Tyndall°Centre
for Climate Change Research

Adaptation to climate change in international river basins in Africa: a review

Marisa Goulden, Declan Conway & Aurelie Persechino

December 2008

Tyndall Centre for Climate Change Research Working Paper 127

Adaptation to climate change in international river basins in Africa: a review*

MARISA GOULDEN[1,2**], DECLAN CONWAY[3,1] & AURELIE PERSECHINO[3,2]

1. Tyndall Centre for Climate Change Research, University of East Anglia, Norwich, NR4 7TJ, United Kingdom
2. Overseas Development Group, University of East Anglia, Norwich, NR4 7TJ, United Kingdom
3. School of Development Studies, University of East Anglia, Norwich, NR4 7TJ, United Kingdom

Tyndall Working Paper 127, December 2008

* This paper has been submitted and reviewed for *Hydrological Sciences Journal*
**Corresponding address and email: Overseas Development Group, University of East Anglia, Norwich, NR4 7TJ, United Kingdom. m.goulden@uea.ac.uk

Abstract

This paper reviews current knowledge of the potential impacts of climate change on water resources in Africa and the possible limits, barriers or opportunities for adaptation to climate change in internationally shared river basins. Africa faces significant challenges to water resources management in the form of high variability and regional scarcity, set within the context of generally weak institutional capacity. Management is further challenged by the transboundary nature of many of its river basins. Climate change, despite uncertainty about the detail of its impacts on water resources, is likely to exacerbate many of these challenges. River basins and the riparian states that share them differ in their capacities to adapt. Without appropriate cooperation adaptation may be limited and uneven. Further research to examine the factors and processes that are important for cooperation to lead to positive adaptation outcomes and the increased adaptive capacity of water management institutions is suggested.

Key words
Climate change, adaptation, water resources, Africa, transboundary rivers, international river basins, conflict, cooperation

INTRODUCTION

Africa's fresh water resources are vital to the support of livelihoods (particularly agriculture and fisheries-based livelihoods), food security and power generation as well as growing domestic and industrial needs. Water resources are under pressure from increasing demand and competing uses. Climate change threatens to put further pressure on water resources due to a possible increase in the already high variability in rainfall and river flows and changes to the geographical distribution of water resources, some areas possibly becoming drier, whilst others becoming wetter (Kundzewicz *et al.*, 2007). Water users and water resource management institutions have to adapt to this variability, changes in demand and the effects of climate change, which whilst they may be significant in the future they are also uncertain.

Adaptation may be complicated by the transboundary nature of water resources. An estimated 90% of all Africa's surface freshwater resources are located in river basins and lakes that are shared between two or more countries (United Nations Development Programme, 2006). There are 60 international river basins within the African continent, covering 62% of the continent's area. There are five river basins in Africa that are shared by eight or more countries (Congo, Niger, Nile, Zambezi and Lake Chad) and 30 are shared by more than two countries (Wolf *et al.*, 1999).

International rivers in Africa pose particular management challenges because of competing national interests and limited mechanisms for cooperative action between nations that share major river basins. There are many examples in Africa where water management has been compromised by climate variability and competing transboundary needs for water (or power generation from water); for example, the Manantali Dam in Senegal (Magistro & Lo, 2001), the Mtera Dam in Tanzania (Lankford *et al.*, 2004) and the current low levels in Lake Victoria (Pearce, 2006).

The transboundary nature of many of the World's great rivers and increasing water scarcity has led to ideas of 'water wars' or conflict over water resources (Gleick, 1993). However, nations that share international river basins have histories of both conflict and cooperation over water resources (Yoffe *et al.*, 2003). Despite the benefits proposed from cooperation over shared resources there are many barriers to cooperative action. These barriers are political, social, institutional, physical and geographical.

In this paper we use the term conflict not just to refer to armed violent conflict between nations, but also to a range of types of negative interaction that encompass mild verbally-expressed discord and cold interstate relations to hostile military acts or declarations of war between states or their representatives and institutions (Yoffe *et al.*, 2003). Conflict can also refer to negative interactions between societal groups at a sub-state scale. Similarly the term cooperation encompasses a range of positive interactions that can take many forms (see Yoffe *et al.* 2003) and occur between a number of different actors at different scales. Keohane (2005) describes how "cooperation occurs when actors adjust their behaviour to the actual or anticipated preferences of others, through a process of policy coordination"(p51) and distinguishes it from harmony, where no adjustments are needed. He goes on to say that "cooperation should not be viewed as the absence of conflict, but rather as a reaction to conflict or potential conflict" (p54).

This paper reviews literature on climate change and its impacts on water resources in Africa, literature on adaptation to climate change for water resource management and literature on conflict and cooperation in international or transboundary river basins. The review is used to identify the challenges that climate change represents to water

resources management in the context of cooperative and non-cooperative behaviour of river basin nation states and their institutions. The aims of the paper are:
i) to identify what is known about the need and the potential for adaptation to climate change in international river basins, and the processes and factors that may either constrain or enhance adaptation, and
ii) to identify opportunities for further research to enhance our understanding of how to promote appropriate adaptation to both current climatic variations and future climate change in international river basins.
The next section reviews current understanding of water resources in Africa, how they change as climate changes and interactions between climate change impacts and socio-economic change. The following section explores processes of managing change in river basins, framed around ideas of adaptation to climate change. There then follows a section that sets adapting to climate change (vis-à-vis barriers and opportunities) in the context of theory and observation of cooperative and conflictual behaviour around water resources in international river basins. The final section uses insights from the review to identify areas of understanding and highlight opportunities for further study.

CLIMATE CHANGE AND WATER RESOURCES IN AFRICA

Water resources in Africa

Africa is characterised by a wide variety of climate systems ranging from humid equatorial, through seasonally-arid tropical, to sub-tropical Mediterranean type climates. Annual precipitation in Africa is estimated at about 20 360 km^3 (Aquastat Survey, 2005). Disparities between countries and regions are very important. With more than 7500 km^3/year, the central region receives 37% of all precipitation in Africa in an area that accounts for less than 20% of the total. In contrast, the northern region, with an area similar to the central region, receives less than 3% of total precipitation (Aquastat Survey, 2005). Although a dry regime (rainfall < 400 mm/yr) covers 41% of the continent, the intermediate regime (>400 <1000 mm/yr) covering 25% of the continent attracts greater concern than the other regimes as changes in precipitation would result in serious changes in surface water supply. The intermediate regime shows high seasonality and includes three densely populated regions: Southern Africa (including the Orange and Limpopo basins); most of East Africa, (including a large section of the upper Nile basin); and the East-West band stretching from Senegal to Sudan (broadly similar to the Sahel) which crosses a number of important river basins (including Lake Chad, the Niger, the Upper Volta, and the Senegal).

This review concentrates primarily on surface water resources in international river basins, whilst recognizing the importance of groundwater which currently represents 15% of Africa's water resources and is used by 75% of the population, mainly in North Africa (AfDB *et al.*, 2000). Green water, present in soil moisture reserves and evaporated to the atmosphere from soil and vegetation (Falkenmark, 1995), is vital in supporting natural ecosystems and rainfed agricultural production systems. Potential evaporation rates are high throughout Africa and, along with precipitation patterns, are important for determining seasonal variations in soil moisture and surface water availability. In some instances riparians in international basins may use basin precipitation as the basis for calculating total water availability so that accounting for green and blue water flows (and changes thereof) is relevant to discussions and agreements on water allocation. The hydrological monitoring network for surface water in Africa is poorly developed with generally sparse coverage and short fragmentary records, although some long reliable records exist for strategic locations in parts of the Nile Basin and on major rivers in West Africa (Senegal, Niger, Congo; Conway *et al.*, in press). Monitoring networks for groundwater are currently inadequate (Groundwater and Climate in Africa, 2008), whilst soil water is not generally monitored.

African water resources are not evenly distributed throughout the continent and are often not located where there is the greatest demand. Africa has 17 rivers with catchment areas greater than 100 000 km^2 and 11 over 250 000 km^2 in area (see Table 1). It has more than 160 lakes larger than 27 km^2, most of which are located around the equatorial region and sub-humid East African highlands within the Rift Valley (AfDB *et al.*, 2000). River channels and basin watersheds make up almost 40% of Africa's international borders and all of the major African rivers traverse one or more international boundaries (de Wit & Stankiewicz, 2006). Table 1 shows the number of countries sharing and total area of each of the 11 largest international river basins in Africa (all over 250 000 square kilometres in area and shared by between three and 13 countries). The basin discharge varies greatly according to region and specific characteristics of the rivers, with the highest discharge being in the Congo basin and lowest in the Orange basin in Southern Africa. All of these river basins have high levels of variability, in particular the rivers of west and Southern Africa for which the coefficient of variation at the gauging stations shown in Table 1 were over 20% for the period 1961 to 1990. Three basins can be described as experiencing water stress (defined by United Nations Development Programme, 2006 as less than 1700 cubic metres per person per year) whilst two of these, the Orange and the Limpopo, both in Southern Africa experience water scarcity (defined as less than 1000 cubic metres of water per person per year, United Nations Development Programme, 2006). The Nile and Volta basins have the highest average population densities and are approaching situations of water stress. These statistics mask considerable variability within the basins and only refer to renewable water resources and not to people's ability to access water (Rijsberman, 2006).

The high levels of variability in rainfall and river flows in Africa across a range of spatial and temporal scales have important consequences for the management of water resource systems (Peel *et al.*, 2004; Conway *et al.*, in press). Throughout Africa this variability brings significant implications for society and causes widespread acute human suffering and economic damage (Conway & Hulme, 1996). Although most of the African population (roughly 69%) lives, on average, in conditions of relative water abundance, this does not reflect the poor access to clean drinking water and sanitation (Vorosmarty *et al.*, 2005). Only 62% of African's had access to improved water supply in 2000 despite the considerable improvements during the 1990s (WHO/UNICEF, 2000). Current population trends and patterns of water use indicate that more African countries will exceed the limits of their "economically usable, land-based water resources before 2025" (Ashton, 2002).

Table 1 Comparison table for eleven international river basins in Africa**.**

Basin Name	Number of countries[1]	Total area of basin[1] (sq. km)	Basin discharge[1] (cubic km of water per year)	Gauging station[2]	River flow[2] (m^3s-1) (at gauging station)	Coefficient of Variation of river flow[2] (%)	Population[1] (x 10^3)	Population density [1] (persons/ km^2)	Water stress[1] (cubic metres per person per year)
WEST AFRICA									
Lake Chad	8	2388700	100	N'djamena (River Chari)	892	42	37300	16	2800
Niger	11	2113200	330	Dire	870	29	82100	39	4100
Senegal	4	436000	30	Bakel	549	48	4420	10	5800
Volta	6	412800	40	Senshi Hal.	1044	68	20100	49	1900
CENTRAL AFRICA									
Congo/Zaire	13	3691000	1270	Kinshasa	42418	13	63200	17	20000
EAST AFRICA									
Nile	11	3031700	330	El Deim (Blue Nile)	1454	20	160000	53	2000
Juba-Shibeli	3	803500	20	-	-	-	14600	18	1100
SOUTHERN AFRICA									
Zambezi	9	1385300	330	Victoria Falls	1183	38	28800	21	11300
Orange	4	945500	7	-	-	-	13100	14	540
Okavango	4	706900	30	Mohembo	869	22	973	1	30700
Limpopo	4	414800	10	-	-	-	11800	28	890

[1] Data source: Transboundary Freshwater Spatial Database (http://www.transboundarywaters.orst.edu/database/transfreshspatdata.html)

[2] Data source: Conway et al. (in press)

Climate change in Africa

Against a backdrop of existing high levels of variability climate change will alter the timing, distribution and quantity of water resources. The IPCC Fourth Assessment Report provides a comprehensive review of climate model projections for different regions in Africa. These are based on a set of 21 models from their Multi-Model Data (MMD) set using the A1B emissions scenario[3] focusing on the change in climate between the period 1980 to 1999 (to represent the current climate) and 2080 to 2099 (to represent the future; Christensen *et al.*, 2007).

