RESEARCH ARTICLE

Impact of climate change on the hydrologic cycle and implications for society

Dagbegnon C. Sohoulande Djebou and Vijay P. Singh*

Department of Biological & Agricultural Engineering and Zachry Department of Civil Engineering, Texas A&M University, College Station, TX 77843-2117, USA

Abstract: Should we attribute all natural disasters, such as floods, droughts, extreme rainfall, extreme snowfall, glacial melting, changes in space-time distribution of rainfall, changes in ecosystems, earthquakes, fire hazards, hurricanes, tsunamis, tornadoes, heat waves, extreme cold weather, wind storms and health epidemics, to climate change? This question often comes up when we review the burgeoning literature on climate change and its impacts. Although climate change is still being debated in certain political, social and economic quarters, there is overwhelming and undeniable scientific evidence supporting climate change. Climate change impacts virtually every facet of society — scientific, technological, environmental, ecological, social, cultural, economic, and political. As a result, strategies for mitigating the impacts and adapting to climate change must be broad and integrated. Some of the impacts stem from the chain reactions in the earth system. Therefore, the socio-economic dimension should be an integral part of climate change discussion. Current literature on climate change is less than balanced among domains of scientific and human thought. This would probably change in the future, since the adaptation strategies are becoming an increasing concern in the scientific community. This article examines the impacts caused by climate change on the hydrologic cycle and discusses their repercussions for the society. It also provides suggestions that may be relevant for redefining policies aiming to improve water security at local and global levels.

Keywords: climate change, hydrologic cycle, water crisis, environment, society, adaptation, policy

*Correspondence to: Vijay P. Singh, Department of Biological & Agricultural Engineering, Texas A&M University, College Station, TX 77843-2117, USA; Email: vsingh@tamu.edu

Received: February 10, 2016; **Accepted:** March 26, 2016; **Published Online:** April 2, 2016

Citation: Sohoulande Djebou D C and Singh V P, 2016, Impact of climate change on the hydrologic cycle and implications for society. *Environment and Social Psychology*, vol.1(1): 36–49. http://dx.doi.org/10.18063/ESP.2016.01.002.

1. Introduction

The hydrologic cycle, often called water cycle, is one of the main components of the planetary system regulating human, animal and plant life. This cycle also forms the foundation of other cycles, such as carbon cycle, nitrogen cycle, etc. Therefore, the stability of water cycle is critical for the sustainability of biological populations and ecosystem. Empirical observations allude that the stability of the hydrologic cycle is being threatened by climate change.

Human civilizations developed along the banks of major rivers, primarily because of easy access to usable water. Therefore, most major cities of the world have major rivers flowing through them. The engineering of water resources systems has played a critical role in the birth and growth of several ancient civilizations (Mithen and Black, 2011; Viollet, 2007). Nowadays, the hydrologic engineering technologies count among the factors that have favored the demographic growth during the last century. Unfortunately, the demographic growth has exacerbated pressure on land-use, water resources, fossil fuel energy and natural resources. The result of these actions has been drastic for the natural environment and the terrestrial climate system. These actions have also impacted the water cycle, since remarkable hydrologic alterations have been reported as a consequence of climate change (Huntington, 2006). Changes in the hydrologic cycle have become more frequent in the terrestrial ecosystems. The evidences of these changes are expressed by the abnormal frequency of water crisis and hydrologic hazards whose effects extend to economic, social, political and cultural sectors. Unfortunately, engineering cannot overcome the current changes in the water cycle. The alteration of the water cycle is an alarming threat for the stability and sustainability of human societies and natural ecosystems (Hanjra and Qureshi, 2010). This is true when we refer to the human story. Indeed in the past, prolonged deficits of water budget contributed to scenarios, such as the decline of civilizations, the desertification, and the extinction of ecological systems.

Today, this reality raises substantial concerns about the future of the planet and the society, since the Earth has been facing serious and repeated water cycle issues for the past few decades (Hanjra and Qureshi, 2010). Recently, the concerns became a challenge for a wide range of actors, including policy makers, scientists, water resources professionals, farmers, and regular civilians. Actions promoting the understanding of climate change and adaptation are now encouraged at different levels of the society. As a result, the literature on climate change and its impact have increased considerably during the past decade. However, studies on climate change impact are reported sometimes by assuming the concept vaguely. Hence, we want to point out the complexity of the concept and the necessity to elucidate different aspects of climate change when addressing its impacts. In this paper, we discuss the concept of climate change and its hydrologic impacts and then analyze related societal implications. The content of the paper may serve as a baseline of information and improve the awareness of social and water resources implications of climate change.

