Lakes, the difference between White Nile river flows measured at Owen Falls and downstream at Mongalla.

4.2 Decadal and interannual variability

A sample of rainfall and river flow records is shown in Figure 2 for West Africa. These highlight strong regional homogeneity in temporal behaviour as all the series show the marked downturn in rainfall and river flow around 1970 that characterises the climate of the Sahel during the last century. Many series also show humid conditions during the 1950s and 1960s. These features have been analysed in detail, for example rainfall by Lamb (1982), Nicholson (1983) and Hulme (1992), river flow by Sircoulon (1976, 1985) and both by Mahe and Olivry (1999). Unfortunately it has not been possible to update most of these series beyond 2002, however, recent studies by L'Hôte et al. (2002) and Dai et al. (2004) note that rainfall conditions in the Sahel have not returned to those prior to the early 1970s. Rainfall and river flows certainly reached their lowest point in the mid-1980s and have stabilised and in most cases recovered somewhat.

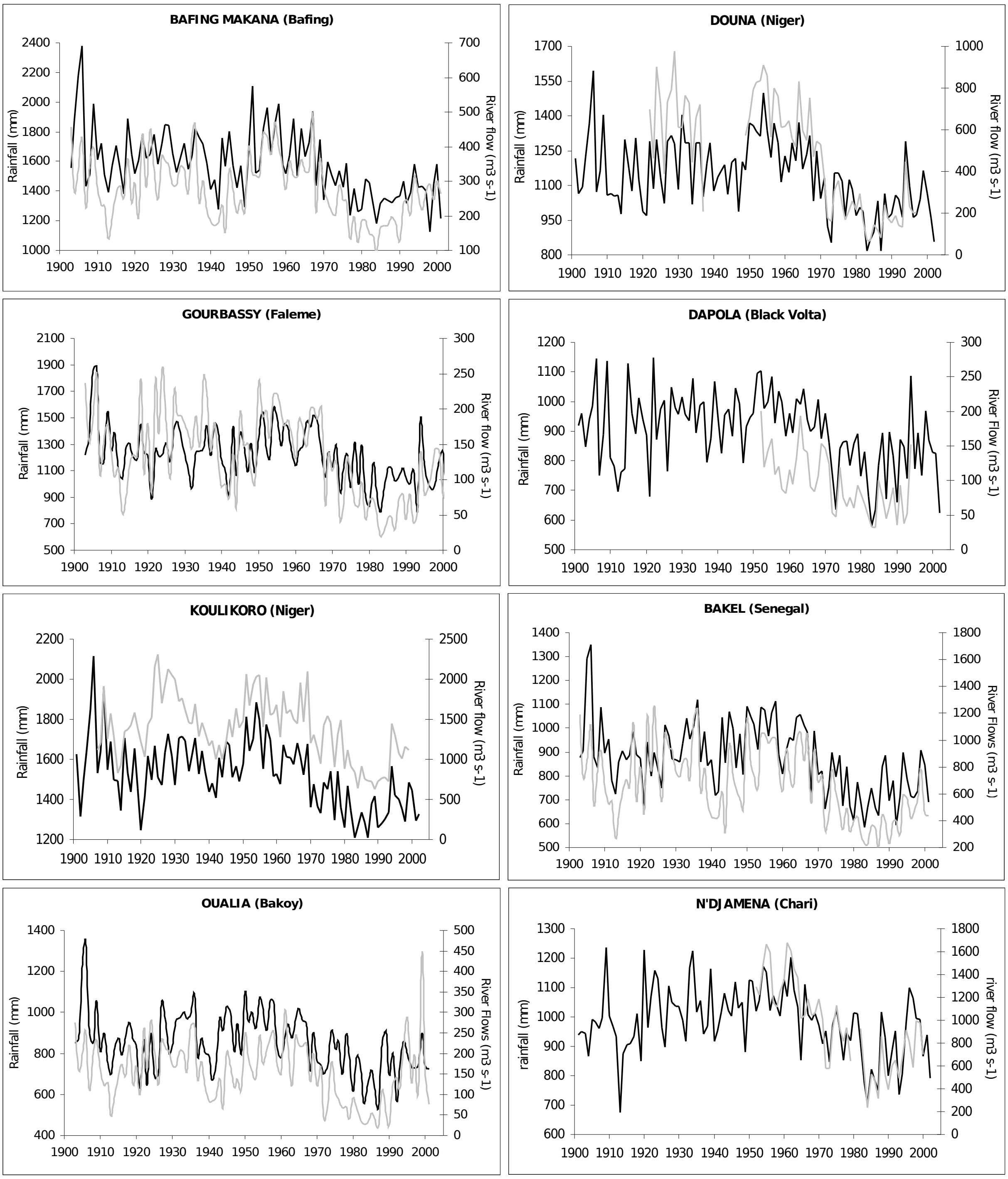


Figure 2: Annual rainfall (black line) and river flow (grey line) series for West Africa; Bafing Makana, Douna, Gourbassy, Volta, Niger, Senegal Bakel, Oualia and Ndjamena. Note different vertical scales and record lengths for river flow (see Table 1 for detail) and standard record lengths for rainfall (1901-2002).

The Chari and Logone rivers are the main tributaries of Lake Chad and join at Ndjamena to form the Ndjamena River just before entering the lake. Although it is the most easterly of this group of rivers it shows similar temporal behaviour with its decrease leading to the dramatic lowering and shrinking of Lake Chad since the 1970s (Lemoalle, 2004). The Chari and Logone, with their origins in the Adamawa highlands of Cameroon and the Central African Republic, where rainfall averages 1600mm/annum, are the main tributaries of Lake Chad (Sepulchre et al., in press). Under present climatic conditions, these two rivers contribute ~90% of the lake's water, with the remaining 10% coming from local rainfall and deliveries by the El Beid and Komadougou Yobe rivers (Birkett, 2000). The Chari and Logone join at Ndjamena just before entering the lake to form the Ndjamena River. Severe droughts occurred during the 1970s and 1980s leading to widespread sinking of boreholes and development of a large-scale irrigation system that promoted water loss through evaporation (Birkett, 2000). The more 'recent' reduction in the lake's surface area is the outcome of sustained decrease in river flow due to persistent rainfall failures, human induced increase in evaporation losses and poor management of irrigation water.

The two longest river flow records are shown for Central Africa in Figure 3. The region is dominated by the Congo and the Bangui forms its main northern tributary draining large parts of the Central African Republic, south of Lake Chad (in fact the decrease in rainfall and flows post-1970 is similar to the West African region). The Congo's rainfall and river flows have been quite stable with only the 1960s (wet) and 1980s (dry) showing any decadal patterns of variability. The other river basins (series not shown) exhibit quite marked interannual variability (high CVs) and modest decadal or trend like patterns.

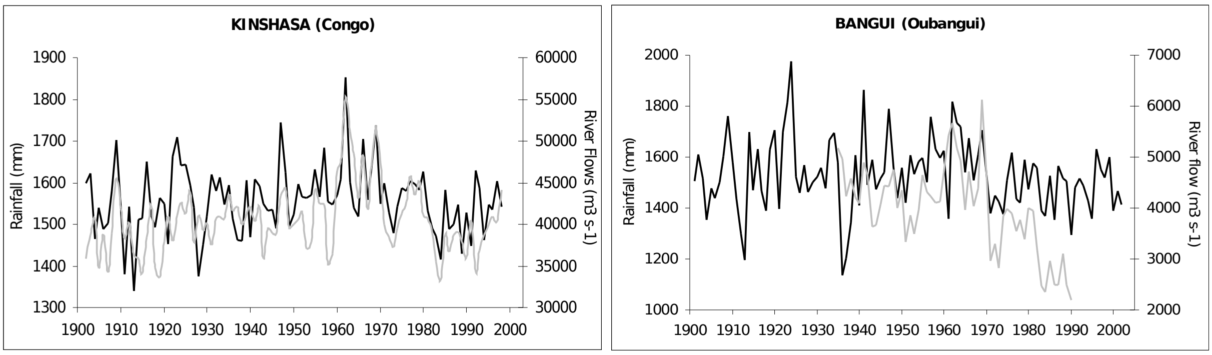


Figure 3: Annual rainfall (black line) and river flow (grey line) series for Central Africa; Kinshasa (Congo) and Bangui (Oubangui). Note different vertical scales and record lengths for river flow (see Table 1 for detail) and standard record lengths for rainfall (1901-2002).

Figure 4 shows four examples from East Africa, again chosen for display because of their long river flow records.

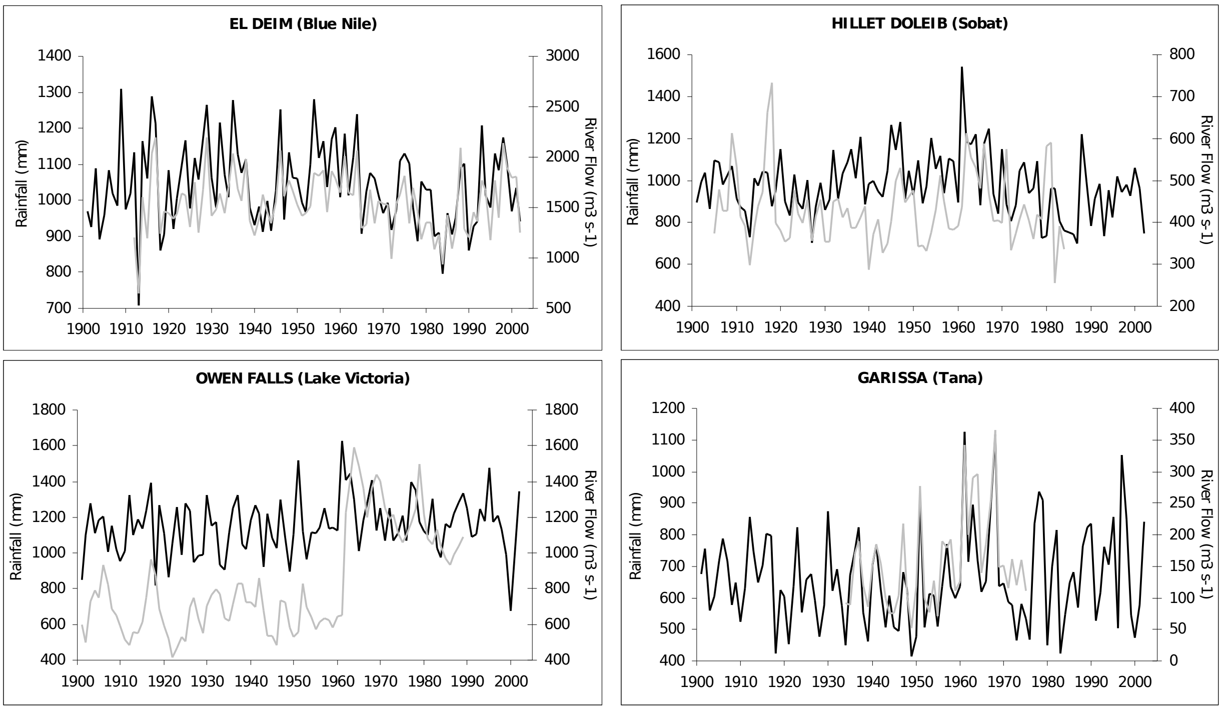


Figure 4: Annual rainfall (black line) and river flow (grey line) series for East Africa; Blue Nile, Sobat, Lake Victoria outflows and Tana. Note different vertical scales and record lengths for river flow (see Table 1 for detail) and standard record lengths for rainfall (1901-2002).

Temporal behaviour in river flows, and to a lesser extent rainfall, is regionally less homogeneous. The Blue Nile (and Atbara, not shown) display some features similar to West Africa, humid 1950s and dry 1970s and 1980s but has recovered more than West African river flows have. The Sobat is more stable and shows intermediate behaviour to the Blue Nile and Atbara to the north and Lake Victoria and other rivers to the south. The marked rise in outflows from Lake Victoria after 1961 has been explained using the lake's water balance to show it resulted from a series of extremely wet years in the 1960s and a slight increase in the short rains after the 1960s combined with lake storage effects (Piper et al., 1986; Sene and Plinston, 1994; Conway, 2002). Many other East African lakes show marked increases in level in 1961 (and in other years such as 1968, 1978, 1982 and 1997) but these have been much shorter in duration. Most of the extreme years are associated with Indian Ocean Dipole events (Saji et al., 1999) which sometimes bring severe flooding and socio-economic disruption (Conway, 2002). The smaller rivers such as Tana (Figure 4) and Kagera show the short-lived effects of major rainfall extremes that produce high levels of interannual variability with modest decadal variability. The two rivers in Southern Africa (Figure 5) have stable rainfall series but quite high decadal variability in river flows which is discussed below.