Table 2 summarises for each sub-region of Africa, the main changes in temperature and precipitation between the present and future periods. Results are presented as changes in mean temperature and precipitation for the mean of all the climate models and their range (due to differences in the projections produced by different climate models). The climate models show a consistent response in both mean annual and seasonal temperature change in all sub-regions, projecting warmer conditions ranging from +3.2°C (East Africa) to +3.6°C (Sahara) by the 2080s. Nearly all models project wetter conditions in West and East Africa (+2% and +7%, respectively) while drier conditions are projected in Southern Africa and the Sahara (-4% and -6%, respectively). It is important to note that individual models generate large, but disparate, responses in the Sahel, such that, at present, there is no clear signal of future rainfall patterns in this region.

According to Christensen *et al.* (2007) projections concerning extreme events in the tropics remain uncertain. There is a tendency for monsoonal circulations to result in increased precipitation despite a tendency towards weakening of the monsoonal flows themselves. The main and most understood climate drivers of interannual and decadal rainfall variability in Africa 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). At present, model simulations of future climate do not show clear tendencies in the future behaviour of these large-scale drivers (Merryfield, 2006; Conway *et al.*, 2007).

Overall these results suggest that warming is very likely to be larger than the global annual mean warming throughout the continent and in all seasons. On balance higher temperatures are likely to increase evaporative demand throughout Africa. Annual rainfall is likely to decrease in much of Mediterranean Africa and the northern Sahara. Rainfall in Southern Africa is likely to decrease in much of the southern hemisphere winter rainfall region and western margins. Annual rainfall in East Africa is likely to increase but it is unclear how rainfall in the Sahel, the Guinean Coast and the southern Sahara will evolve.

---

[3] Emissions scenario A1B represents a mid-range emission profile for a future world scenario characterised by rapid economic growth, a global population that peaks in the mid-21st century and then declines and with technology based on a balance of fossil fuel and non-fossil fuel energy sources (Nakicenovic 2000). Although A1B has been chosen as a 'best-guess' scenario there are already indications that we are currently above this and the higher emissions scenarios used by the IPCC in terms of emissions (Raupach et al 2007).

Table 2. Changes in mean temperature and precipitation between present day and 2080s. Multi-model means and model range shown, based on Christensen *et al.* (2007).

Region	Temperature		Precipitation	
	Annual	Seasonal[4]	Annual	Seasonal[4]
West Africa (12S,20W to 22N,18E)	+3.3°C with an inter-model range of +1.8°C to +4.7°C.	Warming in all seasons ranging from +3.0°C (DJF) to +3.5°C (MAM).	Increase of 2% with an inter-model range of -9% to +13%.	Increase in all seasons (ranging from 1% to 6%) except for MAM where a slight decrease is projected (-3%)
East Africa (12S,22E to 18N,52E)	+3.2°C with an inter-model range of +1.8°C to +4.3°C.	Warming in all seasons ranging from +3.1°C (DJF, SON) to +3.4°C (JJA).	Increase of 7% with an inter-model range of -3% to +25%.	Increase in all seasons ranging from 4% (JJA) to 13% (DJF).
Southern Africa (35S,10E to 12S,52E)	+3.4°C with an inter-model range of +1.9°C to +4.8°C.	Warming in all seasons ranging from +3.1°C (DJF, MAM) to +3.7°C (SON).	Decrease of 4% with an inter-model range of -12% to +6%.	Decrease in JJA (-23%) and SON (-13%). No changes in DJF and MAM.
Sahara (18N,20E to 30N,65E)	+3.6°C with an inter-model range of +2.6°C to +5.4°C.	Warming in all seasons ranging from +3.2°C (DJF) to +4.1°C (JJA).	Decrease of -6% with an inter-model range of -44% to +57%.	Decrease in all seasons (ranging from -4% to -18%) except for SON where a slight increase is projected (+6%).

Climate change impacts, socio-economic change and water resources in Africa

During the coming century, increasing population, changing patterns of water use, and concentration of population and economic activities in urban areas will further pressurise Africa's freshwater resources (Arnell, 2006). In addition, changes in land cover and land use, the construction of upstream reservoirs, and pollution from domestic, industrial and agricultural sources will exacerbate problems related to timing and quality of water supplies. The high spatial and temporal variability of water resource availability and its uneven spatial distribution means that water scarcity is a major concern in some parts of Africa. Vorosmarty *et al.* (2005) estimate water stress to be high for 25% of Africa's population with a further 13% experiencing water stress due to drought once a generation. Climate change threatens to put further pressure on water resources already under pressure. Arnell (2004) estimates the population at risk of increased water stress in Africa to be 75-250 million and 350-600 million people by the 2020s and 2050s, respectively. The results from a selection of climate impact studies of surface water resources in Africa are presented in Table 3. Most of these studies combine climate change scenarios (derived from global climate models) with hydrological models to simulate river flow response to changes in temperature, potential evaporation (PE) and rainfall (see Gleick, 1986). Such studies generally demonstrate greater proportional changes in river flows than precipitation and fairly modest responses to increasing temperature or PE. The overall

[4] DJF = December, January, February; MAM = March, April, May; JJA = June, July, August; SON = September, October, November

effects on river flows show a wide range of outcomes, even for the same rivers, primarily due to differences in future precipitation scenarios between climate models.

These studies rarely incorporate sophisticated representation of PE, soil moisture dynamics and land cover, or a focus on changes in the frequency/magnitude of extreme events. In many of the most socio-economically important basins in Africa evaporative losses are high and, other things being equal, likely to increase as the climate warms. Understanding future patterns of evaporation and transpiration and their interaction with land cover change is a key area for further research. Very few studies have considered the effects of climate change on groundwater in Africa. In the future, the demand for groundwater is likely to increase as total water use increases (Kundzewicz *et al.*, 2007). Demand may also increase in response to changes in surface water availability. Although groundwater systems generally respond more slowly to climate change than surface water systems, climate change will affect groundwater recharge rates, i.e., the renewable groundwater resource, and groundwater levels (Kundzewicz *et al*., 2007). However, even knowledge of current recharge and levels in both developed and developing countries is poor. Because of groundwater's importance in water supply at smaller scales in Africa changes in availability could have disproportionately large effects on human wellbeing and stability of supply in regions with strongly seasonal precipitation regimes.

It is important to include changes in water availability and demand due to non-climatic factors such as population growth, and changes in per capita and agricultural water demand (Conway *et al.*, 1996; Vorosmarty *et al.*, 2000; Alcamo *et al.*, 2003; Arnell, 2004; Alcamo *et al.*, 2007). Economically and demographically driven growth in demand generally leads to large changes in per capita water availability and often outweighs climatically-induced changes. For example, Alcamo *et al.* (2007) found that in most areas of river basins (~90%), the main cause of increasing water stress was growth in water withdrawals and in much smaller areas (~10%) it was a decrease in water availability due to climate change. What is clear from these types of analyses is that the interaction of underlying drivers of demand is moving many countries and international basins inexorably towards increasing water scarcity and river basin closure (Molle, 2003). Per capita indicators of water scarcity tend to be lower in areas with high population density and high water use. Many of these areas also experience high interannual variability and surface flows show high sensitivity to climatic perturbations (Vorosmarty *et al.*, 2005; Conway *et al.*, in press). It is these areas (much of Southern and Northern Africa) where climate change is most likely to exacerbate the challenge of achieving sustainable and equitable water resource management. In water scarce areas where precipitation is projected to increase (East Africa) scarcity may be alleviated, but this will depend on whether increases in precipitation are large enough to offset increases in PE. Indeed, the sub-basin scale dynamics of rainfall-runoff relationships, soil moisture and the role of increased PE will be critical in determining water availability in many areas.

Climate change will affect demand for water through direct physical effects and socio-economic effects such as behavioral changes in water consumption in response to higher temperatures. In most countries agriculture is by far the largest sector of water use (especially the large irrigators, Egypt, Sudan, South Africa) and irrigation will be directly affected, for example due to higher rates of evaporation. Climate change may reinforce moves to expand irrigation (small and large scale) in Africa as a means of supporting economic growth through the agricultural sector (e.g. Andah *et al.*, 2004; Commission for Africa, 2005). Whether such developments will be maladaptive from a climate change perspective will depend upon what happens to surface water availability; primarily driven by the overall changes in precipitation. Potential adaptations and their possible transboundary implications are discussed in more detail in the next section.

Changes in precipitation patterns and river flow regimes will cause changes in the frequency and magnitude of floods and droughts across Africa. In coastal areas increasing flood risk will be exacerbated by sea level rise, also caused by climate change. Flooding and drought will have wide-ranging secondary impacts on, for example, food security, hydroelectric power generation, domestic water supply and so on (Kundzewicz *et al.*, 2007). However, few studies have considered the effects of changes in variability and magnitude/frequency of extreme events on river flows or on the recharge of groundwater. This is primarily due to the difficulty of generating reliable scenarios from climate models at the scale required for impacts modelling. In the past extreme events have brought significant challenges to management and also played a key role in prompting ex poste management and policy responses, for example in the Nile (Conway, 2005) and South Africa (Schulze, 1997).

ADAPTATION TO CLIMATE CHANGE IN RIVER BASINS

The impacts of climate change and other stresses on water resources and changes to flooding risks in the future will require adaptation on the part of water resource management institutions and water users. In this section we examine the challenges of adaptation in the water sector, evidence for types of adaptation that are already occurring and factors that might influence the success of adaptation in river basins. The majority of the literature on adaptation in the water sector currently comes from the US, Canada and Europe. We draw on this literature and ask what might be the additional challenges to adaptation in the African continent where the institutional capacity of management institutions, water scarcity and the transboundary nature of many of the river basins may all have an impact on the ability to adapt. The terms adaptation and adaptive capacity are used in this paper in the sense used by the IPCC, where *adaptation* describes "changes in processes, practices and structures to moderate potential damages or to benefit from opportunities associated with climate change" (Smit & Pilifosova, 2001, p879) and *adaptive capacity* refers to “the potential, or ability of a system to adapt to climate change stimuli or their effects or impacts” (Smit & Pilifosova, 2001, p894).

Challenges of adaptation to climate change: decision making under uncertainty

Current water resource and floodplain management systems in river basins in developed countries assume that the climate is stationary and that probabilities for hydrologic variables can be estimated from the long term observational record. However, it is increasingly being recognised that this assumption of stationarity is no longer valid with the changes in climate that are underway and are expected for the future (Olsen, 2006; Milly *et al.*, 2008).

Table 3. Summary of studies on climate change impacts on surface water resources in Africa.

Region	Projected changes in water resources[5]	Authors
Africa	By 2050, water stress will increase over 62.0–75.8% of total river basin area and will decrease over 19.7–29.0% of this area.	Alcamo *et al.*, 2007
	Decrease in perennial drainage will significantly affect present surface water access across 25% of Africa by 2100.	de Wit & Stankiewicz, 2006
East Africa	Runoff in Eastern Africa is projected to possibly increase by 2050.	Arnell, 2003; Strzepek & McCluskey, 2006
	Increase in runoff of 20 to 40% by 2050 in Eastern equatorial Africa.	Milly *et al.*, 2005
	Except during the 2001-2005 period, the total average annual inflow volume of the **Lake Ziway** might decline up to 19.47% for A2a- and 27.43% for B2a-scenarios.	Abraham, 2006
	Future **Nile** discharge (up to 2100) will decrease slightly (-2%) or will remain relatively stable compared to the current situation (average over 1750–2000 AD).	Aerts *et al.*, 2006
	Lake Tana: if the temperature is increased by 2°C and: 1) no change in rainfall → decrease in annual flow by 11.3%; 2) decrease in rainfall by 10% to 20% → decrease in runoff by 29.3% to 44.6%; 3) increase in rainfall by 10% to 20% → increase in runoff by 6.6% to 32.5%.	Tarekegn, 2000
	Reduction in runoff in **Nile** by 2050 (around 3%)	Manabe *et al.*, 2004
	Increase in water withdrawals in the **Nile** by 2025 mainly because of population and economic growth (Application to a business-as-usual scenario)	Alcamo *et al.*, 2003
	By 2025, propensity for lower **Nile** flows (in 8 out of 8 scenarios).	Strzepek *et al.*, 2001
	White Nile flows sensitive to changes in Lake Victoria levels .	Sene, 2000
	Five out of six climate models produced an increase in **Nile** flows at Aswan, with only one showing a small decrease.	Yates & Strzepek, 1998
	Range (due to differences between GCM scenarios) of –9% to +12% changes in mean annual **Nile** flows for 2025.	Conway & Hulme, 1996
	Divergence between climate model results for the **Nile** basin; two produced increases and two produced decreases in flows.	Strzepek & Yates, 1996
	By 2050, the combined effects of climate change, land-use change, and water resources management on future water availability in **Egypt** range from a large water surplus to a large water deficit.	Conway *et al.*, 1996
Southern Africa	Decrease in runoff of 10 to 30% by 2050 in Southern Africa.	Arnell, 2003; Milly *et al.*, 2005
	Change in discharge relatively small in the **Zambezi** by 2050.	Manabe *et al.*, 2004
	Increase in water withdrawals in the **Limpopo** mainly because of population and economic growth (for a business-as-usual scenario).	Alcamo *et al.*, 2003
	Decrease in annual mean water flow in **Okavango** River by 14% (B2 scenario) or 20% (A2 scenario)	Andersson *et al.*, 2006
North Africa	Runoff is projected to possibly decrease by 2050.	Arnell, 2003
	Most of North Africa: stabilization or decrease in water withdrawals between 1995 and 2025.	Alcamo *et al.*, 2003
Central Africa	Runoff is projected to possibly decrease by 2050.	Arnell, 2003
	Increase in runoff of 12% in **Congo** by 2099 compared to the recent discharge values.	Aerts *et al.*, 2006
	Increase in water withdrawals in the **Congo** mainly because of population and economic growth (for a business-as-usual scenario).	Alcamo *et al.*, 2003
West Africa	Significant increase in runoff in regions of heavy rainfall (e.g. coastal region of Africa around the Gulf of Guinea) by 2050.	Manabe *et al.*, 2004
	Increase in runoff of 61% in **Volta** by 2099 compared to the recent discharge values.	Aerts *et al.*, 2006