2. Climate Change

2.1 What is Climate Change?

Climate is defined by the average state of the weather conditions prevailing in a region over a long period of time. Thus, we may consider climate change as the manifestation of abnormal trends or abnormal change of atmospheric conditions. The Intergovernmental Panel on Climate Change (IPCC) refers to climate change as "the state of the climate that can be identified statistically by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer". In general, climate is characterized by meaningful seasonality assessed through temperature, precipitation, wind movement, isolation, etc. Generally, climate features a steady picture of the terrestrial system. However, since its formation, the Earth's system has encountered various changes. The evidences of these changes are traceable by considering the main geological periods. For instance, during the quaternary period, the Pleistocene epoch was characterized by repeated glaciation phases (Huybers, 2006). These glaciations ended during the Holocene epoch resulting in a more stable climatic state. Hence, the Earth's climate has never been the same since its formation. However, the changes that occurred during different geological periods were natural, progressive and took thousands of years. The paradox with the actual climate change is more in terms of the origin and the time frame. Actually, the origin of the current change in the Earth's climate is more anthropogenic and the main changes noted are sudden.

2.2 Causes of Climate Change

As mentioned, change in climate is not a new occurrence. During different geological epochs, the global climate has changed in various ways. But these historical changes took place progressively over centuries. This is not the case with the currently observed changes in the Earth's climate. Actually, the changes observed during this last century have been more brutal and rapid, departing significantly from the historical pace. This may be an evidence that this climate change is not driven by natural factors (Kondrat′ev *et al.*, 2003), but the causes are more embedded in the global carbon cycle (Kondrat′ev *et al.*, 2003; Blasing, 1985). The carbon cycle refers to the natural exchange of carbon between the lithosphere, the biosphere and the atmosphere. During the last century, the net anthropogenic emission emanating from fossil energy sources and industries (cement production particularly), combined with land-use change, have disrupted the natural equilibrium existing within the different components of the global carbon cycle (Kondrat′ev *et al.*, 2003; Jepma and Munasinghe, 1998). Explicitly, human activities during the last and current centuries have generated huge quantities of greenhouse gases (GHGs) and aerosols in the atmosphere (IPCC, 2014). The result is that GHGs and aerosols concentration in the atmosphere have increased considerably. In addition, considerable forest lands have been changed across the globe due to urbanization, expansion of agricultural lands, wood industry and wildfires. The natural sequestration process controlled by photosynthetic activities of plants are thereby disturbed and significantly lessened. This situation has resulted in significant alterations of the atmospheric energy balance. Moreover, the situation is exacerbated by the increase of solar radiation flux, as a consequence of the ozone layer depletion. The resultant of all these abnormalities explains the actual increase of the global temperature (IPCC, 2013; Blasing, 1985). Figure 1 depicts this increasing trend of the earth warming during the period 1880 to 2015. The GHGs causing the increase in temperature or global warming are carbon dioxide (CO_2), followed by methane (CH_4), nitrous oxide (N_2O), and ozone (O_3). The estimated changes in the atmospheric concentration of the GHGs are presented in Table 1. Comparison of the atmospheric concentrations of the GHGs in 2010 to their historical concentrations (before 1750) reveals the tremendous changes that are responsible for the global temperature rise.

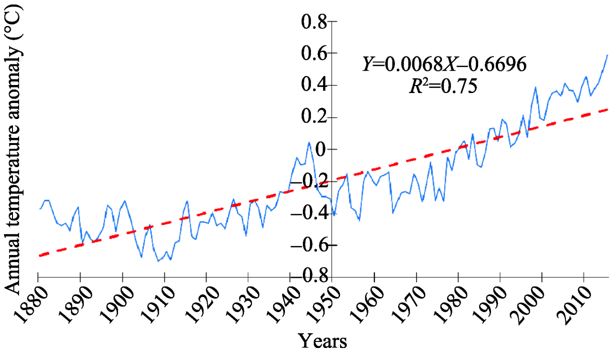

Figure 1. Global land-ocean temperature anomalies over the period 1880 to 2015. Anomalies are annual estimated based on the climate state of the period 1971–2000. The data plotted corresponds to the entire globe 90S-90N latitude and is released by the National Oceanic and Atmospheric Administration (http://www.ncdc.noaa.gov).