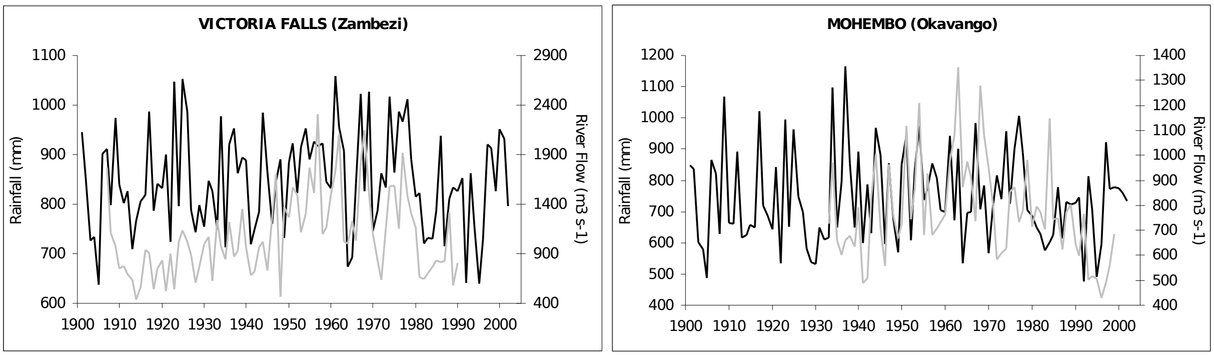


Figure 5: Annual rainfall (black line) and river flow (grey line) series for Southern Africa; Zambezi and Okavango. Note different vertical scales and record lengths for river flow (see Table 1 for detail) and standard record lengths for rainfall (1901-2002).

Figure 6 demonstrates the magnitude of 20-year trends that have been experienced over the last century. The results are unsurprising, given the previous analysis, however, what the plots serve to show that future trends related to climate change will need to be large and prolonged over time, in order to enable formal attribution, and to create conditions beyond those which have already been experienced during modern times. Table 3 lists the minimum and maximum 20 year trends in absolute terms and expressed as per cent of long term means. Twenty-year trends in rainfall have ranged from +/- 3 per cent per annum whereas river flows have ranged from -15 to +11 per cent per annum. These results provide a context within which to set projections of future rates of change and are discussed in Section 6.4.

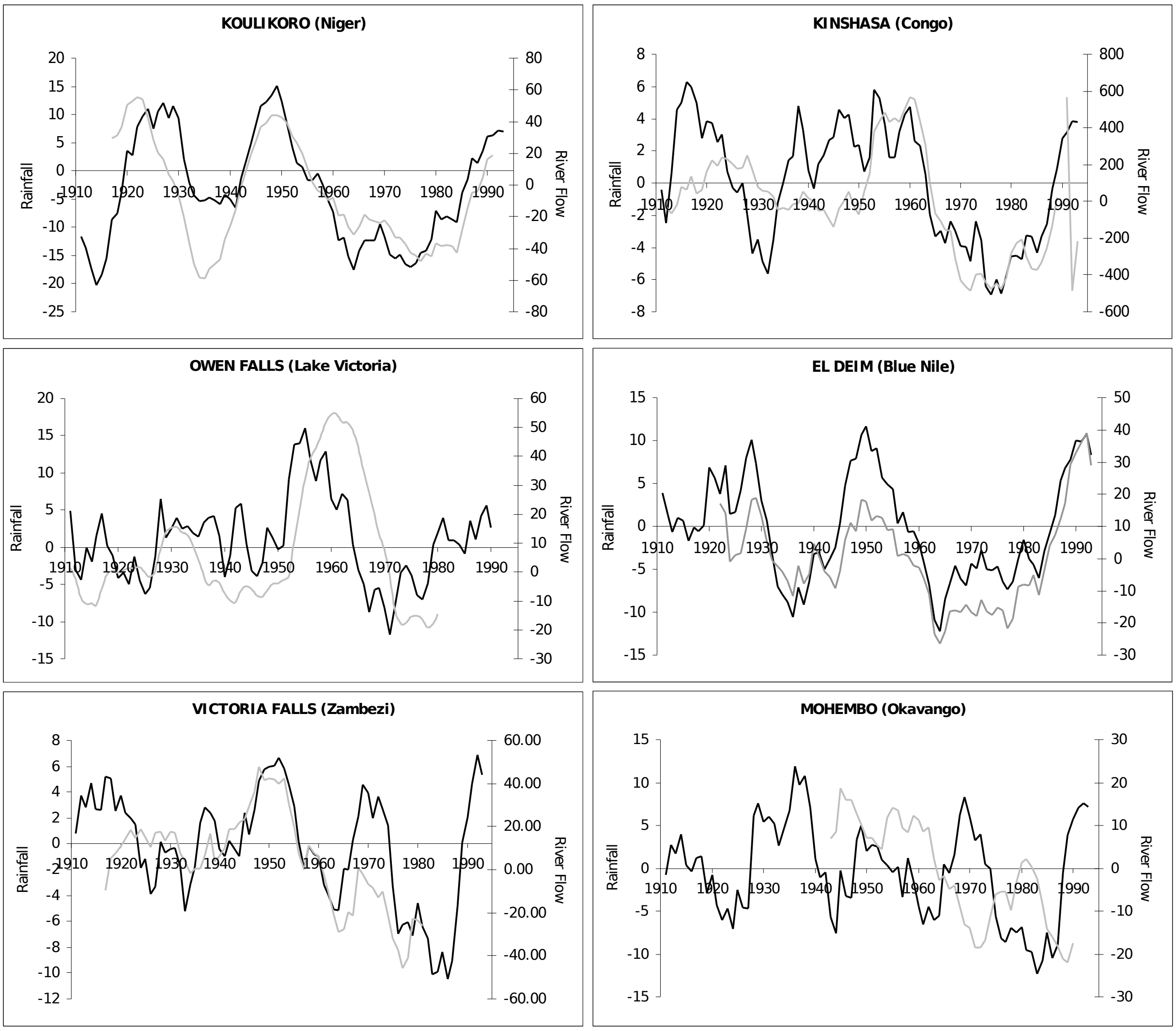


Figure 6: 20-year running trend in rainfall (black line) and river flow (grey line) series for examples from the four regions; West Africa Niger, Central Africa Congo, East Africa Lake Victoria and Blue Nile, Southern Africa Zambezi and Okavango. Note different vertical scales and record lengths for river flow (see Table 1 for detail) and standard record lengths for rainfall (1912-1993). Trend is expressed as mm yr^{-1} for rainfall and m^3 s^{-1}/yr for river flow.

Stations	**Rivers**	**Rainfall**				**River Flow**			
		Absolute (mm yr^{-1})		**% of Rainfall (1961-1990 mean)**		**Absolute (m^{3}s^{-1}/yr)**		**% of River flow (1961-1990 mean)**	
		MIN	**MAX**	**MIN**	**MAX**	**MIN**	**MAX**	**MIN**	**MAX**
West Africa									
Koulikoro	Niger	-20	15	-1.4	+1.0	-59	56	-4.9	+4.6
Douna	Niger	-19	13	-1.8	+1.2	-50	32	-15.1	+9.6
Niamey	Niger	-12	9	-1.7	+1.3	-31	4	-3.9	+0.5
Makurdi	Benue	-11	14	-0.9	+1.2	-132	-4	-4.2	-0.1
Onitsha	Niger	-12	9	-1.3	+1.0	-146	22	-2.6	+0.4
Dire	Niger	-16	12	-1.6	+1.2	-35	36	-4.0	+4.1
Bafing M.	Bafing	-25	21	-1.7	+1.4	-13	14	-5.6	+6.0
Gourbassy	Faleme	-25	15	-2.2	+1.3	-8	6	-8.3	+6.2
Bakel	Senegal	-19	14	-2.4	+1.7	-38	32	-6.9	+5.8
Oualia	Bakoy	-17	14	-2.1	+1.8	-10	13	-8.6	+11.2
Senshi H.	Volta	-12	11	-1.2	+1.1	-40	43	-3.8	+4.1
Dapola	B. Volta	-14	11	-1.7	+1.3	-5	1	-5.6	+1.1
N'Djamena	Chari	-11	11	-1.2	+1.2	-43	21	-4.8	+2.4
Central Africa									
Kinshasa	Congo	-7	6	-0.5	+0.4	-485	567	-1.1	+1.3
Ouesso	Sangha	-17	18	-1.1	+1.2	-31	15	-2.0	+1.0
Bangui	Oubang.	-18	13	-1.2	+0.9	-102	68	-2.7	+1.8
Lambarene	Ogoue	-12	12	-0.7	+0.7	-52	70	-1.1	+1.5
Makokou	Ivindo	-12	17	-0.7	+1.1	*Time series too short*			
Fougamou	NGounie	-19	18	-1.0	+1.0	*Time series too short*			
East Africa									
El Deim	Blue Nile	-12	12	-1.2	+1.2	-26	39	-1.8	+2.7
Owen Falls	L.Vict.	-12	16	-1.0	+1.3	-19	55	-1.6	+4.6
Hillet D.	Sobat	-23	12	-2.4	+1.2	-7	7	-1.6	+1.6
Owen Falls	Equat.L.	-11	11	-0.9	+0.9	-18	17	-4.8	+4.6
Garissa	Tana	-13	19	-1.8	+2.7	*Time series too short*			
Kilo3	Atbara	-17	13	-2.9	+2.2	-15	10	-5.1	+3.4
Nyaka Ferry	Kagera	-6	15	-0.6	+1.4	-1	24	-0.2	+3.6
Southern Africa									
Victoria F.	Zambezi	-10	7	-1.5	+1.1	-46	48	-3.9	+4.1
Mohembo	Okavan.	-12	12	-1.6	+1.6	-22	19	-2.6	+2.2

Table 3: Absolute Maximum/Minimum 20-yr trends and Maximum/Minimum 20-yr trends expressed as a per cent of long term rainfall and river flow (1961-1990).

5. RAINFALL-RUNOFF RELATIONSHIPS

5.1 Regional relationships

Figure 7 shows the strength of regression relationships between annual rainfall and runoff during 1961-90 and 1931-60. Rivers in West Africa generally display very strong relationships, with rainfall accounting for around 60-70 per cent of river flow variability. In Central Africa relationships are slightly weaker but still quite robust (around 50 per cent variance explained). Relationships in East and Southern Africa are substantially weaker, with the exception of the Blue Nile, which drains much of central and northern Ethiopia.

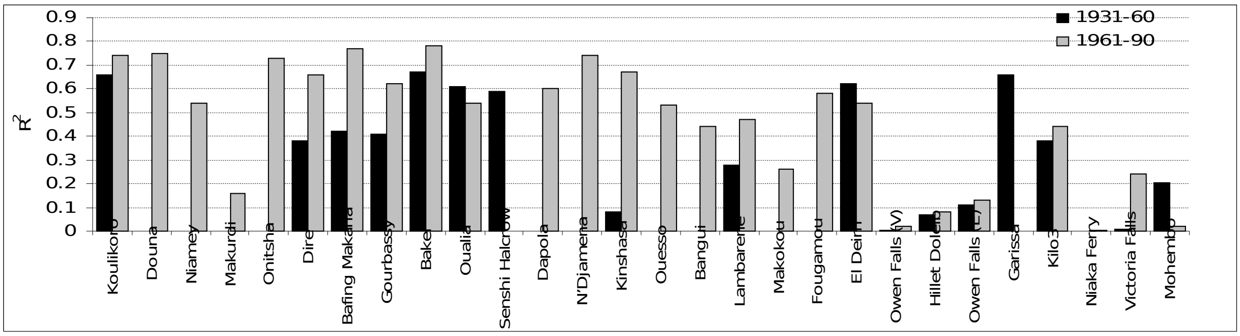


Figure 7: Strength of regression relationships (R^2) between rainfall and runoff for the 30-year periods 1931-60 and 1961-90 (results shown for all rivers with >20 years flow data).

To help explain some of these differences Figure 8 shows the nature of the relationships for examples typical of each region.