[5] These studies use a number of different climate change scenarios

A number of different future climate scenarios have been used for impact assessments for the purpose of adaptation (for example, Warwick *et al.*, 2003). However, the scenario approach has been seen as problematic because different climate models produce a wide range of different scenarios (Stakhiv, 1998). Furthermore these may not represent the full range of possibilities and the credibility of individual scenarios is hard to evaluate (Kundzewicz *et al.*, 2007). The use of subjective probabilities, or probability distribution functions, has been experimented with (Kundzewicz *et al.*, 2007), but according to Olsen (2006) the difficulty of reaching agreement amongst experts on subjective probabilities may be a drawback to this approach. New *et al.* (2007) demonstrate, for an example of the River Thames in the UK, that probabilistic climate change impacts information generated from a large ensemble Global Climate Model can enable the estimation of the potential risk of different adaptation options. However, they recognise that this method does require a detailed analysis of the different sources of uncertainty in the impacts model and may require resources beyond the scope of many organisations.

Olsen (2006) suggests the need for new approaches such as minimizing the regret of making a wrong decision or minimizing vulnerability. An example of this is provided by Dessai and Hulme (2007) who demonstrate an approach that analyses the robustness of adaptation decisions taken by a water service provider in the UK water sector to uncertainties in climate change. Aerts and Droogers (2004a) emphasize that adaptation measures are related to a number of stressors in addition to climate change including, for example, land use change, population growth, competition between sectors etc. Dessai *et al*. (2008) conclude that, given the deep uncertainties in climate prediction and the reality that climate is only one factor influencing adaptation decisions, an approach that avoids heavy reliance on climate prediction and instead assesses the robustness of adaptation decisions to a range of plausible futures is preferable. Stakhiv (1998) recommends that a 'no-regrets' strategy could be provided by the use of the adaptive management principle for water resource management.

Experience of adaptations in the water sector

A number of different frameworks are used in the literature to distinguish between different types of adaptation in the water sector. Drawing on the work of the UK Climate Impacts Programme[6], Tompkins *et al.* (2005) distinguish between responses that *build adaptive capacity* and those that deliver *adaptation actions*. They also distinguish between *planned* adaptations that are implemented specifically to respond to climate change and *unplanned* adaptation that was not specifically designed with climate change adaptation in mind. De Loe *et al*. (2001), writing about the Canadian water sector, use a framework developed from the hazards literature (for example, Burton *et al.*, 1993) to categorise the three main types of available adaptations: *accepting losses*, *preventing effects* or *changing uses or locations*. *Supply-side* and *demand-side* are also terms that have been used to distinguish between adaptations to reducing water availability that either increase water supply or decrease demand (Kundzewicz *et al.*, 2007). Aerts and Droogers (2004a) develop a framework called the 'Adaptation Methodology for River Basins' which includes a participative approach with stakeholders to define the factors influencing water resources, their impacts and influence on water resource management decisions, identification of adaptation options and criteria for evaluating the performance of these options.

[6] See http://www.ukcip.org.uk/resources/tools/database.asp

A wide variety of adaptation options exist. Some of these are listed by Kundzewicz *et al.* (2007): supply-side adaptation options include exploiting groundwater, increasing storage in reservoirs, desalination of sea water, rain-water harvesting and water transfers between river basins. Demand-side adaptations include improvement of water-use efficiency and recycling of water, reduction of demand for irrigation by changing crops or cultivation practices, reduction of demand by importing agricultural products (use of 'virtual water' (Allan, 1998)), sustainable water use practices, use of water markets to reallocate water between uses, and use of economic incentives such as metering and pricing. According to Kundzewicz *et al.* (2007) there are two main approaches for adaptations to increased flood risk: either modify the floodwater or modify the system's susceptibility to flood damage. There are advantages and disadvantages to each of these options and approaches and the relative benefits depend on local circumstances (Kundzewicz *et al.*, 2007).

Tompkins *et al.* (2005) review evidence for adaptation in the UK water sector and find that both planned and unplanned adaptation is already happening both for changes in water supply and demand and for flood risk management. By building an inventory of adaptations they see that adaptations are occurring mainly in the public sector but also in the private sector and other sectors. However, they find more examples of institutions building adaptive capacity than examples of adaptation actions already taking place. They suggest that there is a high level of awareness of climate change in the UK sector and that legislation and regulation are important drivers of adaptation, for example requirements of the EU Water Framework Directive.

Adaptations may involve trade-offs between meeting the demands of different sectors, for example, maintaining power production or maintaining in-stream flows for fish (Payne *et al.* 2004 in Kundzewicz *et al.* 2007). Tanaka *et al.* (2006) find that adaptation of California's water supply system will involve significant transfers among water users as well as changes in the operation of groundwater storage and adoption of new technologies. Water markets, already existing in the USA, Canada, Chile and Australia and developing in several other regions of the world, provide a way of achieving such transfers of water (Kundzewicz *et al.*, 2007).

Examples of adaptations to climate change in the water sector in developing countries are less documented. This is perhaps because developing countries have many pressing issues to deal with besides the impact of climate change on water resources (Kabat *et al.*, 2002). A number of possible adaptation options have been suggested by Ragab and Prudhomme (2002) for arid and semi-arid regions. These include, what the authors describe as conventional solutions: developing storage dams and irrigation schemes, inter-basin transfers of water through networks of pipes and canals and further development of groundwater resources. They also list a number of more innovative solutions: rainwater harvesting, desalination, cloud seeding, water storage in underground reservoirs and the development of salt tolerant crops to make use of brackish water and, alternatively, solutions that reduce the demand for water such as reducing leaks and evaporation, improving efficiency of irrigation and recycling of water. Some of these measures are already being implemented in African river basins, for example in the Nile Basin (Conway, 2005) and Orange Basin (Kistin & Ashton, 2008), although actions may not be specifically taken to deal with climate change risks. Where water resource management decisions are taken without considering possible future climate change impacts, then maladaptation may result, as vulnerabilities to future climate change are increased.

The exploitation of groundwater has been important for developing more reliable and better quality water supplies for rural communities in many parts of Africa, as well as other parts of the developing world (Hiscock *et al.*, 2002). The use of groundwater has also been suggested as an adaptation option to climate change impacts on water resources (Kundzewicz *et al.*, 2007). However, Hiscock *et al.* (2002) find that there are already many examples of unsustainable use of groundwater and suggest that to be sustainable, strategies to develop groundwater should be flexible enough to deal with future scenarios, including climate change.

Determinants of adaptive capacity and factors influencing the success or limitations of adaptations

Studies of adaptive capacity to stresses in a variety of systems have identified a number of different determinants of adaptive capacity that are specific to the system, sector and location and can also vary over time (Yohe & Tol, 2002; Smit & Wandel, 2006). These determinants of adaptive capacity include: the range of technological options available for adaptation; the availability of resources and their distribution; institutional structures and the decision making criteria of institutions; human capital; social capital; access to risk spreading mechanisms; the management of information; and the public's attribution of and exposure to the stress (Yohe & Tol, 2002).

Adaptation options and the constraints on water management and adaptation in the water sector are specific to the context in which they occur (Ivey *et al.*, 2004; Arnell & Delaney, 2006; Shepherd *et al.*, 2006). In addition, the goals or objectives of adaptation are important for determining whether adaptation is successful or whether there are limits or barriers to adaptation (Adger *et al.*, in press). In order to be effective adaptation should fit with existing management systems and objectives.

Four different types of limits on adaptation to changes in water quantity and quality have been identified (Kundzewicz *et al.*, 2007; Arnell & Charlton, 2008). Firstly, there may be physical limits that may constrain the performance of a particular adaptation option. Secondly, economic constraints occur if some adaptations are considered too costly. Then there may be socio-political barriers to adaptation according to the attitudes or reactions of stakeholders to proposed adaptation options and, finally, the capacity of water management institutions may limit the ability to promote or implement adaptations (Kundzewicz *et al.*, 2007; Arnell & Charlton, 2008).

Physical limits are geographically specific, for example some adaptation options may be unavailable in ‘closed’ river basins, those where there is no dry season outflow of usable water and where additional withdrawal of water by one user decreases the amount of water available to other users (Seckler *et al.*, 1998; Turton, 2003). There may also be a physical limit to the reduction in water demand that is possible without harming the health and livelihoods of the population, for example (Kundzewicz *et al.*, 2007). The highly variable flows in many African rivers basins also provide barriers or challenges to their management (Lankford & Beale, 2007).

Socio-political barriers exist where adaptations are considered undesirable by some stakeholders, such as the metering of water for example (Shepherd *et al.*, 2006). Miller *et al.* (1997) find that adaptation can be subject to conflict. Changes in demand or expectations of water services may be necessary or society may have to accept trade-offs between different uses of water (Kundzewicz *et al.*, 2007). Socio-political barriers to adaptation can sometimes be overcome, for example Penning-Rowsell *et al.* (2006) found that extreme climate events such as flooding events can trigger change in policy by creating windows of opportunity. Similarly Arnell and Delaney (2006) found that incentives for building adaptive capacity to deal with climate change in the UK public water supply sector depend on an improved awareness of climate change, which can be triggered by extreme events.

Economic barriers to adaptation arise because adaptation is often costly (Miller *et al.*, 1997; Tanaka *et al.*, 2006). However, the costs of not adapting to climate change can be much greater than the costs of adapting to climate change (Stern, 2007), as Boko *et al.* (2007) illustrate for the Berg River Basin in South Africa.

Moser (2008) draws attention to the many ways in which the decisions, actors, processes, institutional structures and mechanisms that make up governance can be involved in determining adaptation actions. Institutions and governance structures in the water sector can either facilitate or hinder adaptation by different stakeholders at different scales (Ivey *et al.*, 2004; Naess *et al.*, 2005) and will determine the overall social impacts of changes in water availability (Kundzewicz *et al.*, 2007). However, since institutional settings differ significantly both within and between countries, substantial differences in the efficiency, equity, and flexibility of water use and infrastructure development result (Kundzewicz *et al.*, 2007). For example, Tompkins *et al.* (2005) find that the legislative framework in the UK explicitly promotes adaptation by private sector water supply companies and studies of water resource management systems in the US have suggested that enough institutional flexibility exists to adapt to changes in growth, demands and also climate (Frederick *et al.*, 1997; Stakhiv, 1998). However, in developing countries existing legal frameworks and institutions are often too weak to address the challenges currently faced by the water sector (Levina, 2006). Given that over the short to medium term future climate change is likely to exacerbate existing challenges to water resources management (scarcity, flood risk) there are many situations where adaptation will fit closely with current management objectives. This has been referred to as a 'no-regrets' strategy (Stakhiv, 1998; de Loë *et al.*, 2001). A significant objective for many countries in Africa is to reduce the large adaptation gap that already exists in many situations.