Table 1. Greenhouse gases and their atmospheric characteristics. The information in the table is based on data released by the Carbon Dioxide Information Analysis Center (CDIAC) of the United States Department of Energy (DOE). Note that ppm = parts per million, ppb = parts per billion, and ppt = parts per trillion

GHGs	Main sources	Lifetime (years)	Atmospheric concentration	
			Before 1750	Current (2010)
Carbon dioxide (CO_2)	Fossil energy, industry, wildfire	100–300	280 ppm	395.4 ppm
Methane (CH_4)	Fossil energy, agriculture, domestic wastes	12	722 ppb	1893 ppb
Nitrous oxide N_2O	Fertilizers, industry	121	270 ppb	326 ppb
Ozone (O_3)	Fossil energy, industry	hours or days	237 ppb	337 ppb
Chlorofluorocarbons (CFCs)	Foams, solvents, refrigerants	45–100	0	236–527 ppt
Hydrofluorocarbons (HFCs)	Industrial processes	13.4	0	75 ppt
Hydrochlorofluorocarbons (HCFCs)	Foams, solvents, refrigerants	11.9	0	231 ppt
Hydrobromofluorocarbons (HBFCs)	Solvents, cleaning agents, fire extinguisher, refrigerants	9.2–17.2	0	24 ppt
Sulfur hexafluoride (SF_6)	Electricity, chemistry	3200	0	7.39 ppt
Bromochlorofluoromethane ($CBrClF_2$/$CBrClF_3$)	Fire protection	16–65	0	3.3–4.1 ppt
Carbon tetrachloride (CCl_4)	Solvents, cleaning agents, fire extinguisher, refrigerants	26	0	85 ppt

2.3 Measuring Climate Change

While climate change is regarded by many people as a concept, it is in fact a geophysical phenomenon with a physical meaning. However, there is no standard manner for quantifying the magnitude of climate change in time and space. Frequently the global temperature fluctuation is used as an accepted indicator of change in the Earth's climate system. However, the practical arguments of climate change are customarily established through its impacts. Common evidences of climate change are the trend of glacier recession, ice sheets shrinking, the rise of sea levels, the fresh water crisis, the increased trend of natural hazards, and the alteration of ecological systems (Parmesan and Yohe, 2003; Walther *et al*., 2002). Hence, the practical expression of climate change seems more visible through its effects. Nevertheless, these effects are widely spread at different levels of terrestrial and social systems (Figure 2). Therefore, these impacts of climate change can be reasonably categorized, based on ordinal, temporal, or spatial criteria. For instance, in terms of ordinal leveling, one can set the rise of temperature as the primary impact of climate change. Phenomena such as glaciers and ice sheets melting, increase of evapotranspiration, etc., follow as second order impacts, since they result from the increase of global temperature. In the same manner, the rise of sea levels, the ecological and environmental alterations, the persistence of drought and frequent occurrences of extreme precipitation may be ranged as third order impacts, because they are more the consequences of the second order impacts. For instance, IPCC (2013) emphasized that glacial melting is the major contributor to the rise of sea levels. After the second order impacts, the social and economic issues related to water crisis arise. These latter issues represent a different category of impacts which fall in the bottom of the ordinal ranking. However, the social and economic impacts are the most concerning aspects for communities. Often, relevant mitigation and adaptation strategies to climate change are devised at the environmental and ecological levels. This framework expounds a certain hierarchy among the climate change effects, as illustrated in Figure 2. In the same manner, distinctions of climate change effects may include time and space. Indeed, the impact varies, depending more or less on the time scale (seasonal, decadal, centennial, etc.) and the spatial scale (global, regional, local, etc.).

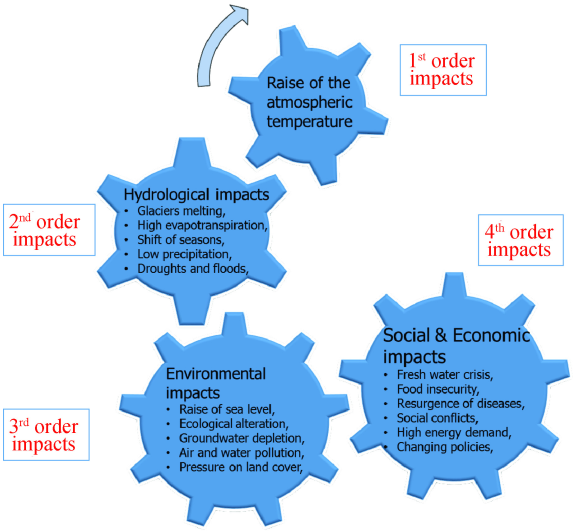

Figure 2. Hierarchy of the impacts of climate change focusing on the hydrologic framework. Here we target the rise of global temperature as the primary impact of climate change, then we derive different levels of impacts. In the chart, each down level impact is a sub-consequence of the upper level impacts.