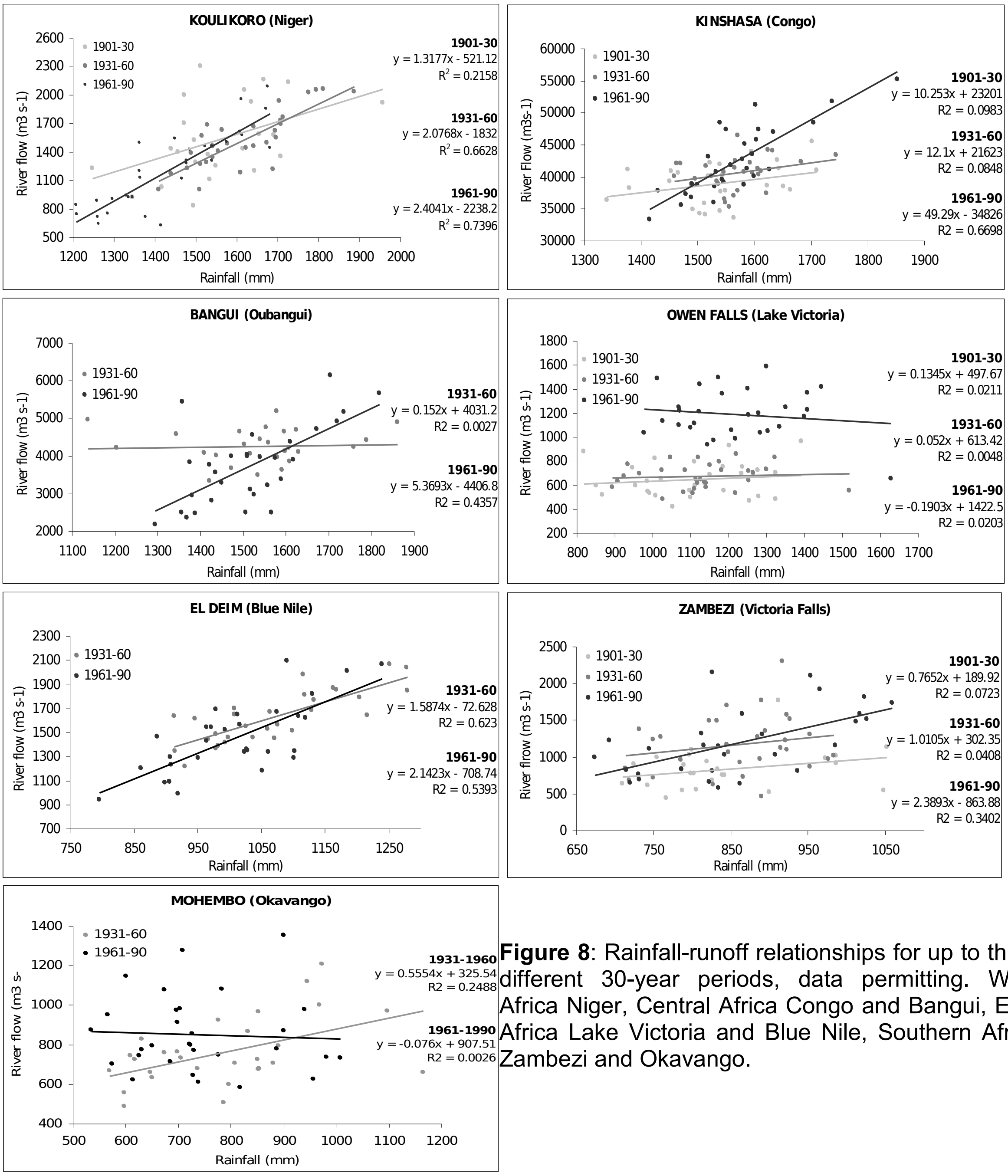


Figure 8: Rainfall-runoff relationships for up to three different 30-year periods, data permitting. West Africa Niger, Central Africa Congo and Bangui, East Africa Lake Victoria and Blue Nile, Southern Africa Zambezi and Okavango.

The Niger at Koulikoro (upstream of the Inland Delta) is fairly typical of West Africa. Nearly all show much weaker (and generally lower gradient) relationships during the period 1901-30, with stronger relationships (and generally higher gradient) across both 1931-60 and 1961-90. In Central Africa the results are less consistent, with fairly weak relationships in the Lambarene and Makokou (both have wide scatter and obvious pattern, plots not shown), and stronger but highly unstable relationships in the Congo and Bangui. Both rivers only produce strong relationships during 1961-90, prior to then Figure 8 shows almost random patterns, although a moderately positive relationship exists for the Congo. The other rivers in Central Africa generally show reasonable linear relationships but data are only available for 1961-90 so it is not possible to comment on their temporal stability.

In East Africa many of the river systems possess complex drainage systems due to the Rift Valley and other physiographical features. For instance the Sobat and Equatorial Lakes experience non-linear effects of over-bank losses and lake level-area effects on inflow-outflow relationships resulting in weak relationships with significant non-stationary behaviour (see below). Outflows from Lake Victoria show a very weak relationship to basin rainfall even during periods of stationary conditions. Lake outflows are constricted so that their response to wet years is attenuated leading to a smoothed response. Difficulties in estimating lake rainfall have been identified in efforts to model the lake's water balance (the lake has an area of about 78,000km^2; Piper et al., 1986; Ba and Nicholson, 1998). Rivers with less complex hydrology show better results such as the Blue Nile (Figure 8) and Tana (not shown). The two rivers in Southern Africa are shown in Figure 8 to have very weak relationships due their complex runoff response to rainfall. Further exploration of the basin's physiography may shed light on this although for the Zambezi data quality may be a critical factor. We have been unable to trace any metadata for this river flow record and therefore its accuracy is open to question (see next section). In addition, the upper basin, draining parts of Angola, is unlikely to have had many rain gauges present throughout the whole period.

5.2 Analysis of non-stationary behaviour

It is clear from the previous section that significant shifts in rainfall, runoff and rainfall-runoff relationships have occurred across SSA. To explore this in more detail Table 4 lists breakpoint years and whether series show evidence of breakpoints using four statistical tests (described in Section 2) and Table 5 lists their strength (R^2), intercept and slope before and after breakpoints (identified in rainfall and river flow series separately).

Region - River	Station	Buishand	Pettitt		Lee & Heghinian	Hubert
WEST	*All stations show similar results*	**R**	**R**	**1967** **1970**	**1967** **1971**	**1967** **1972**
CENTRAL	*Tests are accepted for most of the stations, except:*	**A**	**A**	**-**	**no common date**	**-**
Oubangui	*Bangui*	*A*	*R*	*1970*	*1970*	*1935 1938* *1969*
EAST	*Tests are accepted for most of the station, except:*	**A**	**A**	**-**	**no common date**	**-**
Sobat	*Hillet Doleib*	*R*	*R*	*1967*	*1978*	*1960 1961* *1978*
Kagera	*Nyaka Ferry*	*R*	*R*	*1929*	*1929*	*1929 1997*
SOUTHERN	*All stations show different results*					
Zambezi	*Victoria Falls*	*A*	*A*	*-*	*1901*	*-*
Okavango	*Mohembo*	*A*	*A*	*-*	*1978*	*-*

Region - River/Lake	Station	Buishand	Pettitt		Lee & Heghinian	Hubert
WEST	*All stations show similar results, except:*	**R**	**R**	**1967** **1971**	**1967** **1971**	**1967** **1971**
Niger	*Makurdi*	*R*	*R*	*1976*	*1971*	*1981* *1988*
Chari	*Ndjamena*	*R*	*R*	*1971*	*1971*	*1964 1982*
CENTRAL	*All stations show similar results, except:*	**R**	**R**	**1970**	**1969** **1971**	**1969** **1971**
Congo	*Kinshasa*	*R*	*A*	*1922*	*1981*	*1959 1969* *1981*
Ogooue	*Fougamou*	*A*	*A*	*-*	*1977*	*1977*
EAST	*All stations show different results*					
Kagera	*Nyaka Ferry*	*R*	*R*	*1961*	*1961*	*1961 1964*
Lake Victoria	*Owen Falls*	*na*	*R*	*1961*	*na*	*1961 1970*
Equatorial L.	*Owen Falls*	*R*	*R*	*1960*	*1919*	*1916 1918* *1960*
Sobat	*Hillet Doleib*	*A*	*A*	*-*	*1981*	*-*
Blue Nile	*El Deim*	*A*	*A*	*-*	*1913*	*1913 1978* *1987*
Atbara	*Kilo3*	*R*	*R*	*1964*	*1964*	*1915 1916* *1964*
Tana	*Garissa*	*R*	*R*	*1955*	*1955*	*1960 1968*
SOUTHERN	*All stations show different results*					
Zambezi	*Victoria Falls*	*R*	*R*	*1945*	*1945*	*1945 1980*
Okavango	*Mohembo*	*R*	*R*	*1986*	*1992*	*1960 1969* *1992*

Table 4: Breakpoint years identified using four statistical tests on rainfall (top panel) and river flow series (lower panel). A = test is accepted, the series are “stationary”, R = test is rejected, the series are not “stationary”, « - » = no break detected, na = test is not applied (series non-normal or gap / missing data).

Basin	Stations	1931-1960			1961-1990		
		R^2	Intercept ($m^3 s^{-1}$)	Slope	R^2	Intercept ($m^3 s^{-1}$)	Slope
WEST AFRICA							
Niger	Koulikoro	0.66	-1832	2.08	0.74	-2238	2.40
	Douna	-	-	-	0.75	-998	1.25
	Niamey	-	-	-	0.54	-505	1.89
	Makurdi	-	-	-	0.16	-736	3.23
	Onitsha	-	-	-	0.73	-3401	0.07
	Dire	0.38	-510	1.38	0.66	-832	1.67
Senegal	Bafing M.	0.42	-203	0.31	0.77	-377	0.41
	Gourbassy	0.41	-76	0.19	0.62	-180	0.24
	Bakel	0.67	-887	1.73	0.78	-828	1.70
	Oualia	0.61	-190	0.39	0.54	-246	0.45
Volta	Senshi H.	0.59	-2990	3.91	-	-3416	-
	Dapola	-	-	-	0.60	-127	0.26
Chari	N'Djamena	-	-	-	0.74	-1691	2.76
CENTRAL AFRICA							
Congo	Kinshasa	0.08	+21667	12.10	0.67	-33407	49.29
	Ouesso	-	-	-	0.53	-1341	1.88
	Bangui	0.001	+4096	0.09	0.44	-4407	5.37
Ogooué	Lambarene	0.28	+373	2.49	0.47	-94	2.66
	Makokou	-	-	-	0.26	+1228	0.40
	Fougamou	-	-	-	0.58	+90	0.32
EAST AFRICA							
Nile	El Deim	0.62	-73	1.59	0.54	-709	2.14
	Owen Falls	0.005	+613	0.05	0.02	+1423	-0.19
	Hillet D.	0.07	+265	0.14	0.08	+313	0.13
	Owen Falls	0.11	+378	-0.20	0.13	-19	0.28
	Kilo3	0.38	+102	0.45	0.44	-77	0.62
	Nyaka Fer.	0.001	+379	0.03	0.003	+575	0.08
Tana	Garissa	0.66	-87	0.36	-	-	-
SOUTHERN AFRICA							
Zambezi	Victoria F.	0.04	+302	1.01	0.34	-864	2.39
Okavango	Mohembo	0.25	+326	0.56	0.0012	+831	0.05

Table 5: Regression relationships (R^2), intercept and slope between rainfall and runoff for the 30-year periods 1931-1960 and 1961-1990 (results shown for all rivers with >20 years flow data).

The shift/discontinuity in West African rainfall and river flow series around 1970 has been previously documented (Paturel et al., 1998; Mahe and Olivry, 1999; Mahe et al., 2001) and is common to all the series presented here. What this analysis identifies is the possible existence of changes in rainfall-runoff relationships as highlighted by large differences between intercepts (smaller differences in slope) which are very marked in the cases of Douna and Niamey (Figure 9) and Dire, Gourbassy, Bakel and Ndjamena (not shown). Some rivers show a greater change in the slope factor such as the Niger (Koulikoro, Figure 9), Makurdi, Oualia, and Volta (Senshi Halcrow). In the Sudano-Guinean area the prolonged rainfall decline since the beginning of the 1970s led to a persistent deepening of groundwater levels. The percentage of baseflow in the annual discharge of all rivers in West Africa is thus correspondingly lower since the drought exacerbates the effects on river flows (except for Sahelian rivers, where the groundwater contribution to surface runoff is insignificant, Mahe et al., 2005). This is visible through the increase of the depletion coefficient (Bricquet et al., 1997; Orange et al., 1997; Olivry et al., 1998; Mahe et al., 2000), which means that the groundwater resources have declined, rapidly draining out since the 1970s. These shifts are likely to primarily reflect non-linear dynamics in runoff response but due to the prolonged duration of the change in rainfall patterns they may also incorporate effects of land cover change. Detailed reconstruction of land cover changes and hydrological modelling would be required to determine the relative importance of these factors.