Integrated Water Resources Management (IWRM) and adaptive water management are seen by some as suitable approaches for enhancing adaptive capacity in the water sector (Stakhiv, 1998; Pahl-Wostl *et al.*, 2005; Raadgever *et al.*, 2006; Kundzewicz *et al.*, 2007). Pahl-Worstl *et al.* (2005) advocate a transition to adaptive water management involving strong stakeholder participation and participatory action research in order to meet the major challenges caused by climate and global change. However, developing countries face considerable barriers to implementing IWRM and adaptive management, since it is reliant on the adaptive capacity of national institutions (Allan *et al.*, 2002; Raadgever *et al.*, 2006).

Adaptation in international river basins in Africa

There are few studies that address adaptation to climate change in international river basins. The transboundary issue is not discussed in the Water chapter of the IPCC 4th Assessment Report and appears only briefly in the Africa chapter in relation to cross-border management of floods in Mozambique and mention of the international nature of water management in West Africa and the Okavango. Neither does the chapter on Managing Transboundary Waters in the 2006 Human Development Report consider climate change adaptation. Aerts and Droogers (2004b) examine adaptive strategies to climate change in seven case studies of river basins across the globe, including the Volta, in West Africa. A major ongoing European Union funded research project on adaptive water management called NeWater, consists of seven case studies of international river basins in Europe, Asia, and Africa (the Nile and Orange basins, Pahl-Wostl *et al.*, 2005).

International river basins in Africa differ with respect to the opportunities available for, or barriers to adaptation. Table 4 shows some indicators that can be used to illustrate differences in potential adaptive capacity for the eleven largest African international basins examined earlier in this paper (see also Table 1). The GDP and HDI figures show that not only do river basins differ considerably in the basin mean value of these indicators (calculated as a simple arithmetic mean of the values for each country in the basin) but also there is considerable difference between the countries within the basins (indicated by the minimum and maximum values). The GDP figures can be taken as an indication of national economic resources available for adaptation and HDI figures as an indication of differential social vulnerability to climate change impacts, although these are only two of a number of possible indicators of adaptive capacity and social vulnerability (Brooks *et al.*, 2005). Basins with a higher mean GDP, such as the Orange basin in Southern Africa, might be expected to have a higher adaptive capacity because they are more likely to have the financial resources to address transboundary water resource management issues. Those basins with a large range of GDP and HDI values within the basin indicate situations of great inequality, where adaptive capacity is likely to vary largely within the basin and some countries may be better placed to adapt than others, for example the Lake Chad, Congo and Zambezi basins. Without effective basin-wide institutions and agreements this could result in uneven adaptation, with one country's adaptation potentially causing negative impacts on another country within the basin, for example.

The institutional arrangements for managing transboundary water resources are therefore also very important for adaptive capacity. The basins listed in Table 4 differ in the institutional arrangements for managing transboundary water and in the number and type of treaties or agreements between riparian nations within the basin. The number of treaties reflects in part the number of countries sharing a river basin and the history of cooperation between them (see Table 4). For example, the Nile Basin has a large number of treaties, which go back to the colonial era (see Waterbury, 2002). Not all of the treaties in African international river basins are exclusively related to water resource management and many of them are bi-lateral or multi-lateral agreements that do not involve all riparian countries. Different institutional arrangements accompany these treaties. Some agreements provide flexibility mechanisms or transboundary institutions that could assist adaptation whilst others may have terms that limit adaptation of some riparians or water users (Fischhendler, 2004; Drieschova *et al.*, 2008; Kistin & Ashton, 2008). In addition to treaties there are other forms of cooperation which can add to adaptive capacity and either may be enshrined in formal agreements or occur informally. These are discussed in the next section on cooperation and conflict in international basins.

The 'Basins at Risk' indicator in Table 4 is taken from a global scale analysis of international river basins by Yoffee *et al.*(2003). In this study the authors identified a number of factors contributing to risk of future conflict over fresh water resources including: high population density; low per capita GDP; overall unfriendly relations (as derived from a database of events); the presence of politically active minority groups and limited or no freshwater treaties. These indicators were then combined in a single 'Basins at Risk' indicator that was used to categorise basins into three types. Type 1 basins are those that are "negotiating current conflict", do not have basin wide treaties, and have a high potential for disputes (e.g. the Nile basin). Type 2 basins are those that have factors pointing to the potential for future conflict and have existing issues that have raised protests or tensions within the basin (e.g. Lake Chad, Senegal and Okovango basins). Type 3 basins have similar factors as Type 2 but without evidence for existing tensions or protests (e.g. Zambezi and Limpopo basins). The remainder of the basins listed in Table 4 were not identified as being 'at risk' by Yoffee *et al.* (2003).

Socio-political barriers to adaptation are likely to be influenced by the power relations and politics between riparian states and are apparent in the often competing priorities and interests for water development amongst different riparian states, for example in the Nile River Basin.

The more highly developed basins are those that have a high number of dams, a high density of dams and a larger irrigated area in comparison to other river basins (although small compared to the potential irrigable area). The Southern African river basins of the Zambezi, Orange and Limpopo fall into this category. The Orange and Limpopo river basins are already water scarce, as indicated in Table 1. Expansion of existing water use in these basins is limited and they are regarded as 'closed' river basins (Turton, 2003). This is of particular concern because they are likely to be exposed to serious climate change impacts as they are also the basins that are projected to experience decreasing runoff in the future with climate change (see Table 4). This suggests that there may be physical limits to some types of adaptation in these and similar international basins, such as, for example, increased storage and expansion of irrigation systems. Adaptations based on demand management are likely to be particularly important in these water scarce basins. In Southern Africa adaptations to water scarcity also involve inter-basin transfers of water and more of these are contemplated for the future, for example between the Orange, Limpopo and Zambezi river basins (Kistin & Ashton, 2008).

Of the potential adaptations to changing water demand and to climate change impacts that different states may undertake some may have transboundary implications. For example expansion of water storage and irrigation facilities may reduce flow to downstream riparians especially if their design does not incorporate the likelihood of changing river flows with climate variability and future climate change. This is already an issue of concern, for example, in Mozambique, the downstream riparian in the Limpopo and Zambezi basins (Wirkus & Böge, 2006) and could become important in other river basins such as the Volta in West Africa (Andah *et al.*, 2004) the Nile (Conway, 2005) and the Orange Basin (Heyns *et al.*, 2008). Basin wide or bilateral agreements that allow for proportional allocation of water to different states or users are one possible solution to this problem (Lankford & Beale, 2007; Drieschova *et al.*, 2008). It is possible that small-scale programmes of rainwater harvesting, which may be supported as adaptations (for example, through National Adaptation Plans of Action) if adopted on a very large scale could have transboundary implications as has been speculated for the Ethiopian Highlands in the Nile basin (Whittington, 1997). Adaptations to changing demand or supply of water may occur in the wider political economy, outside the immediate sphere of water resources management, for example through trade in agricultural products, or 'virtual water' trade (Allan, 1998, 2006).

The impacts of extreme climate events often possess a transboundary dimension, for instance, Benson & Clay (1998) describe an example of water mismanagement at Lake Kariba in the Zambezi basin during the 1991-92 drought in south-eastern Africa. Fluctuations in the level of Lake Victoria in the Nile Basin, such as the floods of 1997 to 1998 and the recent large decline in levels since 2005, have impacted upon lake-shore communities in Kenya, Tanzania and Uganda (Conway *et al.*, 2005; Pearce, 2006). Both climate variability and management of the lake outflow in Uganda for hydroelectric power are likely to have been responsible for the recent decline in lake levels (Goulden, 2006; Pearce, 2006; Sutcliffe & Petersen, 2007). If climate change is manifest as higher variability and magnitude/frequency of extremes then they are likely to become important triggers of adaptation in water resource management, however, their role as contributors to cooperative action between river basin states is poorly understood.

Further research is needed on what adaptations are occurring at both national and international scales in African international river basins and what factors are driving these adaptations. Also, further research could identify the particular limitations to adaptation due to the transboundary nature of the resource and the existing institutional arrangements. We propose that the nature of interactions between countries in international river basins has an important influence on adaptive capacity. These interactions, in particular the role of conflict and cooperation in international river basins, are explored in the next section.

COOPERATION AND CONFLICT IN INTERNATIONAL RIVER BASINS

Climate change, water wars and conflict in the literature

The international nature of many of the World's great rivers and increasing scarcity of water has led to discussions in the academic literature of the growing potential for violent conflict, or 'water wars', between riparian nations over shared water resources (Gleick, 1993; Toset *et al.*, 2000; Swain, 2001; Gleditsch *et al.*, 2006). A related body of literature links environmental scarcity in broader terms with conflict (Homer-Dixon, 1991; Homer-Dixon, 1994; Gleditsch, 1998; Hauge & Ellingsen, 1998). The potential for security problems or violent conflict at an international or sub-national level has also been discussed in relation to the impacts of climate change by Gleick (1989) and more recently in a special issue of Political Geography (Gleick, 1989; Barnett & Adger, 2007; Hendrix & Glaser, 2007; Meier *et al.*, 2007; Nordas & Gleditsch, 2007; Raleigh & Urdal, 2007).

Table 4 Comparison of indicators of adaptive capacity for international river basins (see footnotes for data sources)

Basin Name	Number of countries[7]	Number of dams (dam density = number/ 1x10[6] Km[2]) [7]	Irrigated area[7] (km[2])	Irrigable area[7] (km[2] x10[3])	Number of treaties[8]	GDP per capita (2005) basin mean[9] (max - min)	HDI (2005) basin mean[9] (max - min)	Basins at Risk code[10]	Change in future basin runoff with climate change[11]
WEST AFRICA									
Lake Chad	8	1 (0)	1130	1600	2	1677 (244-6621)	0.53 (0.37-0.82)	2	-
Niger	11	10 (0.1)	2980	2060	10	769 (216-3112)	0.45 (0.34-0.73)	0	Small increase [12]
Senegal	4	0 (0)	367	383	5	513 (350-707)	0.47 (0.38-0.55)	2	-
Volta	6	3 (0.2)	386	508	3	506 (358-900)	0.45 (0.37-0.55)	0	Large[12] or very large[13] increase
CENTRAL AFRICA									
Congo/Zaire	13	22 (0.4)	69	4200	2	1012 (106-5821)	0.48 (0.38-0.68)	0	Either small[12] to moderate[13] increase, or decrease[14]
EAST AFRICA									
Nile	11	12 (0.1)	52200	2710	18	392 (106-1207)	0.48 (0.38-0.71)	1	Small decrease[12,13] or large increase[14,15]
Juba-Shibeli	3	0 (0)	2270	861	1	352 (157-547)	0.46 (0.41-0.52)	0	-

Table continues on next page.

[7] Transboundary Freshwater Spatial Database (http://www.transboundarywaters.orst.edu/database/transfreshspatdata.html)
[8] The African Transboundary Water Law Page (http://www.africanwaterlaw.org/html/default.asp)
[9] United Nations Development Programme (2006)
[10] Basins at Risk: 0=not at risk; 1=Negotiating current conflict; 2= Indicators and protests over water; 3 = indicators only (Yoffee *et al*. 2003)
[11] Small = 0 to 5%, Moderate = >5 to <20%, Large = 20 to <50%, Very Large = 50% and over
[12] Runoff change by 2050 (Manabe *et al.* 2004),
[13] Change in discharge 2001 to 2099 (Aerts *et al.* 2006)
[14] Runoff change by 2050 (Arnell 2003)
[15] Runoff change by 2050 (Milly *et al*. 2005)

Table 4 continued. Comparison of indicators of adaptive capacity for international river basins (see footnotes for data sources)

Basin Name	Number of countries[7]	Number of dams (dam density = number/ $1x10^6$ Km^2) [7]	Irrigated area[7] (km^2)	Irrigable area[7] (km^2 $x10^3$)	Number of treaties[8]	GDP per capita (2005) basin mean[9] (max - min)	HDI (2005) basin mean[9] (max - min)	Basins at Risk code[10]	Change in future basin runoff with climate change[11]
SOUTHERN AFRICA									
Zambezi	9	35 (1.2)	1430	1530	9	1415 (123-5846)	0.49 (0.38-0.65)	3	Small[12] or moderate to large[14,15] decrease
Orange	4	33 (2.5)	6820	1260	5	3695 (808-5846)	0.63 (0.55-0.67)	0	moderate to large decrease[14,15]
Okavango	4	1 (1)	-	932	1	2795 (259-5846)	0.57 0.45-0.65)	2	moderate to large decrease[10,11]
Limpopo	4	40 (3.4)	4750	542	1	2887 (259-5846)	0.56 (0.38-0.67)	3	moderate to large decrease[10,11]

Nordas and Gleditsch (2007) find that the links between climate change, national security and armed conflict have increasingly been made by governmental and international organisations in recent years without reference to sufficient empirical evidence. The papers of the special issue highlight two causal links between climate and conflict: fighting over resources, such as food and water, diminished by climate change impacts; and tensions caused by migration of large numbers of people fleeing climate impacts (Barnett & Adger, 2007; Nordas & Gleditsch, 2007; Reuveny, 2007). However, they show little evidence for organised armed conflict but more for unorganised violence. Nordas and Gleditsch (2007) highlight a need for more systematic studies and more sophisticated conflict models that consider both the kinds of violence that could be expected and the links to specific impacts of climate change, both positive and negative as well as likely adaptation measures. There are fewer examples of studies that look at the issue of security or conflict with respect to the impacts of climate change on water resources in international river basins (Gleick, 1988; van der Molen & Hildering, 2005).