3. Hydrologic Cycle

3.1 What is Hydrologic Cycle?

The hydrologic or water cycle describes a natural set of continuous and dynamic processes through which water masses in the form of liquid, vapor or solid, move, circulate and are stored within the earth system (IPCC, 2013). It defines the sequence of transitions where the Earth's water (i.e., oceanic, cryospheric, and continental moisture) evaporates into and travels in the atmosphere, condenses to form clouds, returns to the earth surface as precipitation, runs off to the oceans as streamflow, and ultimately evaporates again. This cycle controls the circulation and the state of moisture within the atmosphere, the biosphere (transpiration), the cryosphere, the pedosphere, and the lithosphere. Actually, water is a dynamic component of the Earth system. Depending on the temperature and pressure, water is found in three main states, including liquid, solid, and vapor. The water masses involved in the cycle include atmospheric water vapor, marine waters, continental waters, glaciers and ice sheets. While changing states, the water masses move in time and space, like a cycle, within the earth-atmosphere system. This cycle is perpetual and displays consistent seasonality. The movement of water is driven by different energy gradients, including gravity, pressure, temperature as well as the difference of concentration (e.g., stomatal conductance for plants transpiration). In sum, the water cycle embeds several terrestrial phenomena among which we can list evapotranspiration, surface water flow, groundwater flow, and water storage (glaciers, ice covers, aquifers). The impact of climate change extends to each of the components and the processes involved in the water cycle.

3.2 Components of the Cycle Being Impacted

Based on the persistent abnormalities observed, we can assert that all the components of the water cycle are affected somehow by climate change. But the magnitude of the changes varies distinctly in time and space, depending on the hydrologic component. In the regions experiencing more climate change, the impact is remarkable at different levels of the hydrologic cycle (Huntington, 2006). The changes may be examined by focusing on the main components of the water budget, namely precipitation, infiltration (including groundwater flux and base-flow), runoff, and evapotranspiration. However, the disturbances caused by climate change are also sensed with different magnitudes, depending on the component targeted, the time and the location. Several hydrologic processes are then disturbed. For instance, some regions of the globe experience a decreasing trend of precipitation amount. At the same time, several regions are reported with extraordinary peaks of precipitation, while others are still having stable precipitation patterns. Within this mixture of scenarios, the increasing frequency of abnormal precipitation patterns is dominant across the globe. The regular balance of the water budget is thereby affected, and the finality is a recurrent fresh water crisis.

4. Impact of Climate Change on the Water Cycle

4.1 Impact on Precipitation

While increasing heat is the primary physical expression of climate change on the terrestrial system, discerning the effect of increasing heat on precipitation is not systematic. Logically, most scientists concur that an increased atmospheric moisture is a consequence of more oceanic evaporation due to the increase of sea surface temperature (see Table 2). However, it is unclear how all this would impact the terrestrial water cycle. Nonetheless, the impact of climate change on precipitation is experienced in different ways across the globe. As reported in Table 2, the annual precipitation scenarios present heterogeneous trends, depending on the latitude band. However, the more frequent impact is probably the high disorder in precipitation patterns. For instance, the recurrence of typhoons in the Asia-Pacific region during the last decades has been linked with climate change (Tu *et al.*, 2009).

Table 2. Meaningful changes observed in the climate system over the past and current centuries. Table constructed based on analyses reported in various sources, including the IPCC reports (2013 and 2007)