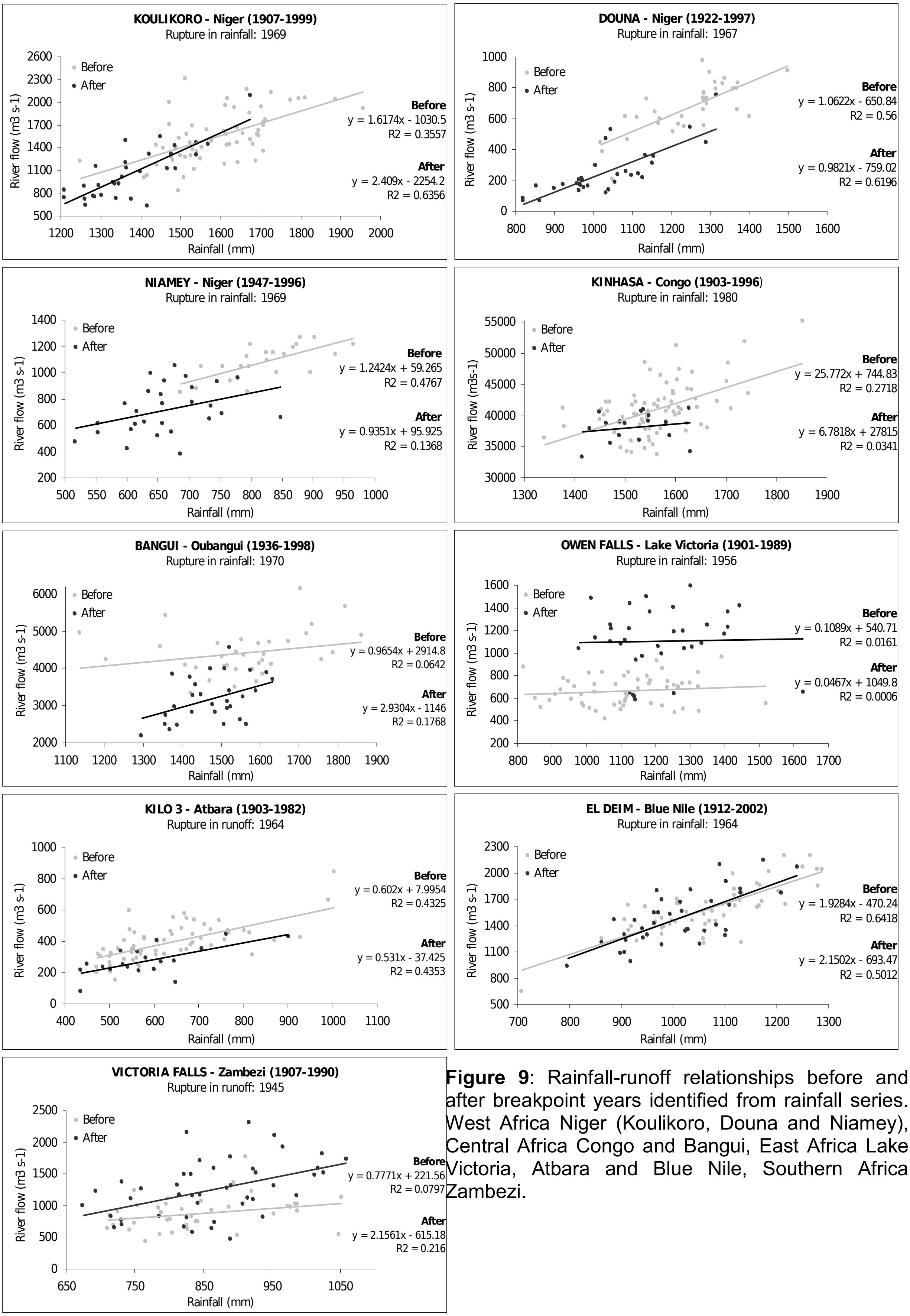
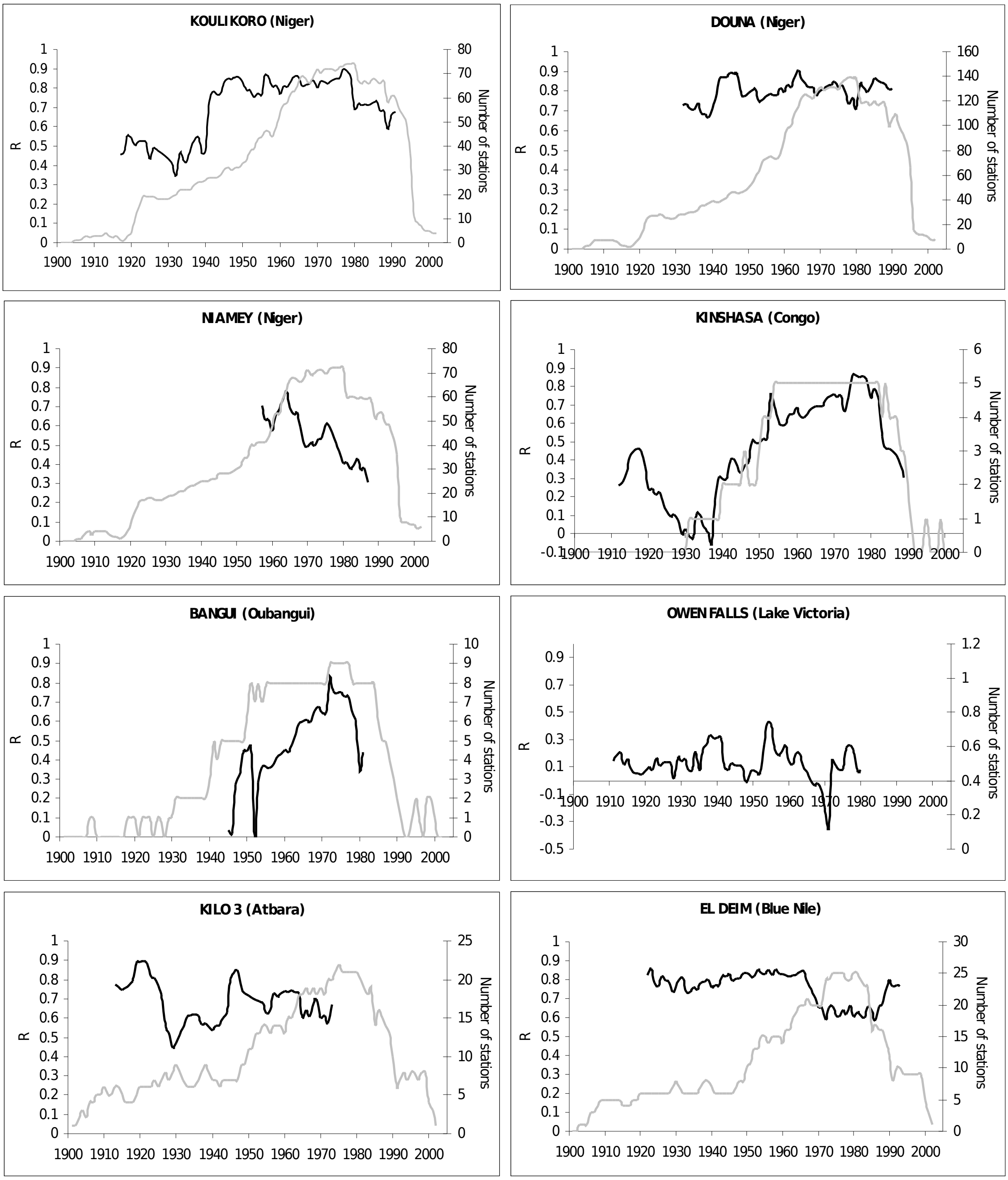


Figure 9: Rainfall-runoff relationships before and after breakpoint years identified from rainfall series. West Africa Niger (Koulikoro, Douna and Niamey), Central Africa Congo and Bangui, East Africa Lake Victoria, Atbara and Blue Nile, Southern Africa Zambezi.

Figure 10 shows time series of 20-year running correlations between rainfall and river flows for three of the West African rivers and the total number of rainfall stations within range of all the grid boxes in the basins. The temporal pattern for the Niger at Koulikoro is similar to Bafing Makana, Gourbassy and Bakel, showing highest correlations between the 1950s and 1980s, which is the period with the best rainfall station coverage. Correlations tend to strengthen moderately from the 1920s to the 1950s (as station density rises) and most records show a rapid (step-like) decay roughly around 1980 at which point data from the 1990s would just begin to feed into the relationships as data from 1970 are removed. This behaviour most likely reflects the dramatic decline in rainfall stations after 1990, with numbers in most cases dropping from over 50 to less than 10 between the late 1980s and early 1990s.



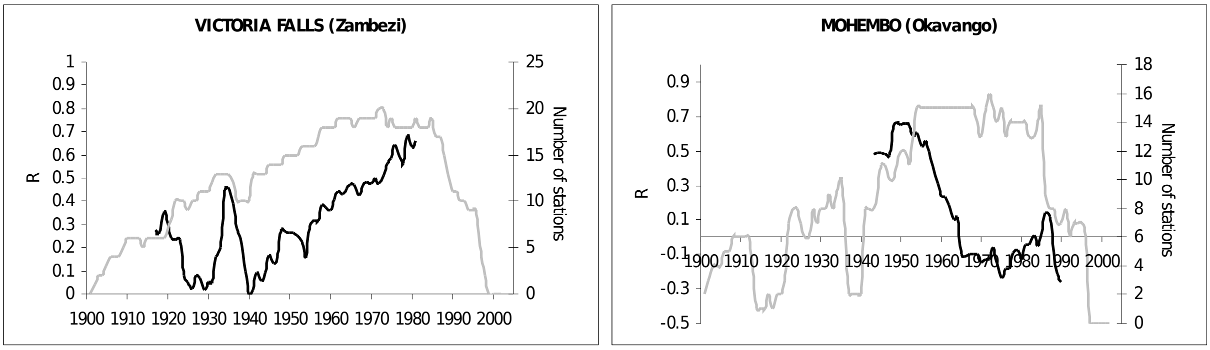


Figure 10: 20-year running correlation between rainfall and river flow (black line) and the total number of rainfall stations (grey line) within range of grid boxes in the basin. West Africa Niger (Koulikoro, Douna and Niamey), Central Africa Congo and Bangui, East Africa Lake Victoria, Atbara and Blue Nile, Southern Africa Zambezi and Okavango.

The time series of rainfall stations in Central Africa (Figure 9 Congo and Bangui) shows their extreme scarcity for this region during most of last century. The Congo shows a rainfall breakpoint in 1980 (1981 river flows) that is associated with a modest difference in the slope and marked reduction in the strength of the rainfall-runoff relationship. The running correlation is highly unstable until 1940 because no rainfall stations contributed to the basin until 1930; and from then on, only five contributed to this vast basin. Considering the paucity of data, the relationship with river flow is remarkably strong from the 1950s to the 1980s. Similar observations hold for the Bangui where the absolute low numbers of rainfall stations and their change over time are likely to account for shifts in the nature of their rainfall-runoff relationships.

East Africa has had better rainfall station coverage than Central Africa, although not as good as West Africa. Figures 9 and 10 show that the Blue Nile has a remarkably stable and robust relationship over time, which is somewhat surprising given the low number of rainfall stations contributing to the rainfall series and the complex large basin (Conway, 2000). The Atbara, just to the north and with a similar number of contributing stations, has a weaker and much less stable relationship and a breakpoint in river flows that occurred in 1964 when runoff decreased. This phenomenon may be related to construction of the Khasm el Girba reservoir upstream of the river gauge in the early 1960s. The Sobat and Kagera both show very weak rainfall-runoff relationships probably because of the combined effects of low rainfall station density and substantial over-flows in wet years because of their complex wetland hydrology. The relationship between Lake Victoria outflows and rainfall (Figures 9 and 10) shows clearly the non-stationary behaviour (also present in Equatorial Lakes and Kagera river series) associated with the dramatic rise in Lake level between 1961 and 1964.

The previous section highlighted the weak relationships between rainfall and runoff in both of our southern African basins where rainfall station coverage is poor and running correlations between rainfall and river flows generally weak (Figure 10). For the Zambezi before ~1960 correlation is very low (with a short peak caused by a couple of years 'in phase' during the 1930s) and after ~1960 it slowly increases. A quite marked shift in the rainfall-runoff relationship exists before and after the 1945 breakpoint in river flow; with substantially higher runoff after this point being possibly related to the integrity of the river flow series (Figure 9). The early part of the Okavango record produces reasonable correlations but from the 1950s these decrease to random behaviour. Neither series shows a clear relationship with station density, a result that is somewhat surprising and difficult to explain.

6. DISCUSSION

6.1 Hydrometeorological data in Africa

The collection, quality control and regular update of the data sets used in this analysis results from the long term collective efforts of many individuals and funding sources. The compilation and quality assurance of the hydrological records has been time consuming and even with extensive contacts across Africa we have not been able to update many records. Our choice of river basins and hydrological series represents most of the key long duration high quality records for large international rivers in SSA. These series are a valuable scientific resource and should be recognised as benchmark stations for studying environmental change. The decline in the overall number of sites, their frequency of reporting and in some cases quality of measurements, are major concerns for the understanding of environmental change in SSA. Although this is part of a global phenomenon with hydrological data (Vörösmarty et al., 2001), the situation is particularly bad in SSA. The massive decline in rainfall stations used in CRU TS 2.1 from the 1980s onwards severely constrains efforts to accurately monitor climate variability and confidently model biophysical systems. This is part of Africa's wider financial, political and institutional challenges to climate research (Washington et al., 2006).

Halting this trend will not be straightforward, current efforts to re-engage African governments and donors through demonstrating the practical and economic value of such measurements (e.g. CLIMDEV) may founder due to lack of widespread support. These calls follow on from many previous attempts to support and develop observations in Africa (Hydromet, 1982; World Bank, 1989, HYCOS and so on). Without political will to invest in the collection of such data and with the reluctance of donors to support recurrent costs indefinitely, a strategic and pragmatic approach is called for. This should be based on identifying a limited set of benchmark sites for long-term international support because of their significance for understanding global environmental change. To overcome some of the limitations of *in situ* data compilation, it would be useful to overlap and extend our river basin rainfall series using merged/ full satellite products.

6.2 Rainfall-runoff relationships

Our results show a complex pattern of behaviour that includes: strong but non-stationary relationships, with most examples in West Africa; a large group from across Africa with marked variations in strength, often but not always, showing the influence of rainfall station density; weak almost random behaviour (particularly in Southern Africa, but examples occur in all other regions); and very few examples of strong, temporally stable relationships.