This growing body of literature linking climate change impacts to the potential for violent conflict contrasts with much of the literature on international river basins. Wolf (1998) examines historic water conflicts and suggests that there have been few examples of wars over water historically and that international water is more likely to induce cooperation than violent conflict due to a number of factors including the shared interests of riparians, the resilience of institutions where cooperative water regimes have been established and the high economic cost of war compared to the cost of water. This view is supported by a study by Yoffe *et al.* (2003) in which the authors examine the Transboundary Freshwater Dispute of historical incidents over international waters between 1948 and 1999. For the 122 international river basins that were documented, the number of cooperative incidents (67%) was found to far exceed the number of conflictive events (28%).

Forms of conflict and cooperation

As the Yoffee *et al.* (2003) paper shows, cases of both conflict and cooperation over internationally shared water resources have been documented. A number of papers have attempted to theorise and understand conflict and cooperation. In this section we review the literature that describes how both conflict and cooperation over international rivers can take many forms, occur at various scales, over a variety of issues.

Yoffe *et al.* (2003) developed a Water Event Intensity Scale, which draws from the International Cooperation and Conflict Scale of Azar (1980). The scale ranges from extreme conflict at –7, for a formal declaration of war, through to extreme cooperation at 7 for voluntary unification into one nation. In this scale conflictive interactions include hostile verbal expressions (official or unofficial) and hostile diplomatic, economic or military acts. Cooperative interactions include official verbal expressions of support and cultural, scientific, economic, technological, industrial or military support or agreement (Yoffe *et al.*, 2003). This scale is taken up by Zeitoun and Warner (2006), who combine it with the NATO conflict-development scale to produce a Conflict Intensity Frame (shown in Fig. 1) that differentiates between three main categories of conflict: no significant conflict, cold conflict and violent conflict. Zeitoun and Warner (2006) demonstrate how relations between states can undergo various degrees of intensity of conflict over time and that conflict should not just be understood as violent conflict between nation states: less-intense conflicts are still forms of conflict. Recent theorising on conflict over transboundary water resources by Zeitoun (2007) has expressed the dynamics between states in terms of the securitization of the issue, described as the framing of "the issue in terms of security…. drawing on perceptions of national, local or individual (in)security" (Zeitoun, 2007, p115). The level of securitization ranges from non-politicised (no conflict and some cooperation) through to politicised, securitised and armed (violent conflict). Here, it is the perceptions of states as to how water sharing issues relate to threats to national security that define the level of securitisation.

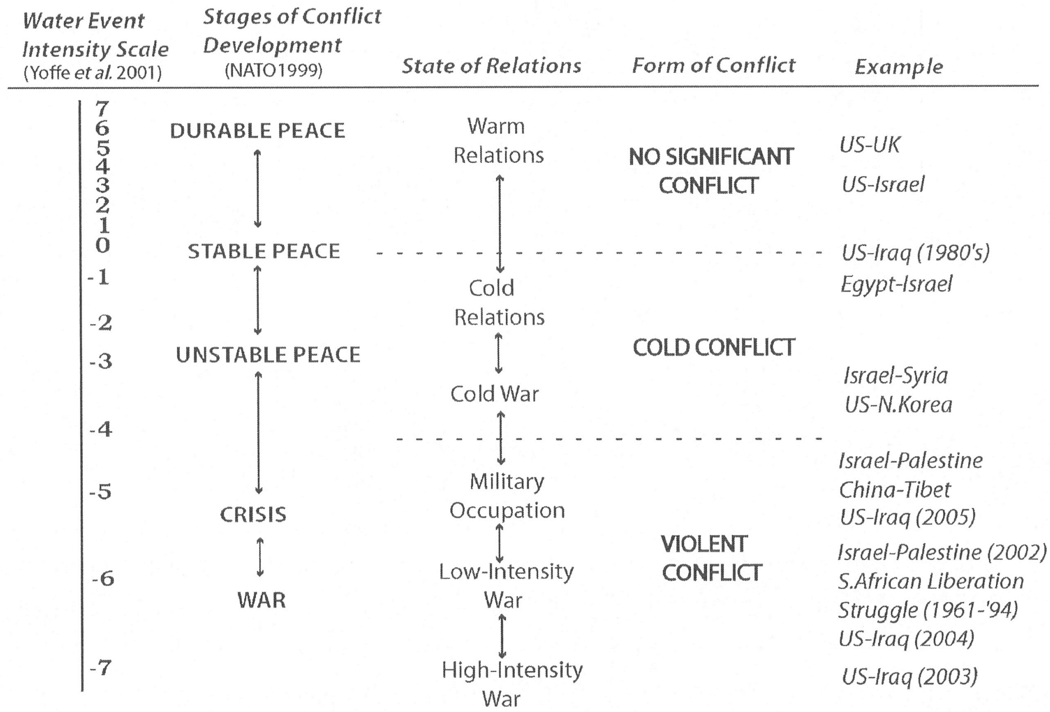

Fig. 1 Conflict Intensity Frame by Zeitoun & Warner (2006)

Until recently cooperation has been less theorised than conflict (Mirumachi, 2007, Allan, personal communication). Kistin (2006) warns against employing a simplistic dichotomy of conflict and cooperation to describe relations between riparian states and that cooperation should not be seen just as the absence of conflict. Mirumachi (2007) develops a typology of levels of cooperation adapted from Tuomela (2000). These are: confrontation of an issue; ad hoc collaboration; technical collaboration; risk-averting cooperation and risk-taking cooperation.

Cooperation over internationally shared water resources can occur through a number of different formal or informal mechanisms. Formal mechanisms include international conventions, bilateral or multilateral treaties or agreements involving some or all riparian states, joint river management institutions and joint projects. Informal mechanisms can include knowledge or data sharing. Formal institutions involved in cooperation in African river basins include institutions of the African Union: the African Ministerial Council on Water (AMCOW); and the New Partnership for Africa's Development (NEPAD) and also the UN Economic Commission for Africa (ECA). There are a number of important regional institutions such as the Southern

African Development Community (SADC) and the East African Community (EAC) that have a remit that includes transboundary resource management amongst other goals of political, economic and environmental cooperation and regional integration (Wirkus & Böge, 2006). In SADC these goals are implemented through the SADC Protocol on Shared Water Resources (Kistin & Ashton, 2008). Several African river basins have a river basin organisation as well as a number of bilateral or multilateral agreements, for example the Senegal, Niger, Lake Chad, Okovango, Limpopo, Orange and Zambezi basins (United Nations Economic Commission for Africa, 2000; Wirkus & Böge, 2006). The Nile Basin does not have a river basin organisation or any agreements involving all riparian countries, although there are a number of bilateral treaties that date back as far as 1891 (United Nations Economic Commission for Africa, 2000). However, there have been a number of cooperative programmes the latest of which is the Nile Basin Initiative started in 1999, which has a number of projects aimed at developing trust amongst stakeholders in the basin and encouraging sustainable development of Nile water resources (Wirkus & Böge, 2006; Nile Basin Initiative, 2007)

Treaties are varied and use a number of different principles, many of which are enshrined in the 1997 Watercourses Convention: universal participation, equitable use, avoiding significant harm, sovereign equality and territorial integrity, information exchange, consultation, prior notification, environmental protection, peaceful dispute resolution (Conca, 2006). However, in a study of the principals incorporated into international river agreements Conca (2006) found that there are tensions between some of the principals, such as those of 'no significant harm' and 'equitable use'. Waterbury (2002) describes how different riparian countries in the Nile basin defend their rights to Nile waters based on one or other, or occasionally both of these two principles. Egypt gives prominence to the principal of significant harm to defend its existing uses of Nile waters, whilst Ethiopia argues for equitable use to allow it to develop its use of Nile water (Waterbury, 2002). Despite these and other impediments to the formation of international agreements in many river basins, Wolf *et al.* (2003) find that co-riparian relations are more cooperative in basins that have treaties and a high density of dam infrastructure than those basins that have a high density of dams but no treaties.

Wolf *et al.* (2003) found that cooperation occurs over a wide range of issues in international river basins including joint management, water quantity, water quality, infrastructure, hydropower and economic development, whilst most conflictive events occur over just two issues: water quantity and infrastructure. In contrast Wolf (2007) describes most water disputes as revolving around three issues: quantity, quality and timing. Emphasis on benefit sharing as a mechanism for cooperative river basin management can lead to a broader range of issues being included in negotiations and agreements between riparians, for example including issues of trade, immigration and environmental protection as well as issues of water use for irrigation, domestic water supply or hydropower generation, for example (Sadoff *et al.*, 2002). For example, projects being planned under the NBI include several joint multi-purpose projects that provide different benefits to several riparian countries including the provision of electricity, flood protection and irrigation (Nile Basin Initiative, 2007).

The scale at which interactions occur is important for understanding conflict and cooperation in international river basins. Whilst extreme conflict (i.e. war) over water, or other renewable resources, is seen as unlikely at the international scale by Wolf (1998), there is evidence for regional disputes over water and other natural resources

(Homer-Dixon, 1994; Wolf, 1998; Meier *et al.*, 2007). Wolf finds that "geographic scale and intensity of conflict are inversely related" (1998, p261) and asserts that there is the highest potential for violence at the regional scale (within-countries), whilst there is little potential for violence between states (Wolf, 2007). Much of the literature on climate and conflict referred to at the start of this section presents examples of conflict at the regional scale (Meier *et al.*, 2007; Raleigh & Urdal, 2007).

Whilst nation states are the key stakeholders considered in the international relations approach to the study of international rivers, a number of different stakeholders are involved in these interactions, including the executive authorities and policy making elites of the riparian states at national and local government level, and non-state actors, such as international donor institutions, multi-national firms, civil society and the environment (Waterbury, 2002; Wolf *et al.*, 2003; Furlong, 2006). Engagement with different stakeholders can be important for the public acceptance of proposed measures of cooperation (Huisman *et al.*, 2000).

The benefits of cooperation and the disadvantages of conflict

Cooperation in international river basins is seen as desirable and to yield benefits (Sadoff & Grey, 2002; Waterbury, 2002; United Nations Development Programme, 2006). Sadoff and Grey (2002) describe four types of benefits. The first of these are described as benefits granted *to the river* by cooperative basin-wide environmental management, for example improvements in water quality, maintenance of biodiversity and conservation of wetlands, floodplains and groundwater recharge areas. Secondly they describe potential benefits *from the river*, for example hydropower, irrigation, flood and drought management and navigation. The third type of proposed benefits are benefits *because of the river*, for example reduced risk of conflict between riparian nations and increased food and energy security, and fourthly, benefits *beyond the river* such as integration of regional infrastructure, markets and trade. Sadoff and Grey (2002) suggest that there are costs to non-cooperation as well as to cooperation and that depending on the particular circumstance the scale of benefits may or may not outweigh the costs of cooperation. In the absence of strong cooperation, Zeitoun and Warner (2006) assert that even the varying intensities of conflict that commonly exist but fall short of violent conflict or war have negative consequences on the less powerful riparians.