Climate factor	Feature	Changes		Additional fact	Sources
		Period 1	Period 2		
Temperature	Trend of global earth temperature	1906–2005: warming trend is 0.06°C/decade	1956–2005 : warming trend is 0.13°C/decade	–	IPCC 2007
	Average earth temperature	1880–1974: average earth global temperature climbed by 0.3°C.	1975–2010: average earth global temperature increased by 0.5°C	–	IPCC 2007
	Land Surface Air Temperature	1901–1950 : increased by 0.097°C per decade	1951–2012 : increased by 0.175°C per decade	1979–2012 : increased by 0.254°C per decade	Rohde *et al.*, 2013 ; IPCC 2013
Cryosphere	Glaciers (outside Greenland and Antarctica)	1993–2009: Ice mass loss was 0.76 mm/year	2005–2009: Ice mass loss was 0.83 mm/year	–	IPCC 2013
	Perennial ice covers	1980: the extent was 7.9 $\times 10^6$ km^2	2012: the extent was 3.5 × 10^6 km^2	–	IPCC 2013
	Arctic ice packs	1980: annual mean thickness was 3.6 m	2000: annual mean thickness declined to 2.4 m	since 1978, Arctic sea ice extent decreased by 2.7% per decade	IPCC 2013; Rothrock *et al.*, 2008
Oceans	Global sea level	1961–2003: global sea level raised by 1.8 mm/year	1993–2003: global sea level raised by 3.1 mm/year	Correlation between sea level rise and the global temperature	IPCC 2013
	Sea Surface Temperature	1901–1950 :increased by 0.066°C per decade	1951–2012 : increased by 0.071°C per decade	1979–2012 : increased by 0.073°C per decade	IPCC 2013; Ishii *et al.*, 2005
Precipitation	Latitude box : 30°N–60°N	1901–2008: the trend was 3.14 mm/year per decade	1951–2008: the trend was 1.50 mm/year per decade	Estimates using Global Precipitation Climatology Centre GPCC data	IPCC 2013; Becker *et al.*, 2013
	Latitude box : 30°S–30°N	1901–2008: the trend was –0.48 mm/year per decade	1951–2008: the trend was –4.16 mm/year per decade		
	Latitude box : 60°S–30°S	1901–2008: the trend was 2.40 mm/year per decade	1951–2008:the trend was –0.51 mm/year per decade		

Similarly, the activity of tropical cyclones has intensified in the North Atlantic during the last three decades and important socio-economic damages have been reported in the North and Central American countries.

Overall, several regions encounter consistent alterations of the regular precipitation patterns. The alterations can be noted in terms of changes of frequencies of precipitation events, prolonged dryness, decrease in the number of precipitation events, and an increase of extreme precipitation events. At the seasonal level, profound diversions of season onsets and demises are experienced. The impacts of these disturbances (i.e., drifts in season onset and demise, alteration of precipitation patterns) are significant for the society. For instance, the change in precipitation pattern often causes an important agricultural loss in terms of yield. Also, the persistence of low precipitation is likely to jeopardize the sustainability of groundwater resources, since it is often utilized as an option to overcome the deficit of water supply. However, this option of using groundwater has resulted in serious depletion issues. Subsequently, there are more policies aiming to regulate the pressure on groundwater across the globe.

4.2 Impact on Groundwater

The impact on groundwater system may be described by referring to its quality, quantity, and functionality. These three aspects can hardly be dissociated because of the consistency of their mutual effects. Yet the impact is more a pool of sub-consequences related to low precipitation, persistent drought, and land-cover degradation. In natural systems, groundwater plays a critical role, as it sustains streamflow. In gaining stream systems, groundwater is particularly the main supplier of water during periods of no-precipitation. Outside the rainy season, the balance between streamflow and base-flow governs the streamflow behavior. An unbalanced situation often results in low-flow regime and impairments. At that point, the sustainability of aquatic life depends extremely on the ground waterflux. However, groundwater recharge is controlled itself by soil infiltration, land-cover, and precipitation amount. Under climate change, the disturbances in the precipitation regime (yearly precipitation amount concentrated in a few precipitation events), combined with land-cover degradation, significantly alter ground water recharge. Runoff increases and exceptional discharge peaks are clustered in short periods. In the long run, water supply becomes problematic for streams, since groundwater is not recharged adequately. The scenario is more drastic when groundwater is directly pumped for irrigation, domestic and industrial use. Actually, the use of groundwater has become an option for compensating for water deficit. However, this alternative raises important environmental and social concerns. Therefore, it necessitates more involvement of political leadership and law makers.

4.3 Impact on Evapotranspiration

Evapotranspiration is a critical component of the water cycle, and its rate depends on the magnitude of the terrestrial biophysical functionality. The amount of water involved in this phenomenon is a determinant for the local climate. Indeed the long-term balance between evapotranspiration and precipitation governs the gradient of aridity and land-cover features (Sohoulande Djebou *et al*., 2015). Under climate change, the rise of global temperature affects directly the atmospheric water demand (potential evapotranspiration). Finally, the actual moisture release in the atmosphere is higher than normal. The water vapor in the atmosphere results from the pressure exerted on soil moisture, water bodies, and plant transpiration. However, in the long term, there are not sufficient clues that the rise of evapotranspiration would be compensated for by precipitation. We can say that the trend of dryness is remarkable across the globe.