For some basins limited spatial coverage of rainfall stations leads to weak rainfall-runoff relationships. In many cases this limits the ability to establish robust relationships very far back in time (generally prior to the 1950s). However, there are cases where weak relationships exist throughout the period of analysis, even with reasonable station coverage. There are no obvious reasons for this, particularly since some basins produce good results with relatively few rainfall stations. We surmise that the most likely reasons are the combination of data coverage and quality, possibly exacerbated by local physical conditions beyond the scope of this basin-scale analysis, for example, the impact of geology on the regime of the rightbank tributaries of the Congo river (Laraque et al., 2001) and the Niger river (Mahe et al., 2000). It is not easy to explain why some basins show robust stable relationships with rainfall series comprised of relatively few gauges (e.g. the Blue Nile).

Overall the best period for analysis is broadly 1961-1990, the strongest relationships occur in West Africa, reasonable ones in Central (even though station densities are very low), highly variable ones in East Africa because of the Rift Valley's complex hydrology, and very weak relationships in Southern Africa. These variations deserve further study (see below) but one important implication is that for many of the basins analysed here macro-scale modelling using these data will be of limited success. A more detailed analysis of smaller sub-basins would help identify some of the reasons for the weak relationships, and other aspects of the results.

6.3 Land use and land cover change (LUCC)

The high variability and weak rainfall-runoff relationships means that it is difficult to identify and attribute changes in runoff to particular causes, such as climate change or land use or land cover change (LUCC). Recent work on global precipitation variability has identified a climate change signal, which includes Sahel drying (Zhang et al., 2007). However, no other clear patterns emerge across Africa. Gedney et al. (2006) identify a direct effect of CO_2 on transpiration and global runoff patterns, that they postulate has contributed to a recent increase in global runoff. Our results for Africa demonstrate that a complex picture emerges when data are disaggregated by basin. We find that in SSA, robust identification and attribution of hydrological change is severely limited by conflicting behaviour across basins/regions, low signal to noise ratio, sometimes weak rainfall-runoff relationships and limited assessment of the magnitude and potential effects of LUCC or other anthropogenic influences. We have not looked at the role of evaporation in the rainfall-runoff relationships analysed. In many of the most socio-economically important basins in Africa runoff ratios are low, sensitivity to rainfall change is high while evaporative losses are also high and likely to increase as the climate warms. A better understanding of the sensitivity of evaporation and transpiration and their interaction with land cover types is a key area deserving further research.

A sub-question for this study has been to seek evidence for an influence of LUCC in affecting runoff patterns over time. Whilst we have identified many examples of non-stationary rainfall-runoff relationships, to be conclusive this work needs to go further by documenting historical and remotely sensed LUCC in Africa and linking it with empirical and modelling studies to help explain its contribution to observed patterns of change. Our results identify marked changes in runoff ratios (especially in the Sahel after 1970) but these integrate changes in data, non-linearities in the runoff response and the effects of LUCC. Given the shift in rainfall in the Sahel a magnified response is expected. However, regional land cover change (a natural response to drying) and LUCC (in response to underlying socio-economic changes), must surely play some role. Further empirical work at sub-basin and daily scales is necessary to establish better understanding. Modelling studies by Li et al. (2005; 2007) have obtained excellent results simulating river flows in the Niger and Lake Chad basins during humid and dry conditions. Their work shows threshold effects and non-linear hydrological impacts of LUCC. If physically-based models can be shown to simulate well the environmental dynamics displayed in many SSA basins this would strongly support their use for future climate or other impact studies.

6.4 Future Climate Change

Finally we end with some thoughts on the implications of this work for understanding the challenge of climate change for water resources management in Africa. The high levels of variability found in the historical records provide excellent opportunities to understand better their societal effects and adaptive responses (Glantz, 1992; Adger et al., 2003). In addition this variability represents a challenge to modelling land surface processes that determine how rainfall variability drives river flow variability. As already noted it may be some time before climate change signals can be reliably identified in African river flow series. Although we note that the floods in summer 2007 across SSA are unprecedented in their temporal and spatial scale since at least the end of the 19th century. Beyond the immediate humanitarian crisis these events are associated with major and long-term knock-on effects on African economies and infrastructure.

Most projections of future climate and impacts on runoff when averaged across multiple climate models suggest relatively modest changes out to the 2050s vis-à-vis the variability observed during the 20th century. Milly et al. (2005) simulated mean changes in runoff from a suite of climate models (IPCC AR4 set) of roughly +/- 5 to 30 per cent in Africa by the period 2041-60. Empirical analysis of drainage density and its relationship with annual rainfall identifies areas where substantial decreases in perennial drainage might occur, based on results from a similar set of climate models (de Wit and Stankiewicz, 2006).

The areas with reasonable climate model convergence show runoff increases in East Africa and reductions in Southern Africa, but no clear signal for the Sahel and Central Africa (Milly et al., 2005; Christensen et al., 2007). The main and most understood climate drivers of interannual and decadal rainfall variability are Atlantic (and other) Ocean SST patterns (West Africa and the Sahel), ENSO behaviour (West, Southern and East Africa) and Indian Ocean dynamics (East and Southern Africa). However, the underlying drivers of variability in these factors and their African teleconnections are not well captured by climate models and model simulations of future climate do not show clear tendencies in their behaviour (e.g. ENSO, Merryfield, 2006; Indian Ocean, Conway et al., 2007). Improvements in physical understanding and modelling capability will hopefully improve confidence and lead time in seasonal forecasts and climate projections, although non-stationary behaviour in teleconnections may affect progress towards these goals (Richard et al., 2000).

7. CONCLUSIONS

The conclusions are based around our aims which for SSA were to characterise the spatial and temporal dimensions of rainfall and river flow and explore the importance of rainfall for river flow variability. The region is possibly unique in its possession of so many large relatively undisturbed river basins to study long term hydrometeorological behaviour. Rainfall records from a global high resolution product and extensive river flow records from nine major international river basins provide the basis for the analysis. The early and latter decades of last century generally show very sparse coverage of rainfall stations. In most cases we are confident the hydrological series are reliable and possess thorough supporting information, although the Zambezi record is an exception to this. It is quite likely that from around the 1980s the quality of many records may have declined somewhat due to reduced budgets and capacity of national hydrological agencies, conflicts and less international support for these types of activities. From a global change perspective, international efforts to reduce the huge decline in observations need to take a pragmatic approach by supporting a core of benchmark sites with long, good quality records.

Our findings confirm that rainfall variability in SSA is high but also that rainfall provides the dominant control, alongside river basin physiography and human interventions, on interannual and interdecadal variability in river flows and hence surface water availability. River flows in major basins show clear examples of significant variability that challenges the effective management of water resources and results in huge socio-economic costs. We stress the need to couple better understanding of the biophysical drivers of variability (e.g. ENSO, Sahelian desiccation) with actions to strengthen the capacity of African water managers to deal with climatic variability and extremes.

The main findings of this analysis are as follows.

- Station densities in CRU TS2.1 (and other similar products) for Africa before ~1930 and after ~1980 are very low and some basins have very low densities throughout their records (e.g. Congo maximum of five gauges over 3.5 million km^2). Care is required in the interpretation of time series for these periods and regions.
- Trends in rainfall and river flows have been large during the 20th century. Rainfall (river flows) have displayed 20-year trends of up to ±3 (-15/+11) per cent of annual means. Changes in rainfall are magnified in the runoff response. This level of variability presents significant challenges to water resources management.
- On decadal time scales sub-Saharan Africa is characterised by drying across the Sahel after the early 1970s, relative stability punctuated by extreme wet years in East Africa (sometimes spreading into the Congo basin, e.g. 1961), and periodic behaviour underlying high

interannual variability in Southern Africa. Central Africa shows very modest decadal variability with some similarities to the Sahel in adjoining basins. A sub-region of East Africa, the Horn, shows drying in the 1970s and 1980s similar to the Sahel but has recovered substantially during the 1990s.

- Runoff coefficients tend to increase with increasing annual rainfall, they show a widespread decrease in West Africa since the 1970s drought, but no consistent patterns elsewhere.
- Overall the best period for robust rainfall-runoff relationships analysis is broadly 1961-1990. The strongest relationships occur in West Africa, reasonable ones in Central (even though station densities are very low), highly variable ones in East Africa because of the Rift Valley's complex hydrology, and very weak relationships in Southern Africa. During the period 1961-1990 (1931-1960) rainfall explains from 60-80 (40-60) percent of the variability in river flows in West Africa. Equivalent approximations for other regions are 40-70 (insufficient data) per cent in Central Africa, 5-65 (5-65) per cent in East Africa, and only 5-20 (5-20) per cent in Southern Africa.
- For some basins limited spatial coverage of rainfall stations leads to weak rainfall-runoff relationships. However, there are cases where weak relationships exist throughout the period of analysis, even with reasonable station coverage, and cases of robust stable relationships with rainfall series comprised of relatively few gauges. In basins with weak relationships macro-scale modelling using these data will be of limited success without considering data and subbasin scale conditions.
- Our results identify marked changes in runoff ratios and non-stationary rainfall-runoff relationships (especially in the Sahel after 1970) which integrate changes in data, non-linearities in the runoff response and the effects of LUCC. We conclude that for sub-Saharan Africa, robust identification and attribution of hydrological change is severely limited by data limitations, conflicting behaviour across basins/regions, low signal-to-noise ratios, sometimes weak rainfall-runoff relationships and limited assessment of the magnitude and potential effects of LUCC or other anthropogenic influences..
- Promising areas for further research include more detailed, smaller scale catchment analysis to explain facets of large basin response including interactions with LUCC, the use of satellite/merged-gauge estimates of basin rainfall, and better treatment of evaporation.
- This work has concentrated on biophysical variability: there is a need to couple this with the institutional and policy context of water resources management in Africa. More effective management of variability (the foundation for adaptation) will be contingent upon operational capacity which in many parts of Africa is weak.

Acknowledgements

The authors wish to acknowledge John Sutcliffe, Dick Grove and Jacques Sircoulon for their pioneering work on this topic. We also thank the many African hydrological agencies for information and data which supported this analysis. UK-France collaboration was facilitated by a British Council Alliance / EGIDE award (2004-2006).

References

Adger, W.N., Huq, S., Brown, K., Conway, D. and Hulme, M. (2003) Adaptation to climate change in the developing world. *Progress in Development Studies,* **3**, 179-195.

Ardoin-Bardin, S., 2004 : Variabilité hydroclimatique et impacts sur les ressources en eau de grands bassins hydrographiques en zone soudano-saheliénne. Thèse, Laboratoire des Sciences de la Terre et de l'Eau, Université Montpellier II, France.

Ba, M.B., and S.E. Nicholson, 1998: Analysis of convective activity and its relationship to the rainfall over the Rift Valley lakes of East Africa during 1983-90 using the Meteosat infrared channel. *J. App. Met.*, **37**, 1250-1264.

Bader J.C., 1990: Homogénéisation et complètement de la banque de données hydrométriques du bassin du sénégal en amont de Bakel. ORSTOM, Dakar, Sénégal.

Bader J.C., 1992: Etude de l'impact du barrage de Manantali sur le régime hydrologique du Sénégal au niveau de Bakel. ORSTOM, Dakar, Sénégal.

Birkett, C.M., 2000: Synergistic remote sensing of Lake Chad: Variability of basin inundation. *Remote Sensing Environment*, **72**, 218-236.

Bosch, J.M. and J.D. Hewlett, 1982: A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. *Journal of Hydrology*, **55**, 3-23.

Boyer J.F., C. Dieulin, N. Rouche, A. Cres, E. Servat, J.E. Paturel, and G. Mahe, 2006: SIEREM: an environmental information system for water resources. In: *Climate Variability and Change—Hydrological Impacts* (ed. by S. Demuth, A. Gustard, E. Planos, F. Scatena & E. Servat), 19-25, IAHS Publ. 308. IAHS Press, Wallingford, UK.

Bricquet, J.P., F. Bamba, G. Mahe, M. Toure, and J.C. Olivry, 1997: Evolution recente des ressources en eau de l'Afrique atlantique. *Revue des Sciences de l'eau*, **3**, 321-337.

Christensen, J.H., B. Hewitson, A. Busuioc, A. Chen, X. Gao, I. Held, R. Jones, R.K. Kolli, W.-T. Kwon, R. Laprise, V. Magaña Rueda, L. Mearns, C.G. Menéndez, J. Räisänen, A. Rinke, A. Sarr and P. Whetton, 2007: Regional climate projections. In: Climate Change 2007: The physical science basis. *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Christie, F. and J. Hanlon, 2001: Mozambique and the great flood of 2000. James Currey, Oxford.

CLIMDEV http://www.wmo.int/pages///prog/gcos/scXV/10_Development_Activities.pdf Page accessed on 02-12-07.

Conway, D., and M. Hulme, 1993: Recent fluctuations in precipitation and runoff over the Nile subbasins and their impact on main Nile discharge. *Climatic Change*, **25**, 127- 151.

Conway, D., and M. Hulme, 1996: The impacts of climate variability and future climate change in the Nile Basin on water resources in Egypt. *Int. J. Water Resources Development*, **12**, 261-280.

Conway, D., 2000: The climate and hydrology of the Upper Blue Nile River. *The Geographical Journal*, **166**, 49–62.

Conway, D., 2002: Extreme rainfall events and lake level changes in East Africa: recent events and historical precedents. In *The East African great lakes: limnology, palaeolimnology and biodiversity* (ed. E. O. Odada & D. O. Olago) Advances in Global Change Research vol. 12, pp. 63–92. Dordrecht: Kluwer.