Conditions, barriers and limitations of cooperation

Despite the benefits proposed from cooperation over shared water resources in international river basins the literature cites a number of conditions necessary for and barriers or limitations to cooperation that can be political, institutional or geographical.

Wolf (1998) refers to geographical determinants of conflict and cooperation by suggesting that conflict is more likely where the downstream nation is the hegemon, or nation with most power, and upstream countries launch projects that reduce water quantity or quality. Other factors thought to have influence on whether cooperation or conflict occurs include the hydroclimatology, particularly the nature of variability and extremes, the institutional capacity to absorb change and the political situation in the riparian countries, in particular whether countries are democracies or not (Wolf *et al.*, 2003; Yoffe *et al.*, 2003). Van der Zaag and Savenije (2000) describe the foundation for balanced and equitable sharing of international water resources as IWRM, supported by three pillars: technical cooperation; an enabling political environment; and adequate institutions. Wolf (1998) suggests that riparians need incentives for cooperation, such as strong third party encouragement and extensive funding from the international community.

The political aspects of transboundary relations are examined by Zeitoun and Warner (2006) and Zeitoun and Allan (2008). They develop a framework of hydro-hegemony, in which the key factor determining the outcome of competition for water in international river basins is the relative power wielded by each riparian. They also find that the upstream/downstream positions of the riparians and their potential to exploit water through infrastructure and technical capacity also play a role in determining outcomes. They argue that the hydro-hegemon, the riparian state with most power, determines the nature of interactions over water resources and whether they are cooperative or competitive and whether benefits from the river reach weaker riparians or not (Zeitoun & Warner, 2006). Recent research in the Nile basin applying the hydro-hegemony framework has investigated the 'counter-hegemonic' strategies used by weaker riparian states, such as Ethiopia, to oppose or challenge the status-quo maintained by the hydro-hegemon (Egypt, Cascao, 2008).

The idea that cooperation is inherently good has been questioned by (Kistin, 2006; Kistin & Phillips, 2007), who ask what constitutes effective cooperation? They find that many of the existing arrangements for cooperation in international agreements are flawed because of factors relating to inclusivity, data quality and transparency, flexibility, equitability, environmental sustainability, implementation and enforcement. An example of limitations to cooperation related to flexibility is provided by Fischhendler (2004), who finds that treaties often lack mechanisms to deal with climate variability and that this impedes the ability of treaties and institutions to manage a crisis, such as a drought situation. Drieschova *et al.* (2008), in a review of 50 agreements for international river basins, find that there are tradeoffs between flexibility in treaties and the enforceability of the agreements. Nevertheless, there are some documented examples of cooperation that incorporates flexibility in response to water variability for African river basins. For example, Conway (2005) describes a treaty for the Nile Basin that has a mechanism to adapt to water deficits during drought situations. Similarly, Kistin and Ashton (2008) find a variety of flexibility mechanisms in formal agreements in the Orange basin in Southern Africa that provide for adaptive capacity in transboundary water management. However, Kistin and Phillips (2007) conclude that not all cooperation produces positive outcomes and that where circumstances are asymmetrical, inequitable or unsustainable outcomes may result from cooperation.

In the context of climate change an important question is whether barriers to cooperation can be overcome following an emergency such as an extreme climate event that has an impact on one or more country in a international river basin. Huisman et al. (2000) in a study of European international river basins found that disasters with international impacts can lead to a breakthrough that improves transboundary cooperation. However, Waterbury (2002) suggests that "crisis in the quantity or quality of supply may drive users toward cooperation or, alternatively to conflict" (page 166).

CONCLUSIONS

In this paper we have reviewed evidence for climate change and its possible impacts on water resources in Africa, the challenges of adaptation to climate change impacts on water resources, particularly in international river basins and the role of conflict and cooperation in water resource management in international river basins.

Africa faces significant challenges to water resources management in the form of high variability and regional scarcity, set within the context of generally weak institutional capacity. Management is further challenged by the transboundary nature of many of its river basins. Climate change, despite uncertainty about the detail of its impacts on water resources, is likely to exacerbate many of these challenges. Empirical and modelling analyses demonstrate that river flows are highly sensitive to climate perturbations. Studies that project changes in average surface runoff conditions from climate and hydrological models show increases in runoff during the 21^{st} Century for some regions of Africa, for example in the West African river basins of the Niger and Volta, whilst in central and East Africa the studies disagree on the direction and magnitude of change. In Southern Africa, which is already a region prone to water scarcity, the model projections show decreasing surface runoff in the future. However, these projections are uncertain and for the majority of river basins, economically and demographically driven growth in demand is expected to outweigh climate-induced changes.

Globally, adaptation in the water sector is beginning to emerge although evidence suggests this is primarily in the form of building adaptive capacity and no regrets type activities in response to other factors in addition to climate. The combination of uncertainty and the need to consider non-climate factors in water resource management is leading to a greater emphasis on flexibility, adaptive management and responses that are robust to uncertainty (for example, Frederick *et al.*, 1997; Stakhiv, 1998; Pahl-Wostl *et al.*, 2005; Dessai & Hulme, 2007). The nuances of such approaches and their requirements for fairly sophisticated levels of policy and institutional capacity means their application in an African context will require careful consideration and good understanding of local complexities.

The transboundary nature of the resource and its role in these processes is poorly understood, as is the role that climate extremes and future climate change play. International river basins and their riparian states differ in their capacity to adapt to changing water availability and demand and extreme climate events, as indicated by their differing economic resources, social vulnerability, institutional arrangements and the degree of inequality within the basin. This raises concerns that one country's adaptation may cause a negative impact on another country's ability to adapt and emphasises the need for cooperative responses to climate change and other of drivers of change in water resources. Our review highlights several features of cooperation in transboundary water resource management that are relevant to climate change adaptation. Cooperation is seen to have several types of benefits including benefits for water resource management and potentially benefits for adaptation, but there are costs to cooperation as well as costs of non-cooperation (Sadoff & Grey, 2002). Cooperation or conflict occurs at varying intensities and geographic scales in international river basins over a number of issues and through both formal and informal mechanisms. Cooperation should not just be seen as the absence of conflict (Yoffe *et al.*, 2003; Kistin, 2006; Zeitoun & Warner, 2006). The power relations between states sharing a river basin have a major influence on the nature of interactions between states and the outcome of competition for water resources (Zeitoun & Warner, 2006). In addition, the perceptions of states as to how water sharing issues relate to threats to national security define the level of securitisation (Zeitoun, 2007) and this in turn influences interactions. Crisis situations or international emergencies, for example due to flooding or drought, have the potential to either prompt enhanced cooperation or, alternatively, they may exacerbate conflict (Huisman *et al.*, 2000; Waterbury, 2002).

Following on from this review we suggest an agenda for further research on adaptation to climate change in African international river basins. Research is needed to identify current adaptations occurring at both national and international scales and what factors are driving these adaptations. The range of water scarcity conditions and measures of adaptive capacity between basins in Africa suggest that different combinations of adaptation options will need to be considered, including *inter alia*, storage, supply/demand management and the potential for intra-basin virtual water transfers. The specific physical, economic and political situations in African international basins also deserve more attention, in particular, whether and in what way they are unique and how they mediate processes of adaptation and cooperation. For both African and other international basins there is a need to review the appropriateness of existing institutional structures and frameworks for treaties in the context of climate change and research new approaches that are better suited to non-stationary hydrological conditions.

There is some evidence that cooperative mechanisms may enhance water resource management in international river basins and may therefore also enhance adaptation to climate variability, climate change and other pressures on water. However, cooperation needs to be examined carefully for how it contributes to adaptation to climate change for different states in river basins. It can not be assumed that cooperation will facilitate adaptation for all riparian countries due to asymmetric power relations between countries. Research is needed to examine the factors and processes that are important for cooperation to lead to positive adaptation outcomes and increasing adaptive capacity of water management institutions. For example, is the threat of climate change or experiences of past climatic disasters providing an impetus for cooperation or perhaps a justification for counter-hegemony strategies by weaker riparian states? The role of specific extreme climate events in triggering cooperation or conflict could be examined for cases in African international river basins. In addition, where indicators of conflict do exist between riparian states, does this conflict present a limit to adaptation to climate extremes and future climate change?

Acknowledgements

The authors wish to acknowledge the useful comments from three reviewers and helpful discussions with Tony Allen and Naho Mirumachi of Kings College, London and Mark Zeitoun of London School of Economics and Political Science. We also acknowledge the work of Aeron Wolf and colleagues at Oregon State University who have made their data freely available in the Transboundary Freshwater Spatial Database.

References

Abraham, L. Z. (2006) Climate change impact on Lake Ziway Watershed water availability, Ethiopia. MSc Thesis, Fachhochschule Köln University of Applied Sciences Cologne, Cologne, Germany.

Adger, W. N., S. Dessai, M. Goulden, M. Hulme, I. Lorenzoni, D. Nelson, L. O. Naess, J. Wolf and A. Wreford (in press). Limits and barriers to adaptation. *Climatic Change* **xx**(xx), xxxx-xxxx.

Aerts, J. and P. Droogers (2004a). Adaptation for Regional Water Management. In: *Climate change in contrasting river basins: adaptation strategies for water, food and environment* (ed. by J. C. J. H. Aerts and P. Droogers), 1-24. CABI, Wallingford.

Aerts, J., H. Renssen, P. J. Ward, H. de Moel, E. Odada, L. M. Bouwer and H. Goosse (2006). Sensitivity of global river discharges under Holocene and future climate conditions. *Geophysical Research Letters* **33**(19).

Aerts, J. C. J. H. and P. Droogers (2004b). *Climate change in contrasting river basins: adaptation strategies for water, food and environment*. CABI, Wallingford.

AfDB, AU and ECA (2000). The African Water Vision for 2025: Equitable and Sustainable Use of Water for Socioeconomic Development. *African Development Bank, African Union and Economic Commision for Africa,* http://www.uneca.org/awich/African%20Water%20Vision%202025.pdf

Alcamo, J., P. Doll, T. Henrichs, F. Kaspar, B. Lehner, T. Rosch and S. Siebert (2003). Global estimates of water withdrawals and availability under current and future "business-as-usual" conditions. *Hydrological Sciences Journal-Journal Des Sciences Hydrologiques* **48**(3), 339-348.

Alcamo, J., M. Florke and M. Marker (2007). Future long-term changes in global water resources driven by socio-economic and climatic changes. *Hydrological Sciences Journal-Journal Des Sciences Hydrologiques* **52**(2), 247-275.

Allan, J. A. (1998). Virtual water: A strategic resource global solutions to regional deficits. *Ground Water* **36**(4), 545-546.

Allan, J. A. (2006). Virtual water - Part of an invisible synergy that ameliorates water scarcity. *Water Crisis: Myth or Reality?*, 131-150.

Allan, T., W. Cosgrove, R. Connor, A. Hoekstra, F. Kansiime, C. Pahl-Wostl and H. Savenije (2002). Policy Analysis and Institutional Frameworks in Climate and Water. In: *Coping with the impacts of climate variability and climate change in water management: a scoping paper. DWC report number DWCSSO-01 (2002)* (ed. by P. Kabat, R. E. Schulze, M. E. Hellmuth and J. A. Veraart). International Secretariat of the Dialogue on Water and Climate, Wageningen.

Andah, W., N. van de Giesen, A. Huber-Lee and C. A. Biney (2004). Can we maintain food production without losing hydropower? The Volta Basin (West Africa). In: *Climate change in contrasting river basins: adaptation strategies for water, food* *and environment* (ed. by J. C. J. H. Aerts and P. Droogers), 181-194. CABI, Wallingford.

Andersson, L., J. Wilk, M. C. Todd, D. A. Hughes, A. Earle, D. Kniveton, R. Layberry and H. H. G. Savenije (2006). Impact of climate change and development scenarios on flow patterns in the Okavango River. *Journal of Hydrology* **331**(1-2), 43-57.

Aquastat Survey (2005). http://www.fao.org/nr/water/aquastat/regions/africa/index.stm. Last update: Accessed on: 10/10/2008.

Arnell, N. W. (2003). Effects of IPCC SRES emissions scenarios on river runoff: a global perspective. *Hydrology and Earth System Sciences* **7**(5), 619-641.

Arnell, N. W. (2004). Climate change and global water resources: SRES emissions and socio-economic scenarios. *Global Environmental Change-Human and Policy Dimensions* **14**(1), 31-52.