4.4 Impact on Hydrologic Hazards

4.4.1 Floods and Streamflow

The changes observed in the hydrologic system are also expressed by rising frequencies of floods and streamflow alterations. In urban areas, floods are sometimes attributed to poor urbanization planning. However, the rising frequencies of floods are not only resented in urban areas, but also in rural regions. Even wild regions of the globe are experiencing more frequent floods. There is strong evidence that the increase of flood frequencies is related to the increasing trends of extreme precipitation events. However, the extreme events alone cannot explain the changes of flood frequencies. Several factors, including increasing impervious areas and land-cover degradations, significantly reduce infiltration. Base-flow and runoff are then affected and subsequently the risk of flood increases. Floods are damaging to the society and the natural ecosystem. The consequences of floods include crop losses, population displacement, water impairment, poor air quality, diseases expansion, wildlife mortality, and food and energy crises (McLeman and Smit, 2006; Green, 2004). In this section and forth we depict the climate change features associated with floods by analyzing data obtained from the Emergency Events Database EM-DAT at the Centre for Research on the Epidemiology of Disasters, CRED (http://www.emdat.be). Specifically, we illustrate the trends of social implications in different continents over the period 1900–2015. For instance, Figure 3 expounds the trends of the average number of flood events in each continent. We report the yearly averages for individual decades since 1950, including the ongoing period 2010–2015. Figure 3 shows a clear increasing trend of floods across the world.

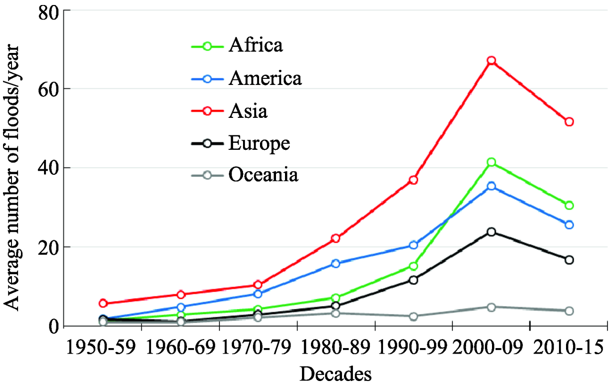

Figure 3. Yearly average number of major floods reported in each continent during different decades since 1950 including the current decade. Plots are based on the information collected from the Emergency Events Database EM-DAT.

Regarding streamflow, consistent changes are attributable to climate change. The most common features of climate change impact on streamflow are in terms of exceptional flow events but also in terms of abnormal low-flow regimes. Although the causes of flow alterations include those of floods, the consequences of streamflow alterations are probably more damaging for societies. Exceptional flow regimes are often accompanied with floods, particularly in low plain topographies. In locations with dams and reservoirs, the exceptional flows cause serious damages due to overflowing. Depending on the type of a dam, overflowing represents a real danger to communities established downstream. Besides these societal consequences, the effects of stream-flow alteration are also related to low-flow regime. Low-flow is often exacerbated by persistent dryness, low precipitation, poor water management and base-flow alteration. The consequences of low-flow include water crisis, water impairment, aquatic life mortality, social conflicts, and pressure on groundwater.

4.4.2 Drought, Extreme Temperature and Storm

Drought may be simply comprehended as a natural hazard which consists of a deficit of water relative to need. It is a prolonged period of abnormally insufficient water supply, resulting generally from low precipitation and high atmospheric water demand. Practically, there are four types of drought, including meteorological, hydrologic, agricultural and economic. However, the hydrologic, agricultural and economic droughts are often the impact of meteorological drought. Indeed, the meteorological drought occurrence is due to the departure of a precipitation threshold derived from a long term precipitation record (minimum 30 years).

The operationalization of the concept of drought is challenging, because the impact of drought varies depending on the region. However, several drought indices have been devised in order to assess drought severity. Although several indices are proposed for drought measurement, only a few are reported with satisfactory application across the globe. The most frequently used indices are the standard precipitation index (SPI) and the Palmer drought severity index (PDSI). While the computation of these indices is complex, they have triggered drought assessment and helped the depiction of drought across the entire globe. Actually, several regions of the globe have revealed persistent droughts with rare severity. The repeated occurrence of these droughts and their preferential installment during the last decades are an evidence of profound changes in the global climate system. The consequences of persistent droughts for the society and the environment are considerable. Besides the deficit in municipal water supply, drought increases the risk of wildfire (Westerling and Swetnam, 2003) and thereby contributes to the ecological extension (Condit, 1998; Ehrlich *et al.*, 1980). However, the understanding of these abnormal drought patterns may imply the consideration of precipitation and temperature. Figure 4A, 4B and 4C present, respectively, the decadal average yearly occurrence of extreme tem-