Conway, D., 2005: From headwater tributaries to international river: Observing and adapting to climate variability and change in the Nile basin. *Global Environmental Change*, **15**, 99-114.

Conway, D., C. E. Hanson, R. Doherty, and A. Persechino, 2007: GCM simulations of the Indian Ocean dipole influence on East African rainfall: Present and future. *Geophys. Res. Lett.*, **34,** L03705, doi:10.1029/2006GL027597.

Dai, A.D., P.J. Lamb, K.E. Trenberth, M. Hulme, P.D. Jones, and P. Xie, 2004: The recent Sahel drought is real. *Int. J. Climat.*, **24**(11), 1323-1331.

de Wit, M., and J. Stankiewicz, 2006: Changes in surface water supply across Africa with predicted climate change. *Science*, **311**(5769), 1917–1921.

Falkenmark, M., 1991: Rapid population growth and water scarcity: The predicament of tomorrow's Africa, in K. Davis and M.S. Bernstam (eds.), pp. 81-94, Resources, environment, population: Present knowledge, future options. Population and Development Review. Oxford University Press, Oxford.

Gedney, N., P.M. Cox, R.A. Betts, O. Boucher, C. Huntingford, and P. Stott, 2006: Detection of a direct carbon dioxide effect in continental river runoff records. *Nature*, **439**, 835-838, doi:10.1038/nature04504.

Glantz, M.H., 1992: Global warming and environmental change in sub-Saharan Africa. *Global Environmental Change*, **2**, 183-204.

Grove, A.T., 1996: African river discharges and lake levels in the Twentieth Century. In T. C Johnson and E. O. Odada (eds.) pp. 95-100, The limnology, climatology and paleoclimatology of the East African Lakes, Gordon and Breach, The Netherlands.

Goulden, M. (2006) Livelihood diversification, social capital and resilience to climate variability amongst natural resource dependent societies in Uganda. PhD thesis School of Environmental Sciences, University of East Anglia, Norwich, UK.

Hamandawana, H., F. Eckardt, and R. Chanda, 2005: Linking archival and remotely sensed data for long-term environmental monitoring. *International Journal of Applied Earth Observation and Geoinformation*, **7**(4), 284–298.

Hamandawana, H., 2007: The desiccation of southern Africa's Okavango Delta: periodic fluctuation or long term trend? *Past Global Changes*, **15**(1), 12–13.

Hamandawana, H., R. Chanda, and F. Eckardt, 2007a: The role of human factors in the degradation of natural resources in and around the Okavango Delta. *International Journal of Environmental Studies*, **64**(5), 589–605.

Hamandawana, H., R. Chanda, and F. Eckardt, 2007b: Natural and human induced environmental changes in the semi-arid distal reaches of Botswana's Okavango Delta. *Journal of Land Use Science*, **2**(1), 57–78.

Hamandawana, H., R. Chanda, and F. Eckardt, *submitted*: Reappraisal of contemporary perspectives on climate change in Southern Africa's Okavango Delta sub-region. *Journal of Arid Environments*.

Hellmuth, M.E., A. Moorhead, M.C. Thomson, and J. Williams, (eds) 2007: Climate risk management in Africa: Learning from practice. International Research Institute for Climate and Society (IRI), Columbia University, New York, USA.

Hulme, M., 1992: Rainfall changes in Africa: 1931-1960 to 1961-1990. *International Journal of Climatology*, **12**, 685-699.

Hulme, M., 1996: Climate change within the period of meteorological records. In Adams, W.M., Goudie, A.S. and Orme A.R. (Eds.). The Physical Geography of Africa, pp. 88-102. Oxford University Press.

Hulme, M., R. Doherty, T. Ngara, M. New, and D. Lister, 2001: African climate change: 1900-2100. *Climate Research*, **17**, 145-168.

Hurst, H. E., 1933: The Nile Basin, Volume IV and Supplements 1-13, Ten day mean and monthly mean discharges of the Nile and its tributaries, Cairo.

HYCOS - http://grdc.bafg.de/servlet/is/1630/ Page accessed on 02-12-07.

Hydromet, 1982: Hydrometeorological survey of the catchments of Lake Victoria, Kyoga and Mobutu Sese Seko: Project findings and recommendations. Geneva: UNDP/WMO.

Janicot, S., 1992: Spatiotemporal variability of West African rainfall. Part I: Regionalization and typings. *Journal of Climate*, **5**(5), 489-497.

Khronostat 1.0, 1998 : Logiciel d'analyse statistique de series chronologiques, IRD ed. Paris.

L'Hôte, Y., G. Mahe, B. Some, and J.P. Triboulet, 2002: Analysis of a Sahelian annual rainfall index updated from 1896 to 2000; the drought still goes on. *Hydrological Sciences Journal*, **47**(4), 563-572.

Lamb, P., 1982. Persistance of subsaharan drought. *Nature*, **299**, 46-47.

Lankford, B.A., and T. Beale, 2007: Equilibrium and Non-equilibrium Theories of Sustainable Water Resources Management: Dynamic River Basin and Irrigation Behaviour in Tanzania. *Global Environmental Change*, **17**, 168-180.

Laraque, A., G. Mahe, D. Orange, and B. Marieu, 2001: Spatiotemporal variations in hydrological regimes within Central Africa during the XXth century. *Journal of Hydrology*, **245**(1-4), 104-117.

Le Barbé, L., and T. Label, 1997: Rainfall climatology of the Hapex-Sahel region during the years 1950-1990. *Journal of Hydrology*, **188-189**, 43-73.

Leblanc, M., G. Favreau, S. Massuel, S. Tweed, M. Loireau, B. Cappelaere, *In press*: Land clearance and hydrological change in the Sahel: SW Niger, Global and Planetary Change.

Leduc, C., G. Favreau, P. Schroeter, 2001: Long-term rise in a Sahelian water-table: The continental terminal in south-west Niger. *Journal of Hydrology*, **243**, 43-54.

Lemoalle, J., 2004: Lake Chad: a changing environment. In J.C.J. Nihoul, P.O. Zavialov and P.P. Micklin (eds), Dying and Dead Seas. NATO ARW/ASI Serie, Kluwer Publ. Dordrecht, pp 321-340.

Li, K.Y., M.T. Coe, and N. Ramankutty, 2005: An investigation of hydrological variability in West Africa using land surface models. *Journal of Climate*, **18**, 3173-3188.

Li, K.Y., M.T. Coe, N. Ramankutty, and R. De Jong, 2007: Modelling hydrological impact of land-use change in West Africa. *Journal of Hydrology*, **337**, 258-268.

Lørup, J.K., J.C. Refsgaard, and D. Mazvimavi, 1998: Assessing the effect of land use change on catchment runoff by combined use of statistical tests and hydrological modelling: Case studies from Zimbabwe. *Journal of Hydrology*, **205**, 147-163.

Lubes-Niel, H., J.M. Masson, J.E. Paturel, and E. Servat, 1998 : Variablite climatique et statistique. Etude par simulation de la puissance et de la robustesse de quelques tests utilises pour verifier l'homogeneïte de chroniques. *Revue des Sciences de l'Eau*, **11**(3), 383-408.

Magistro, J., 2001: Historical and human dimensions of climate variability and water resource constraint in the Senegal River Valley. *Climate Research* Special 11, **19**, 133-147.

Mahe, G., J.C. Olivry, 1999: Assessment of freshwater yields to the ocean along the intertropical Atlantic coast of Africa. *Comptes Rendus de l'Academie des Sciences*, Series IIa, **328**, 621-626.

Mahe, G., J.C. Olivry, R. Dessouassi, D. Orange, F. Bamba, and E. Servat, 2000 : Relations eaux de surface – eaux souterraines d'une rivière tropicale au Mali. *Comptes rendus de l'Academie des Sciences*, Serie IIa, **330**, 689-692.

Mahe, G., Y. L'Hôte, J.C. Olivry, and G. Wotling, 2001: Trends and discontinuities in regional rainfall of West and Central Africa – 1951-1989. *Hydrological Sciences Journal*, **46**(2), 211-226.

Mahe, G., J.E Paturel, E. Servat, D. Conway, and A. Dezetter, 2005: Impact of land use change on soil water holding capacity and river modelling of the Nakambe River in Burkina-Faso. *Journal of Hydrology*, **300**(1-4), 33-43.

Mahe, G., 2006: The impact of land-use/land-cover change and climate variability on the hydrology of the Sahel. In: Demuth S., Gustard A., Planos E., Scatena F. & Servat E. (Eds): Climate variability and change – Hydrological impacts. Proceedings of the Fifth FRIEND World Conference, Publ. AISH no 308, 679-684.

McMahon, T.A., M.C. Peel, R.M. Vogel, G.G.S Pegram, *In press*: Global streamflows – Part 3: Country and climate zone characteristics, *Journal of Hydrology*.

Merryfield, W., 2006: Changes to ENSO under CO_2 doubling in a multi-model ensemble. J. *Clim.*, **19**, 4009–4027.

Milly, P.C.D, K.A. Dune, and A.V. Vecchia, 2005: Global pattern of trends in streamflow and water availability in a changing climate. *Nature*, **438**(17), doi:10.1038/nature04312.

Mitchell, T.D., and P.D. Jones, 2005: An improved method of constructing a database of monthly climate observations and associated high resolution grids. *International Journal of Climatology*, **25**, 693–712.

Nemec, J., and J. Schaake, 1982: Sensitivity of water resource systems to climate variation. *Hydrological Sciences Journal*, **27**(3), 327-343.

New, M., M.C Todd, M. Hulme, and P. Jones, 2001: Precipitation measurements and trends in the twentieth century. *International Journal of Climatology*, **21**, 1889-1922.

Nicholson, S.E., 1983: Sub-Saharan rainfall in the years 1976-1980: evidence of continued drought. *Mon. Weath. Rev.*, **111**, 1646-1654.

Nicholson, S.E., 1996: Environmental change within the historical period. In Adams, W.M., Goudie, A.S. and Orme A.R. (Eds.) The Physical Geography of Africa, pp. 60-87. Oxford University Press.

Nicholson, S.E., 1998: Historical fluctuations of Lake Victoria and other lakes in the northern Rift Valley of East Africa. In: Lehman JT (ed.) Environmental change and response in East African lakes. Kluwer, Dordrecht, p 7–35.

Nicholson, S.E., 1999: Historical and modern fluctuations of lakes Tanganyika and Rukwa and their relationship to rainfall variability. *Climatic Change*, **41**, 53-71.

Nicholson, S.E., 2005: On the question of the ''recovery'' of the rains in the West African Sahel. *Journal of Arid Environments*, **63**, 615–641.

Ogutunde, P.G., J. Friesen, N. van de Giesen, and H.H.G. Savenije, 2006: Hydroclimatology of the Volta River Basin in West Africa: Trends and variability from 1901 to 2002. *Physics and Chemistry of the Earth*, **31**, 1180-1188.

Olivry, J.C., J.P. Bricquet, and G. Mahe, 1998 : Variabilite de la puissance des crues des grands cours d'eau d'Afrique intertropicale et incidence de la baisse des ecoulements de base au cours des deux dernières decennies. In : Servat E., Hugues D., Fritsch J.M. & Hulme M. (Eds) : Water Ressources Variability in Africa during the XXth Century. Proceedings de la conference ABIDJAN'98, ORSTOM/AISH/UNESCO, Publ. AISH no 252, 189-197.

Orange, D., A. Wesselink, G. Mahe, and C. Feizoure, 1997: The effects of climate changes on river baseflow and aquifer storage in Central Africa. Proceedings of Rabat Symposium, 5th IAHS Assembly, IAHS Publ. 240, Sustainability of water resources under increasing uncertainty, 113-123.

Paturel, J.E., E. Servat, B. Kouame, H. Lubes, M. Ouedraogo, and J.M. Masson, 1997: Climatic variability in humid Africa along the Gulf of Guinea. Part two: An integrated regional approach. *Journal of Hydrology*, **191**, 16-36.

Paturel, J.E., E. Servat, M.O. Delattre, and H. Lubes-Niel, 1998 : Analyse de series pluviometriques de longue duree en Afrique de l'Ouest et Centrale non sahelienne dans un contexte de variabilite climatique. *Hydrol. Sci. J.*, **43**(6), 937-946.

Peel, M.C., T.A. McMahon, B.L. Finlayson, and F.G.R. Watson, 2001: Identification and explanation of continental differences in the variability of annual runoff. *Journal of Hydrology*, **250**, 224-240.

Peel, M. C., T.A. McMahon, and B.L. Finlayson, 2004: Continental differences in the variability of annual runoff – update and reassessment. *Journal of Hydrology*, **295**, 185–197.

Piper, B. S., D. T. Plinston, and J. V. Sutcliffe, 1986: The water balance of Lake Victoria. *Hydrol. Sci. J.,* **31,** 25–37.

Richard, Y., S. Trzaska, P. Roucou, M. Rouault, 2000: Modification of the Southern African rainfall variability/ENSO relationship since the late 1960s. *Climate Dynamics*, **16**, 883-895.