Arnell, N. W. (2006). Climate Change and Water Resources: A Global Perspective. In: *Avoiding dangerous climate change* (ed. by H. J. Schnellnhuber and W. P. Cramer), xii, 392 p. Cambridge University Press, Cambridge; New York.

Arnell, N. W. and M. Charlton (2008). Adapting to the effects of climate change on water supply reliability. *Paper presented at a conference on Living with Climate Change: Are there limits to adaptation?*, Royal Geographical Society, London, in preparation.

Arnell, N. W. and E. K. Delaney (2006). Adapting to climate change: Public water supply in England and Wales. *Climatic Change* **78**(2-4), 227-255.

Ashton, P. J. (2002). Avoiding conflicts over Africa's water resources. *Ambio* **31**(3), 236-242.

Azar, E. E. (1980). The Conflict and Peace Data Base (COPDAB). *Journal of Conflict Resolution* **24**(1), 143-152.

Barnett, J. and W. N. Adger (2007). Climate change, human security and violent conflict. *Political Geography* **26**(6), 639-655.

Benson, C., E. J. Clay and World Bank. (1998). *The impact of drought on Sub-Saharan African economies : a preliminary examination*. World Bank, Washington, D.C.

Boko, M., I. Niang, A. Nyong, C. Vogel, A. Githeko, M. Medany, B. Osman-Elasha, R. Tabo and P. Yanda (2007). Africa. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (ed. by M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden and C. E. Hanson), 173-210. Cambridge University Press, Cambridge, UK.

Brooks, N., W. N. Adger and P. M. Kelly (2005). The determinants of vulnerability and adaptive capacity at the national level and the implications for adaptation. *Global Environmental Change-Human and Policy Dimensions* **15**(2), 151-163.

Burton, I., R. W. Kates and G. F. White (1993). *The environment as hazard*. Guilford Press, New York ; London.

Cascao, A. E. (2008). Ethiopia - Challenges to Egyptian hegemony in the Nile Basin. *Water Policy* **10**, 13-28.

Christensen, J. H., B. Hewitson, A. Busuioc, A. Chen, X. Gao, I. Held, R. Jones, R. K. Kiolli, 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* (ed. by S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor and H. L. Miller). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Commission for Africa (2005). Our Common Interest. *Commission for Africa,* http://www.commissionforafrica.org/english/report/thereport/english/11-03-05_cr_report.pdf.

Conca, K. (2006). Global Regime Formation or Complex Institution Building? The Principled Content of International River Agreements. *International Studies Quarterly* **50**, 263-285.

Conway, D. (2005). From headwater tributaries to international river: Observing and adapting to climate variability and change in the Nile basin. *Global Environmental Change-Human and Policy Dimensions* **15**(2), 99-114.

Conway, D., E. Allison, R. Felstead and M. Goulden (2005). Rainfall variability in East Africa: implications for natural resources management and livelihoods. *Philosophical Transactions of the Royal Society of London Series a-Mathematical Physical and Engineering Sciences* **363**(1826), 49-54.

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. *Geophysical Research Letters* **34**(3).

Conway, D. and M. Hulme (1996). The Impacts of Climate Variability and Future Climate Change in the Nile Basin on Water Resources in Egypt. *International Journal of Water Resources Development* **12**(3), 277-296.

Conway, D., M. Krol, J. Alcamo and M. Hulme (1996). Future availability of water in Egypt: The interaction of global, regional, and basin scale driving forces in the Nile Basin. *Ambio* **25**(5), 336-342.

Conway, D., A. Persechino, S. Ardoin-Bardin, H. Hamandawana, C. Dieulin and G. Mahe (in press). Rainfall and river flow variability in sub-Saharan Afica during the 20th century. *Journal of Hydrometeorology*, DOI: 10.1175/2008JHM1004.1

de Loe, R., R. Kreutzwiser and L. Moraru (2001). Adaptation options for the near term: climate change and the Canadian water sector. *Global Environmental Change-Human and Policy Dimensions* **11**(3), 231-245.

de Loë, R., R. Kreutzwiser and L. Moraru (2001). Adaptation options for the near term: climate change and the Canadian water sector. *Global Environmental Change-Human and Policy Dimensions* **11**(3), 231-245.

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

Dessai, S. and M. Hulme (2007). Assessing the robustness of adaptation decisions to climate change uncertainties: A case study on water resources management in the East of England. *Global Environmental Change* **17**(1), 59-72.

Dessai, S., M. Hulme, R. Lempert and R. Pielke (2008). Climate prediction: a limit to adaptation? *Paper presented at a conference on Living with Climate Change: Are there limits to adaptation?*, Royal Geographical Society, London, in preparation.

Drieschova, A., M. Giordano and I. Fischhendler (2008). Governance mechanisms to address flow variability in water treaties. *Global Environmental Change* **18**(2), 285-295.

Falkenmark, M. (1995). Land-water linkages: A synopsis. *Land and water integration and river basin management*, Rome, Italy, Proceedings of an FAO informal workshop.

Fischhendler (2004). Legal and institutional adaptation to climate uncertainty: a study of international rivers. *Water Policy* **6**, 281-302.

Frederick, K. D., D. C. Major and E. Z. Stakhiv (1997). Water Resources Planning Principles and Evaluation Criteria for Climate Change: Summary and Conclusions. *Climatic Change* **37**(1), 291-313.

Furlong, K. (2006). Hidden theories, troubled waters: International relations, the `territorial trap', and the Southern African Development Community's transboundary waters. *Political Geography* **25**(4), 438-458.

Gleditsch, N. P. (1998). Armed conflict and the environment: A critique of the literature. *Journal of Peace Research* **35**(3), 381-400.

Gleditsch, N. P., K. Furlong, H. Hegre, B. Lacina and T. Owen (2006). Conflicts over shared rivers: Resource scarcity or fuzzy boundaries? *Political Geography* **25**(4), 361-382.

Gleick, P. H. (1986). Methods for Evaluating the Regional Hydrologic Impacts of Global Climatic Changes. *Journal of Hydrology* **88**(1-2), 97-116.

Gleick, P. H. (1988). The Effects of Future Climatic Changes on International Water-Resources - the Colorado River, the United-States, and Mexico. *Policy Sciences* **21**(1), 23-39.

Gleick, P. H. (1989). The Implications of Global Climatic Changes for International Security. *Climatic Change* **15**(1-2), 309-325.

Gleick, P. H. (1993). Water and Conflict - Fresh-Water Resources and International Security. *International Security* **18**(1), 79-112.

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

Groundwater and Climate in Africa (2008). The Kampala Statement. Groundwater and Climate in Africa Conference, June 2008. Kampala, Uganda, http://www.gwclim.org/downloads/kampala_statement.pdf.

Hauge, W. and T. Ellingsen (1998). Beyond environmental scarcity: Causal pathways to conflict. *Journal of Peace Research* **35**(3), 299-317.

Hendrix, C. S. and S. M. Glaser (2007). Trends and triggers: Climate, climate change and civil conflict in Sub-Saharan Africa. *Political Geography* **26**(6), 695-715.

Heyns, P. S. V. H., M. J. Patrick and A. R. Turton (2008). Transboundary Water Resource Management in Southern Africa: Meeting the Challenge of Joint Planning and Management in the Orange River Basin. *International Journal of Water Resources Development* **24**(3), 371 - 383.

Hiscock, K. M., M. O. Rivett and R. M. Davison (2002). Sustainable groundwater development. *Geological Society, London, Special Publications* **193**(1), 1-14.

Homer-Dixon, T. (1994). Environmental scarcities and violent conflict: evidence from cases. *International Security* **19**(1), 5-40.

Homer-Dixon, T. F. (1991). On the threshold: environmental changes as causes of acute conflict. *International Security* **16**(2), 76-116.

Huisman, P., J. de Jong and K. Wieriks (2000). Transboundary cooperation in shared river basins: experiences from the Rhine, Meuse and North Sea. *Water Policy* **2**(1-2), 83-97.

Ivey, J. L., J. Smithers, R. C. de Loë and R. D. Kreutzwiser (2004). Community Capacity for Adaptation to Climate-Induced Water Shortages: Linking Institutional Complexity and Local Actors. *Environmental Management* **33**(1), 36-47.

Kabat, P., R. E. Schulze, M. E. Hellmuth and J. A. Veraart, Eds. (2002). *Coping with the impacts of climate variability and climate change in water management: a scoping paper.* DWC report number DWCSSO-01 (2002). International Secretariat of the Dialogue on Water and Climate, Wageningen.

Keohane, R. (2005). *After Hegemony: Cooperation and Discord in the World Political Economy*. Princeton University Press, Princeton.

Kistin, E. (2006). Qualifying Cooperation over Transboundary Waters. *Water Governance for Africa - The challenge of uncertainty and change*, University of Bradford.

Kistin, E. J. and P. J. Ashton (2008). Adapting to change in transboundary rivers: An analysis of treaty flexibility on the Orange-Senqu River basin. *International Journal of Water Resources Development* **24**(3), 385-400.

Kistin, E. J. and D. J. H. Phillips (2007). A Critique of existing agreements on transboundary waters and proposals for creating effective cooperation between co-riparians. *Third International Workshop on Hydro-Hegemony, London 12 and 13 May 2007*.

Kundzewicz, Z. W., L. J. Mata, N. W. Arnell, P. Döll, P. Kabat, B. Jiménez, K. A. Miller, T. Oki, S. Zekai and I. Shiklomanov (2007). Freshwater resources and their management. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (ed. by M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden and C. E. Hanson), 173-210. Cambridge University Press, Cambridge, UK.

Lankford, B. 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**(2), 168-180.

Lankford, B., B. van Koppen, T. Franks and H. Mahoo (2004). Entrenched views or insufficient science?: Contested causes and solutions of water allocation; insights from the Great Ruaha River Basin, Tanzania. *Agricultural Water Management* **69**(2), 135-153.

Levina, E. (2006). Domestic Policy Frameworks for Adaptation in Climate Change in the Water Sector, Part 2: non-Annex I Countries. *OECD, IEA,* October 2006, 1-69.

Magistro, J. and M. D. Lo (2001). Historical and human dimensions of climate variability and water resource constraint in the Senegal River Valley. *Climate Research* **19**(2), 133-147.

Manabe, S., P. C. D. Milly and R. Wetherald (2004). Simulated long-term changes in river discharge and soil moisture due to global warming. *Hydrological Sciences Journal-Journal Des Sciences Hydrologiques* **49**(4), 625-642.

Meier, P., D. Bond and J. Bond (2007). Environmental influences on pastoral conflict in the Horn of Africa. *Political Geography* **26**(6), 716-735.

Merryfield, W. J. (2006). Changes to ENSO under CO2 doubling in a multimodel ensemble. *Journal of Climate* **19**(16), 4009-4027.

Miller, K. A., S. L. Rhodes and L. J. Macdonnell (1997). Water allocation in a changing climate: Institutions and adaptation. *Climatic Change* **35**(2), 157-177.

Milly, P. C. D., J. Betancourt, M. Falkenmark, R. M. Hirsch, Z. W. Kundzewicz, D. P. Lettenmaier and R. J. Stouffer (2008). Climate change - Stationarity is dead: Whither water management? *Science* **319**, 573-574.

Milly, P. C. D., K. A. Dunne and A. V. Vecchia (2005). Global pattern of trends in streamflow and water availability in a changing climate. *Nature* **438**(7066), 347-350.

Mirumachi, N. (2007). Fluxing relations in water history: Conceptualizing the range of relations in transboundary river basins. Proceedings of the 5th International Water History Association Conference - Past and Futures of Water. Tampere, Finland.

Molle, F. (2003). Development trajectories of river basins: A conceptual framework. *International Water Management Institute, Research Report 72,*

Moser, S. C. (2008). Whether our levers are long enough and the fulcrum strong? Exploring the soft underbelly of adaptation decisions and actions. *Paper presented at a conference on Living with Climate Change: Are there limits to adaptation?*, Royal Geographical Society, London, in preparation.

Naess, L. O., G. Bang, S. Eriksen and J. Vevatne (2005). Institutional adaptation to climate change: Flood responses at the municipal level in Norway. *Global Environmental Change Part A* **15**(2), 125-138.