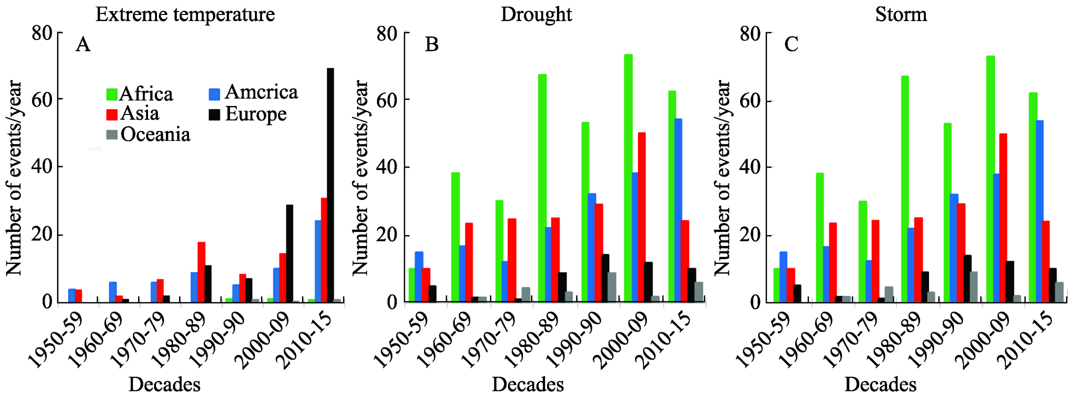

Figure 4. Yearly frequency of extreme temperature, drought and storm in each continent during the successive decades since 1950 to 2015. Estimates are based on the Emergency Events Database EM-DAT.

perature, drought and storm in each continent. We can clearly see that the increasing trend is well represented for these three hydrologic hazards during the successive decades over 1950–2015. Once again, we can infer an evidence of climate change impact.

5. Societal Implications of Climate Change Impact on the Hydrologic Cycle

The societal implications are probably the hidden part of the iceberg, when we consider the hydrologic impacts of climate change. Fresh water is vital for human communities. It is essential for agriculture, domestic use, industry, construction, ecology (wildlife and aquatic life), and environment. Hence, the decline of fresh water is detrimental for human activities and the sustainability of communities and ecosystems. In order to accommodate for the increasing water demand, reservoirs and dams are frequently built. In regions with lesser potential of surface water harvesting, pumping groundwater has become an option. However, most of these compensating strategies seem to suffer from poor long-term planning. Consequently, groundwater depletion, streamflow alteration, and low reservoirs refill are becoming more frequent, inciting more competition for water resources. Along with common hydrologic hazards related to climate change (flood, drought, typhoons, etc.), the competition for fresh water often results in conflicts, population migration, economic losses, poverty, diseases, and human mortality (IPCC, 2014; Reuveny, 2007; Barnett and Adger, 2007). In different parts of this section, we present related implications for human society.

5.1 Social Conflicts and Alteration of Human Well-being

In the water resources sector, social features of climate change may be demonstrated by targeting increased frequencies of hydrologic hazards or the competition for water resources. In fact, hydrologic abnormalities, such as the persistence of drought, increased frequencies of floods, increase of atmospheric water demand, and low precipitations amounts, affect the communities in various ways. At the continental scale, these abnormalities negatively affect food and water security, increasing the gap between developed and developing countries. They are also causes of migration, mortality and profound social instability. However, only the populations under poverty are the most vulnerable to these hydrologic disturbances (IPCC, 2014).

Figures 5 and 6, respectively, present the trends of yearly size of population affected and the yearly number of human deaths caused by floods in each of the five continents during different decades since 1950. From Figure 5 we can infer a general increasing trend of the yearly population size affected over the decades in all continents. This general trend indicates that the hazards have been getting more severe over the years. However, the reality is different when it comes to the number of deaths caused by floods (Figure 6). We note from Figure 6 that the trend of deaths is more alarming in Africa compared to Europe, America, Asia and Oceania. This last pattern may be explained by the level of adaptation strategies developed in each continent. Yet, in terms of climate change adaptation and awareness, important discrepancies exist between developing countries and developed countries. Populations in developing countries are recognized to be most vulnerable to climate change (IPCC, 2014). Like floods, the societal impacts of other hydrologic hazards are comparable.