Saji, N.H., B.N. Boswami, P.N. Vinayachandran, and T. Yamagata, 1999: A dipole made in the Tropical Indian Ocean. *Nature*, **401**, 360-363.

Sarch, M.-T., and E.H. Allison, 2000: Fluctuating fisheries in Africa's inland waters: well-adapted livelihoods, maladapted management. In *Proc. 10th Int. Conf. of the Institute of Fisheries Economics and Trade, Corvallis, OR, 9–14 July 2000*. (Available at http://osu.orst.edu/dept/IIFET/2000/papers/sarch.pdf.)

Savenije, H. H. G., 1996: Does moisture feedback affect rainfall significantly? *Physics and Chemistry of the Earth*, **20**(56), 507-513.

Sene, K.J. and D.T. Plinston, 1994: A review and update of the hydrology of Lake Victoria. *Hyd. Sci. J.*, **39**, 47-63.

Sepulchre, P., M. Schuster, G. Ramstein, G. Krinner, J.-F. Girard, P. Vignaud, and M. Brunet, *in press*: Evolution of Lake Chad Basin hydrology during the mid-Holocene: A preliminary approach from lake to climate modelling. *Global and Planetary Change*.

SIEREM: an environmental information system for water resources. In: *Climate Variability and Change—Hydrological Impacts* (ed. by S. Demuth, A. Gustard, E. Planos, F. Scatena & E. Servat), 19-25, IAHS Publ. 308. IAHS Press, Wallingford, UK.

Sircoulon, J., 1976 : Les donnees hydropluviometriques de la secheresse recente en Afrique intertropicale; Comparison avec les secheresses "1913" et "1940". *Cah. ORSTOM, ser. Hydrol.*, **13**(2), 75-174.

Sircoulon, J., 1985 : La secheresse en Afrique de l'Ouest. Comparaison des annees "1982-1984" avec les annees "1972-1973". *Cah. ORSTOM, ser. Hydrol.*, **21**(4), 75-86.

Sutcliffe, J.V. and Petersen (2007) Lake Victoria: derivation of a corrected natural water level series. *Hydrological Sciences Journal*, **52**(6), 1316-1321.

Sutcliffe, J.V. and D.G. Knott, 1987: Historical variations in African water resources, in S.I. Solomon, M. Beran and W. Hogg (eds.), pp. 463-476, The influence of climate change and climatic variability on the hydrologic regime and water resources. IAHS Publication No. 168, Oxfordshire.

Sutcliffe, J.V. and Y.P. Parks, 1999: The hydrology of the Nile. IAHS special publication No. 5. IAHS Press, Wallingford, Oxfordshire, 179 p.

Tarhule, A., 2005: Damaging rainfall and flooding: The other Sahel hazards. *Climatic Change*, **72**, 355-377.

Tate, E., J. Sutcliffe, D. Conway, and F. Farquharson, 2004: Water balance of Lake Victoria: update to 2000 and climate change modelling to 2100. *Hydrological Sciences Journal*, **49**(4), 563-574.

Troy, B., C. Sarron, J.M. Fritch, and D. Rollin, 2007: Assessment of the impacts of land use changes on the hydrological regime of a small rural catchment in South Africa. *Physics and Chemistry of the Earth*, **32**, 984-994.

UNESCO, 1995: Discharge of selected rivers of Africa. Studies and reports in hydrology, 52. UNESCO, Paris.

van Jaarsveld, A.S., and S.L. Chown, 2001: Climate change and its impacts in South Africa. *TRENDS in Ecology & Evolution*, **16**(1), 13-14.

Vörösmarty, C.J., and D. Sahagian, 2000: Anthropogenic disturbance of the terrestrial water cycle. *BioScience*, **50**, 753-765.

Vörösmarty, C.J. and 17 other authors (2001) Global water data: A newly endangered species. *EOS Transactions, AGU* **82**, pp 54, 56, 58.

Vörösmarty, C.J., E.M. Douglas, P.A. Green, and C. Revenga, 2005: Geospatial indicators of emerging water stress: an application to Africa. *Ambio*, **34**(3), 230–236.

Washington, R., M. Harrison, D. Conway, E. Black, A. Challinor, D. Grimes, R. Jones, A. Morse, G. Kay, and M. Todd, 2006: African climate change: Taking the shorter route. *Bulletin of the American Meteorological Society* , **87**(10), 1355-1366.

Webster, P.J., A.M. Moore, J.P. Loschnigg, and R.R. Lebden, 1999: Coupled Ocean-Atmospheres Dynamics in the Indian Ocean during 1997-98. *Nature*, **401**, 356-360.

World Bank, 1989: Sub-Saharan Africa hydrological assessment Sudan. World Bank-UNDP, RAF/87/030.

World Bank, 2006: Managing water resources to maximise sustainable growth: A country water resources assistance strategy for Ethiopia. Washington DC: World Bank.

Woyessa, Y. E., E. Pretorius, P.S. van Heerden, M. Hensley, L.D. van Rensburg, 2006: Impact of land use on river basin water balance: A case study of the Modder River Basin, South Africa. Colombo, Sri Lanka: Comprehensive Assessment Secretariat. 37p. Comprehensive Assessment Research Report 12, http://www.iwmi.cgiar.org/Assessment/files_new/publications/CA%20Research%20Reports/CARR12-low.pdf

Zhang, X., F.W. Zwiers, G.C. Hegerl, F.H. Lambert, N.P. Gillett, S. Solomon, P.A. Stott, and T. Nozawa, 2007: Detection of human influence on twentieth-century precipitation trends. *Nature*, **448**(7152), 461-465, doi:10.1038/nature06025.

Tyndall°Centre
for Climate Change Research

Tyndall Working Paper series
2000 - 2008

The Tyndall Centre working paper series presents results from research which are mature enough to be submitted to a refereed journal, to a sponsor, to a major conference or to the editor of a book. The intention is to enhance the early public availability of research undertaken by the Tyndall family of researchers, students and visitors. They can be downloaded from the Tyndall Website at:

http://www.tyndall.ac.uk/publications/working_papers/working_papers.shtml

The accuracy of working papers and the conclusions reached are the responsibility of the author(s) alone and not the Tyndall Centre.

Papers available in this series are:

- Barker T., (2008) **The Economics of Avoiding Dangerous Climate Change**: Tyndall Centre Working Paper 117
- Estrada M, Corbera E., Brown K, (2008) **How do regulated and voluntary carbon-offset schemes compare?**: Tyndall Centre Working Paper 116
- Estrada Porrua M, Corbera E., Brown K, (2007) **REDUCING GREENHOUSE GAS EMISSIONS FROM DEFORESTATION IN DEVELOPING COUNTRIES: REVISITING THE ASSUMPTIONS**: Tyndall Centre Working Paper 115
- Boyd E., Hultman N E., Roberts T., Corbera E., Ebeling J., Liverman D, Brown K, Tippmann R., Cole J., Mann P, Kaiser M., Robbins M, (2007) **The Clean Development Mechanism: An assessment of current practice and future approaches for policy**: Tyndall Centre Working Paper 114
- Hanson, S., Nicholls, R., Balson, P., Brown, I., French, J.R., Spencer, T., Sutherland, W.J. (2007) **Capturing coastal morphological change within regional integrated assessment: an outcome-driven fuzzy logic approach**: Tyndall Working Paper No. 113
- Okereke, C., Bulkeley, H. (2007) **Conceptualizing climate change governance beyond the international regime: A review of four theoretical approaches**: Tyndall Working Paper No. 112
- Doulton, H., Brown, K. (2007) **'Ten years to prevent catastrophe'? Discourses of climate change and international development in the UK press**: Tyndall Working Paper No. 111
- Dawson, R.J., et al (2007) **Integrated analysis of risks of coastal flooding and cliff erosion under scenarios of long term change**: Tyndall Working Paper No. 110
- Okereke, C., (2007) **A review of UK FTSE 100 climate strategy and a framework for more in-depth analysis in the context of a post-2012 climate regime**: Tyndall Centre Working Paper 109
- Gardiner S., Hanson S., Nicholls R., Zhang Z., Jude S., Jones A.P., et al (2007) **The Habitats Directive, Coastal Habitats and Climate Change – Case Studies from the South Coast of the UK**: Tyndall Centre Working Paper 108
- Schipper E. Lisa, (2007) **Climate Change Adaptation and Development: Exploring the Linkages**: Tyndall Centre Working Paper 107
- Okereke C., Mann P, Osbahr H, (2007) **Assessment of key negotiating issues at Nairobi climate COP/MOP and what it means for the future of the climate regime.** : Tyndall Centre Working Paper No. 106
- Walkden M, Dickson M, (2006) **The response of soft rock shore profiles to increased sea-level rise.** : Tyndall Centre Working Paper 105
- Dawson R., Hall J, Barr S, Batty M., Bristow A, Carney S, Evans E.P., Kohler J., Tight M, Walsh C, Ford A, (2007) **A blueprint for the integrated assessment of climate change in cities.** : Tyndall Centre Working Paper 104
- Dickson M., Walkden M., Hall J., (2007) **Modelling the impacts of climate change on an eroding coast over the 21st**

Century: Tyndall Centre Working Paper 103

- Klein R.J.T, Erickson S.E.H, Næss L.O, Hammill A., Tanner T.M., Robledo, C., O'Brien K.L.,(2007) **Portfolio screening to support the mainstreaming of adaptation to climatic change into development assistance**: Tyndall Centre Working Paper 102

- Agnolucci P., (2007) **Is it going to happen? Regulatory Change and Renewable Electricity**: Tyndall Centre Working Paper 101

- Kirk K., (2007) **Potential for storage of carbon dioxide in the rocks beneath the East Irish Sea**: Tyndall Centre Working Paper 100

- Arnell N.W., (2006) **Global impacts of abrupt climate change: an initial assessment**: Tyndall Centre Working Paper 99

- Lowe T.,(2006) **Is this climate porn? How does climate change communication affect our perceptions and behaviour?**, Tyndall Centre Working Paper 98

- Walkden M, Stansby P,(2006) **The effect of dredging off Great Yarmouth on the wave conditions and erosion of the North Norfolk coast**. Tyndall Centre Working Paper 97

- Anthoff, D., Nicholls R., Tol R S J, Vafeidis, A., (2006) **Global and regional exposure to large rises in sea-level: a sensitivity analysis**. This work was prepared for the Stern Review on the Economics of Climate Change: Tyndall Centre Working Paper 96

- Few R., Brown K, Tompkins E. L, (2006) **Public participation and climate change adaptation**, Tyndall Centre Working Paper 95

- Corbera E., Kosoy N, Martinez Tuna M, (2006) **Marketing ecosystem services through protected areas and rural communities in Meso-America: Implications for economic efficiency, equity and political legitimacy**, Tyndall Centre Working Paper 94

- Schipper E. Lisa, (2006) **Climate Risk, Perceptions and Development in El Salvador**, Tyndall Centre Working Paper 93

- Tompkins E. L, Amundsen H, (2005) **Perceptions of the effectiveness of the United Nations Framework Convention on Climate Change in prompting behavioural change,** Tyndall Centre Working Paper 92

- Warren R., Hope C, Mastrandrea M, Tol R S J, Adger W. N., Lorenzoni I., (2006) **Spotlighting the impacts functions in integrated assessments. Research Report Prepared for the Stern Review on the Economics of Climate Change**, Tyndall Centre Working Paper 91

- Warren R., Arnell A, Nicholls R., Levy P E, Price J, (2006) **Understanding the regional impacts of climate change: Research Report Prepared for the Stern Review on the Economics of Climate Change,** Tyndall Centre Working Paper 90

- Barker T., Qureshi M, Kohler J., (2006) **The Costs of Greenhouse Gas Mitigation with Induced Technological Change: A Meta-Analysis of Estimates in the Literature**, Tyndall Centre Working Paper 89

- Kuang C, Stansby P, (2006) **Sandbanks for coastal protection: implications of sea-level rise. Part 3: wave modelling**, Tyndall Centre Working Paper 88

- Kuang C, Stansby P, (2006) **Sandbanks for coastal protection: implications of sea-level rise. Part 2: current and morphological modelling**, Tyndall Centre Working Paper 87

- Stansby P, Kuang C, Laurence D, Launder B, (2006) **Sandbanks for coastal protection: implications of sea-level rise. Part 1: application to East Anglia**, Tyndall Centre Working Paper 86

- Bentham M, (2006) **An assessment of carbon sequestration potential in the UK – Southern North Sea case study:** Tyndall Centre Working Paper 85

- Anderson K., Bows A., Upham P., (2006) **Growth scenarios for EU & UK aviation: contradictions with climate policy,** Tyndall Centre Working Paper 84

- Williamson M., Lenton T., Shepherd J., Edwards N, (2006) **An efficient numerical terrestrial scheme (ENTS) for fast earth system modelling**, Tyndall Centre Working Paper 83

- Bows, A., and Anderson, K. (2005) **An analysis of a post-Kyoto climate policy model**, Tyndall Centre Working Paper 82

- Sorrell, S., (2005) **The economics of energy service contracts**, Tyndall Centre Working Paper 81