Nakicenovic, N. (2000). *Special report on emissions scenarios : a special report of Working Group III of the Intergovernmental Panel on Climate Change*. IPCC, Cambridge University Press, Cambridge.

NATO (1999). Environment & Security in an International Context – Final Report March 1999. Committee on the Challenges of Modern Society Report No. 232. Berlin, Germany, North Atlantic Treaty Organisation.

New, M., A. Lopez, S. Dessai and R. Wilby (2007). Challenges in using probabilistic climate change information for impact assessments: an example from the water sector. *Philosophical Transactions of the Royal Society a-Mathematical Physical and Engineering Sciences* **365**(1857), 2117-2131.

Nile Basin Initiative (2007). Nile Basin Initiative Projects Brief. *Nile Basin Initiative Secretariat,* June 2007, pp20.

Nordas, R. and N. P. Gleditsch (2007). Climate change and conflict. *Political Geography* **26**(6), 627-638.

Olsen, J. R. (2006). Climate change and floodplain management in the United States. *Climatic Change* **76**(3-4), 407-426.

Pahl-Wostl, C., T. Downing, P. Kabat, P. Magnuszewski, J. R. Meigh, M. Schlueter, J. Sendzimir and S. Werners (2005). Transition to Adaptive Water Management: The NeWater Project: NeWater Working Paper 1. *Institute of Environmental Systems Research, University of Osnabruck,* August 2005,

Pearce, F. (2006). Uganda pulls plug on Lake Victoria. *New Scientist* **2538**, 12.

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**(1-4), 185-197.

Penning-Rowsell, E., C. Johnson and S. Tunstall (2006). `Signals' from pre-crisis discourse: Lessons from UK flooding for global environmental policy change? *Global Environmental Change* **16**(4), 323-339.

Raadgever, T., E. Mostert and N. van de Giesen (2006). Measuring Adaptive River Basin Management. *2006 AWRA Summer Speciality Conference*, Missoula, Montana, AWRA.

Ragab, R. and C. Prudhomme (2002). Climate change and water resources management in arid and semi-arid regions: Prospective and challenges for the 21st century. *Biosystems Engineering* **81**(1), 3-34.

Raleigh, C. and H. Urdal (2007). Climate change, environmental degradation and armed conflict. *Political Geography* **26**(6), 674-694.

Raupach, M. R., G. Marland, P. Ciais, C. Le Quere, J. G. Canadell, G. Klepper and C. B. Field (2007). Global and regional drivers of accelerating CO2 emissions. *Proceedings of the National Academy of Sciences of the United States of America* **104**(24), 10288-10293.

Reuveny, R. (2007). Climate change-induced migration and violent conflict. *Political Geography* **26**(6), 656-673.

Rijsberman, F. R. (2006). Water scarcity: Fact or fiction? *Agricultural Water Management* **80**(1-3), 5-22.

Sadoff, C. W. and D. Grey (2002). Beyond the river: the benefits of cooperation on international rivers. *Water Policy* **4**, 389-403.

Sadoff, C. W., D. Whittington and D. Grey (2002). *Africa's international rivers: an economic perspective*. World Bank, Washington, D.C.

Schulze, R. E. (1997). Impacts of global climate change in a hydrologically vulnerable region: Challenges to South African hydrologists. *Progress in Physical Geography* **21**(1), 113-136.

Seckler, D., U. Amarasinghe, D. Molden, R. de Silva and R. Barker (1998). World Water Demand and Supply, 1990 to 2025: Scenarios and Issues. Research report 19. *International Water Management Institute,* 40.

Sene, K. J. (2000). Theoretical estimates for the influence of Lake Victoria on flows in the upper White Nile. *Hydrological Sciences Journal-Journal Des Sciences Hydrologiques* **45**(1), 125-145.

Shepherd, P., J. Tansey and H. Dowlatabadi (2006). Context matters: What shapes adaptation to water stress in the Okanagan? *Climatic Change* **78**(1), 31-62.

Smit, B. and O. Pilifosova (2001). Adaptation to Climate Change in the Context of Sustainable Development and Equity. In: *Climate Change 2001: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Third Assessment report of the Intergovernmental Panel on Climate Change.* (ed. by, 877-912. WMO/UNEP.

Smit, B. and J. Wandel (2006). Adaptation, adaptive capacity and vulnerability. *Global Environmental Change*
Resilience, Vulnerability, and Adaptation: A Cross-Cutting Theme of the International Human Dimensions Programme on Global Environmental Change **16**(3), 282-292.

Stakhiv, E. Z. (1998). Policy implications of climate change impacts on water resources management. *Water Policy* **1**(2), 159-175.

Stern, N. (2007). *The Economics of Climate Change: The Stern Review*. Cambridge University Press, Cambridge.

Strzepek, K. and A. McCluskey (2006). District level hydro-climatic time series and scenario analysis to assess the impacts of climate change on regional water resources and agriculture in Africa. CEEPA Discussion Paper Number 13 *The Centre for Environmental Economics and Policy in Africa, University of Pretoria, South Africa. ,* 59 pp.

Strzepek, K. and D. N. Yates (1996). Economic and social adaptations to climate change impacts on water resources: a case study of Egypt. *Water Resources Development* **12**, 229-244.

Strzepek, K., D. N. Yates, G. Yohe, R. J. S. Tol and N. Mader (2001). Constructing 'not implausible' climate and economic scenarios for Egypt. *Integrated Assessment* **2**, 139-157.

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

Swain, A. (2001). Water wars: fact or fiction? *Futures* **33**(8-9), 769-781.

Tanaka, S. K., T. J. Zhu, J. R. Lund, R. E. Howitt, M. W. Jenkins, M. A. Pulido, M. Tauber, R. S. Ritzema and I. C. Ferreira (2006). Climate warming and water management adaptation for California. *Climatic Change* **76**(3-4), 361-387.

Tarekegn, D. (2000). Vulnerability and Adaptation Assessment of Water Resource to Climate Change in the Abay Basin (unpublished), a report submitted to NMSA under the GEF/UNDP supported Climate Change Enabling Activities Project (ETH /97/G31) of Ethiopia.

Tompkins, E. L., E. Boyd, S. A. Nicholson-Cole, K. Weatherhead, N. W. Arnell and W. N. Adger (2005). Linking Adaptation Research and Practice. *Tyndall Centre for Climate Change Research,* May 2005, 70.

Toset, H. P. W., N. P. Gleditsch and H. Hegre (2000). Shared rivers and interstate conflict. *Political Geography* **19**(8), 971-996.

Tuomela, R. (2000). *Cooperation : a philosophical study*. Kluwer Academic Publishers, Dordrecht, London.

Turton, A. R. (2003). A Southern African perspective on transboundary water resource management. *Environmental Change and Security Project Report* (Issue 9 / Summer), pp 75-87.

United Nations Development Programme (2006). *Human Development Report 2006: Beyond scarcity: Power, poverty and the global water crisis*. Palgrave Macmillan, New York.

United Nations Economic Commission for Africa (2000). Transboundary River/Lake Basin Water Development in Africa: Prospects, Problems, and Achievements. *United Nations Economic Commission for Africa,* December 2000,

van der Molen, I. and A. Hildering (2005). Water: cause for conflict or co-operation? *Journal on Science and World Affairs* **1**(2), 133-143.

van der Zaag, P. and H. H. G. Savenije (2000). Towards improved management of shared river basins: lessons from the Maseru Conference. *Water Policy* **2**(1-2), 47-63.

Vorosmarty, 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.

Vorosmarty, C. J., P. Green, J. Salisbury and R. B. Lammers (2000). Global water resources: Vulnerability from climate change acid population growth. *Science* **289**(5477), 284-288.

Warwick, C., K. Bakker, T. Downing and K. Lonsdale (2003). Scenarios as a tool in water management: considerations of scale and application. In: *Water Resources Perspectives: Evaluation, Management and Policy* (ed. by A. S. Alsharhan and W. W. Wood). Elsevier, Amsterdam.

Waterbury, J. (2002). *The Nile Basin: national determinants of collective action*. Yale University Press, New Haven ; London.

Whittington, D. (1997). The implications of Microdam Development in the Ethiopian Highlands and Egypt's New Valley Project for Renegotiating the Nile Waters Agreement. . *Vth Nile 2002 Conference*, Addis Ababa, Ethiopia.

WHO/UNICEF (2000). Global water supply and sanitation assessment: 2000 report. *World Health Organization,* 87 pp. http://www.who.int/entity/water_ sanitation_health/monitoring/jmp2000.pdf.

Wirkus, L. and V. Böge (2006). Transboundary water management on Africa's international rivers and lakes: current state and experiences. In: *Transboundary Water Management in Africa: Challenges for Development Cooperation* (ed. by W. Scheumann and S. Neubert), 15-102. German Development Institute, Bonn.

Wolf, A. T. (1998). Conflict and cooperation along international waterways. *Water Policy* **1**(1998), 251-265.

Wolf, A. T. (2007). A long term view of water and security: international waters, national issues and regional tensions. *WBGU,* 23pp.

Wolf, A. T., J. A. Natharius, J. J. Danielson, B. S. Ward and J. K. Pender (1999). International River Basins of the World. *International Journal of Water Resources Development* **15**(4), 387-427.

Wolf, A. T., K. Stahl and M. F. Macomber (2003). Conflict and cooperation within international river basins: the importance of institutional capacity. *Water Resources Update, Universities Council on Water Resources.* **125**.

Yates, D. N. and K. M. Strzepek (1998). An assessment of integrated climate change impacts on the agricultural economy of Egypt. *Climatic Change* **38**(3), 261-287.

Yoffe, S., A. T. Wolf and M. Giordano (2003). Conflict and cooperation over international freshwater resources: Indicators of basins at risk. *Journal of the American Water Resources Association* **39**(5), 1109-1126.

Yoffe, S. B., A. T. Wolf and M. Giordano (2001). Conflict and Cooperation over International Freshwater Resources: Indicators and Findings of the Basins at Risk. *Journal of American Water Resources Association* **39**(5), 1109-1126.

Yohe, G. and R. S. J. Tol (2002). Indicators for social and economic coping capacity--moving toward a working definition of adaptive capacity. *Global Environmental Change* **12**(1), 25-40.

Zeitoun, M. (2007). The conflict vs. cooperation paradox: Fighting over or sharing of Palestinian-Israeli groundwater? *Water International* **32**, 105-120.

Zeitoun, M. and J. A. Allan (2008). Applying hegemony and power theory to transboundary water analysis. *Water Policy* **10**, 3-12.

Zeitoun, M. and J. Warner (2006). Hydro-hegemony - a framework for analysis of trans-boundary water conflicts. *Water Policy* **8**, 435-460.

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:

- Bows A., Anderson K., (2008) **A bottom-up analysis of including aviation within the EU's Emissions Trading Scheme:** Tyndall Working Paper 126;

- Al-Saleh Y., Upham P., Malik K., (2008) **Renewable Energy Scenarios for the Kingdom of Saudi Arabia:** Tyndall Working Paper 125

- Scrieciu S., Barker T., Smith V., (2008) **World economic dynamics and technological change: projecting interactions between economic output and CO2 emissions :**Tyndall Working Paper 124

- Bulkeley H, Schroeder H., (2008) **Governing Climate Change Post-2012: The Role of Global Cities - London:** Tyndall Working Paper 123

- Schroeder H., Bulkeley H, (2008) **Governing Climate Change Post-2012: The Role of Global Cities, Case-Study: Los Angeles**: Tyndall Working Paper 122

- Wang T., Watson J, (2008) **Carbon Emissions Scenarios for China to 2100**: Tyndall Working Paper 121

- Bergman, N., Whitmarsh L, Kohler J., (2008) **Transition to sustainable development in the UK housing sector: from case study to model implementation:** Tyndall Working Paper 120

- Conway D, Persechino A., Ardoin-Bardin S., Hamandawana H., Dickson M, Dieulin C, Mahe G, (2008) **RAINFALL AND WATER RESOURCES VARIABILITY IN SUB-SAHARAN AFRICA DURING THE 20TH CENTURY:** Tyndall Centre Working Paper 119

- Starkey R., (2008) **Allocating emissions rights: Are equal shares, fair shares? :** Tyndall Working Paper 118

- 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 Salvado**r, 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

• Mitchell, T.D. Carter, T.R., Jones, .P.D, Hulme, M. and New, M. (2004) **A comprehensive set of 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