- Wittneben, B., Haxeltine, A., Kjellen, B., Köhler, J., Turnpenny, J., and Warren, R., (2005) **A framework for assessing the political**

economy of post-2012 global climate regime, Tyndall Centre Working Paper 80

- Ingham, I., Ma, J., and Ulph, A. M. (2005) **Can adaptation and mitigation be complements?**, Tyndall Centre Working Paper 79
- Agnolucci,. P (2005) **Opportunism and competition in the non-fossil fuel obligation market**, Tyndall Centre Working Paper 78
- Barker, T., Pan, H., Köhler, J., Warren., R and Winne, S. (2005) **Avoiding dangerous climate change by inducing technological progress: scenarios using a large-scale econometric model**, Tyndall Centre Working Paper 77
- Agnolucci,. P (2005) **The role of political uncertainty in the Danish renewable energy market**, Tyndall Centre Working Paper 76
- Fu, G., Hall, J. W. and Lawry, J. (2005) **Beyond probability: new methods for representing uncertainty in projections of future climate**, Tyndall Centre Working Paper 75
- Ingham, I., Ma, J., and Ulph, A. M. (2005) **How do the costs of adaptation affect optimal mitigation when there is uncertainty, irreversibility and learning?**, Tyndall Centre Working Paper 74
- Walkden, M. (2005) **Coastal process simulator scoping study**, Tyndall Centre Working Paper 73
- Lowe, T., Brown, K., Suraje Dessai, S., Doria, M., Haynes, K. and Vincent., K (2005) **Does tomorrow ever come? Disaster narrative and public perceptions of climate change**, Tyndall Centre Working Paper 72
- Boyd, E. Gutierrez, M. and Chang, M. (2005) **Adapting small-scale CDM sinks projects to low-income communities**, Tyndall Centre Working Paper 71
- Abu-Sharkh, S., Li, R., Markvart, T., Ross, N., Wilson, P., Yao, R., Steemers, K., Kohler, J. and Arnold, R. (2005) **Can Migrogrids Make a Major Contribution to UK Energy Supply?**, Tyndall Centre Working Paper 70
- Tompkins, E. L. and Hurlston, L. A. (2005) **Natural hazards and climate change: what knowledge is transferable?**, Tyndall Centre Working Paper 69
- Bleda, M. and Shackley, S. (2005) **The formation of belief in climate change in business organisations: a dynamic simulation model**, Tyndall Centre Working Paper 68
- Turnpenny, J., Haxeltine, A. and O'Riordan, T., (2005) **Developing regional and local scenarios for climate change mitigation and adaptation: Part 2: Scenario creation**, Tyndall Centre Working Paper 67
- Turnpenny, J., Haxeltine, A., Lorenzoni, I., O'Riordan, T., and Jones, M., (2005) **Mapping actors involved in climate change policy networks in the UK**, Tyndall Centre Working Paper 66
- Adger, W. N., Brown, K. and Tompkins, E. L. (2004) **Why do resource managers make links to stakeholders at other scales?**, Tyndall Centre Working Paper 65
- Peters, M.D. and Powell, J.C. (2004) **Fuel Cells for a Sustainable Future II**, Tyndall Centre Working Paper 64
- Few, R., Ahern, M., Matthies, F. and Kovats, S. (2004) **Floods, health and climate change: a strategic review**, Tyndall Centre Working Paper 63
- Barker, T. (2004) **Economic theory and the transition to sustainability: a comparison of approaches**, Tyndall Centre Working Paper 62
- Brooks, N. (2004) **Drought in the African Sahel: long term perspectives and future prospects**, Tyndall Centre Working Paper 61
- Few, R., Brown, K. and Tompkins, E.L. (2004) **Scaling adaptation: climate change response and coastal management in the UK**, Tyndall Centre Working Paper 60
- Anderson, D and Winne, S. (2004) **Modelling Innovation and Threshold Effects In Climate Change Mitigation**, Tyndall Centre Working Paper 59
- Bray, D and Shackley, S. (2004) **The Social Simulation of The Public Perceptions of Weather Events and their Effect upon the Development of Belief in Anthropogenic Climate Change**, Tyndall Centre Working Paper 58
- Shackley, S., Reiche, A. and Mander, S (2004) **The Public Perceptions of Underground Coal Gasification (UCG): A Pilot Study**, Tyndall Centre Working Paper 57
- Vincent, K. (2004) **Creating an index of social vulnerability to climate change for Africa**, Tyndall Centre Working Paper 56

high-resolution grids of monthly climate for Europe and the globe: the observed record (1901-2000) and 16 scenarios (2001-2100), Tyndall Centre Working Paper 55

- Turnpenny, J., Carney, S., Haxeltine, A., and O'Riordan, T. (2004) **Developing regional and local scenarios for climate change mitigation and adaptation Part 1: A framing of the East of England** Tyndall Centre Working Paper 54

- Agnolucci, P. and Ekins, P. (2004) **The Announcement Effect And Environmental Taxation** Tyndall Centre Working Paper 53

- Agnolucci, P. (2004) **Ex Post Evaluations of CO2 –Based Taxes: A Survey** Tyndall Centre Working Paper 52

- Agnolucci, P., Barker, T. and Ekins, P. (2004) **Hysteresis and Energy Demand: the Announcement Effects and the effects of the UK Climate Change Levy** Tyndall Centre Working Paper 51

- Powell, J.C., Peters, M.D., Ruddell, A. and Halliday, J. (2004) **Fuel Cells for a Sustainable Future?** Tyndall Centre Working Paper 50

- Awerbuch, S. (2004) **Restructuring our electricity networks to promote decarbonisation**, Tyndall Centre Working Paper 49

- Pan, H. (2004) **The evolution of economic structure under technological development**, Tyndall Centre Working Paper 48

- Berkhout, F., Hertin, J. and Gann, D. M., (2004) **Learning to adapt: Organisational adaptation to climate change impacts**, Tyndall Centre Working Paper 47

- Watson, J., Tetteh, A., Dutton, G., Bristow, A., Kelly, C., Page, M. and Pridmore, A., (2004) **UK Hydrogen Futures to 2050**, Tyndall Centre Working Paper 46

- Purdy, R and Macrory, R. (2004) **Geological carbon sequestration: critical legal issues**, Tyndall Centre Working Paper 45

- Shackley, S., McLachlan, C. and Gough, C. (2004) **The Public Perceptions of Carbon Capture and Storage**, Tyndall Centre Working Paper 44

- Anderson, D. and Winne, S. (2003) **Innovation and Threshold Effects in Technology Responses to Climate Change**, Tyndall Centre Working Paper 43

- Kim, J. (2003) **Sustainable Development and the CDM: A South African Case Study**, Tyndall Centre Working Paper 42

- Watson, J. (2003), **UK Electricity Scenarios for 2050**, Tyndall Centre Working Paper 41

- Klein, R.J.T., Lisa Schipper, E. and Dessai, S. (2003), **Integrating mitigation and adaptation into climate and development policy: three research questions**, Tyndall Centre Working Paper 40

- Tompkins, E. and Adger, W.N. (2003). **Defining response capacity to enhance climate change policy**, Tyndall Centre Working Paper 39

- Brooks, N. (2003). **Vulnerability, risk and adaptation: a conceptual framework**, Tyndall Centre Working Paper 38

- Ingham, A. and Ulph, A. (2003) **Uncertainty, Irreversibility, Precaution and the Social Cost of Carbon**, Tyndall Centre Working Paper 37

- Kröger, K. Fergusson, M. and Skinner, I. (2003). **Critical Issues in Decarbonising Transport: The Role of Technologies**, Tyndall Centre Working Paper 36

- Tompkins E. L and Hurlston, L. (2003). **Report to the Cayman Islands' Government. Adaptation lessons learned from responding to tropical cyclones by the Cayman Islands' Government, 1988 – 2002**, Tyndall Centre Working Paper 35

- Dessai, S., Hulme, M (2003). **Does climate policy need probabilities?**, Tyndall Centre Working Paper 34

- Pridmore, A., Bristow, A.L., May, A. D. and Tight, M.R. (2003). **Climate Change, Impacts, Future Scenarios and the Role of Transport**, Tyndall Centre Working Paper 33

- Xueguang Wu, Jenkins, N. and Strbac, G. (2003). **Integrating Renewables and CHP into the UK Electricity System: Investigation of the impact of network faults on the stability of large offshore wind farms**, Tyndall Centre Working Paper 32

- Turnpenny, J., Haxeltine A. and O'Riordan, T. (2003). **A scoping study of UK user needs for managing climate futures. Part 1 of the pilot-phase interactive integrated assessment process (Aurion Project)**, Tyndall Centre Working Paper 31

- Hulme, M. (2003). **Abrupt climate change: can society cope?**, Tyndall Centre Working Paper 30

- Brown, K. and Corbera, E. (2003). **A Multi-Criteria Assessment Framework for Carbon-Mitigation Projects: Putting "development" in the centre of decision-making**, Tyndall Centre Working Paper 29

- Dessai, S., Adger, W.N., Hulme, M., Köhler, J.H., Turnpenny, J. and Warren, R. (2003). **Defining and experiencing dangerous climate change**, Tyndall Centre Working Paper 28

- Tompkins, E.L. and Adger, W.N. (2003). **Building resilience to climate change through adaptive management of natural resources**, Tyndall Centre Working Paper 27

- Brooks, N. and Adger W.N. (2003). **Country level risk measures of climate-related natural disasters and implications for adaptation to climate change**, Tyndall Centre Working Paper 26

- Xueguang Wu, Mutale, J., Jenkins, N. and Strbac, G. (2003). **An investigation of Network Splitting for Fault Level Reduction**, Tyndall Centre Working Paper 25

- Xueguang Wu, Jenkins, N. and Strbac, G. (2002). **Impact of Integrating Renewables and CHP into the UK Transmission Network**, Tyndall Centre Working Paper 24

- Paavola, J. and Adger, W.N. (2002). **Justice and adaptation to climate change**, Tyndall Centre Working Paper 23

- Watson, W.J., Hertin, J., Randall, T., Gough, C. (2002). **Renewable Energy and Combined Heat and Power Resources in the UK**, Tyndall Centre Working Paper 22

- Watson, W. J. (2002). **Renewables and CHP Deployment in the UK to 2020**, Tyndall Centre Working Paper 21

- Turnpenny, J. (2002). **Reviewing organisational use of scenarios: Case study - evaluating UK energy policy options**, Tyndall Centre Working Paper 20

- Pridmore, A. and Bristow, A., (2002). **The role of hydrogen in powering road transport**, Tyndall Centre Working Paper 19

- Watson, J. (2002). **The development of large technical systems: implications for hydrogen**, Tyndall Centre Working Paper 18

- Dutton, G., (2002). **Hydrogen Energy Technology**, Tyndall Centre Working Paper 17

- Adger, W.N., Huq, S., Brown, K., Conway, D. and Hulme, M. (2002). **Adaptation to climate change: Setting the Agenda for Development Policy and Research**, Tyndall Centre Working Paper 16

- Köhler, J.H., (2002). **Long run technical change in an energy-environment-economy (E3) model for an IA system: A model of Kondratiev waves**, Tyndall Centre Working Paper 15

- Shackley, S. and Gough, C., (2002). **The Use of Integrated Assessment: An Institutional Analysis Perspective**, Tyndall Centre Working Paper 14

- Dewick, P., Green K., Miozzo, M., (2002). **Technological Change, Industry Structure and the Environment**, Tyndall Centre Working Paper 13

- Dessai, S., (2001). **The climate regime from The Hague to Marrakech: Saving or sinking the Kyoto Protocol?,** Tyndall Centre Working Paper 12

- Barker, T. (2001). **Representing the Integrated Assessment of Climate Change, Adaptation and Mitigation**, Tyndall Centre Working Paper 11

- Gough, C., Taylor, I. and Shackley, S. (2001). **Burying Carbon under the Sea: An Initial Exploration of Public Opinions**, Tyndall Centre Working Paper 10

- Barnett, J. and Adger, W. N. (2001). **Climate Dangers and Atoll Countries**, Tyndall Centre Working Paper 9

- Adger, W. N. (2001). **Social Capital and Climate Change**, Tyndall Centre Working Paper 8

- Barnett, J. (2001). **Security and Climate Change**, Tyndall Centre Working Paper 7

- Goodess, C.M., Hulme, M. and Osborn, T. (2001). **The identification and evaluation of suitable scenario development methods for the estimation of future probabilities of extreme weather events**, Tyndall Centre Working Paper 6

- Barnett, J. (2001). **The issue of 'Adverse Effects and the Impacts of Response Measures' in the UNFCCC**, Tyndall Centre Working Paper 5

- Barker, T. and Ekins, P. (2001). **How High are the Costs of Kyoto for the US Economy?**, Tyndall Centre Working Paper 4

- Berkhout, F, Hertin, J. and Jordan, A. J. (2001). **Socio-economic futures in climate change impact assessment: using scenarios as 'learning machines'**, Tyndall Centre Working Paper 3

- Hulme, M. (2001). **Integrated Assessment Models**, Tyndall Centre Working Paper 2

- Mitchell, T. and Hulme, M. (2000). **A Country-by-Country Analysis of Past and Future Warming Rates**, Tyndall Centre Working Paper 1

Tyndall°Centre
for Climate Change Research

For further information please contact

Javier Delgado-Esteban