Figure 7 presents the decadal trends of extreme temperature, drought and storm. Although the magnitude of the change varies, the general paradigms in different continents for these hazards are similar to the ones expounded in Figures 5 and 6. In addition, climate change is demonstrated as a factor of social conflicts (Reuveny, 2007; Barnett and Adger, 2007). When the hydrologic hazards occur, particularly in developing countries, local communities are frequently abandoned

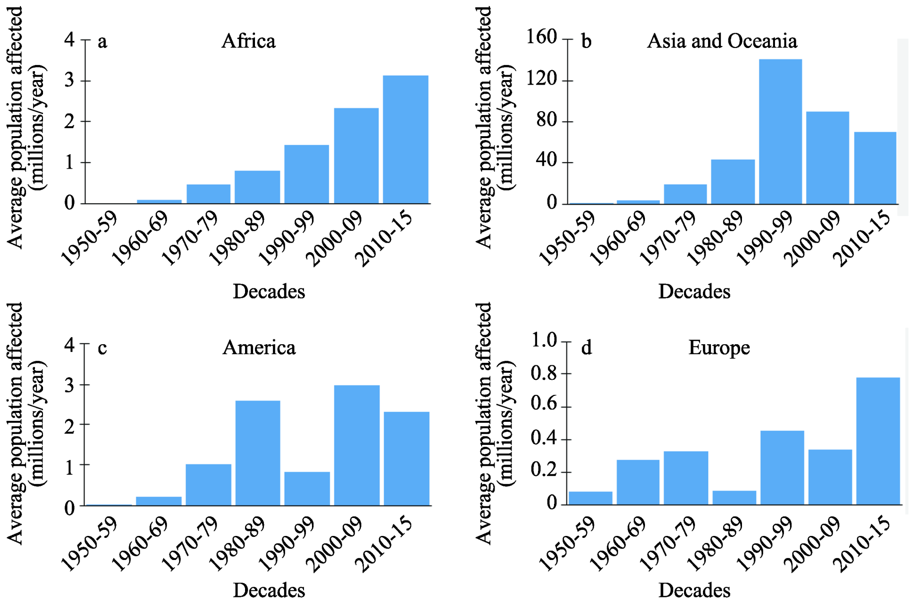

Figure 5. Average size of population affected by floods during different decades since 1950 including the current decade. Estimates are based on the information released by Emergency Events Database EM-DAT.

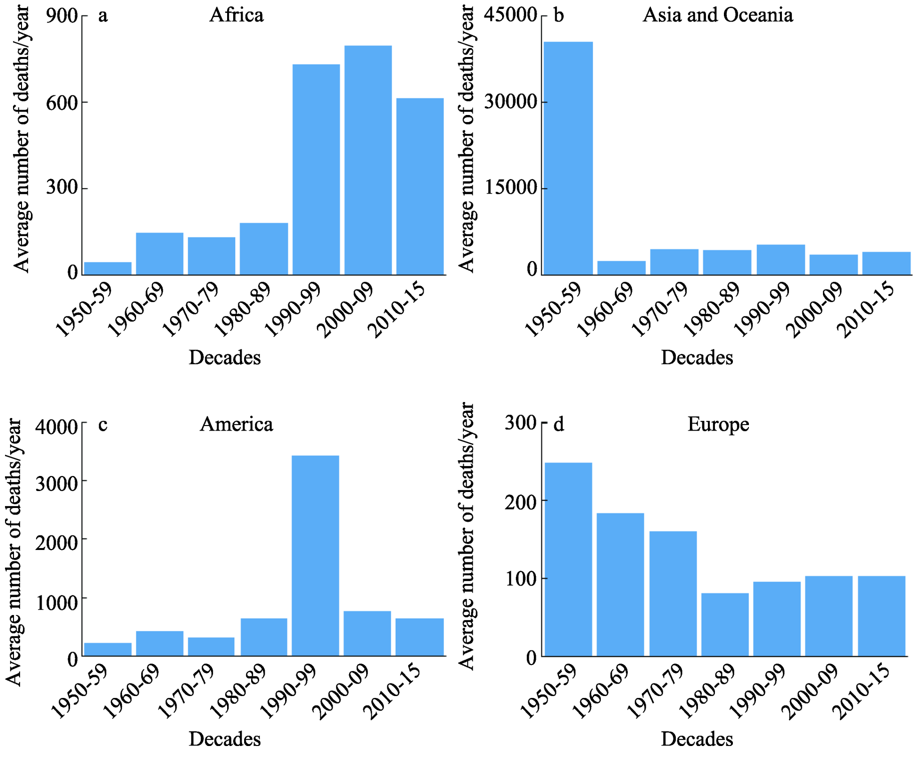

Figure 6. Average yearly number of human deaths caused by floods during different decades since 1950 including the current decade. Estimates are based on the information released by Emergency Events Database EM-DAT.

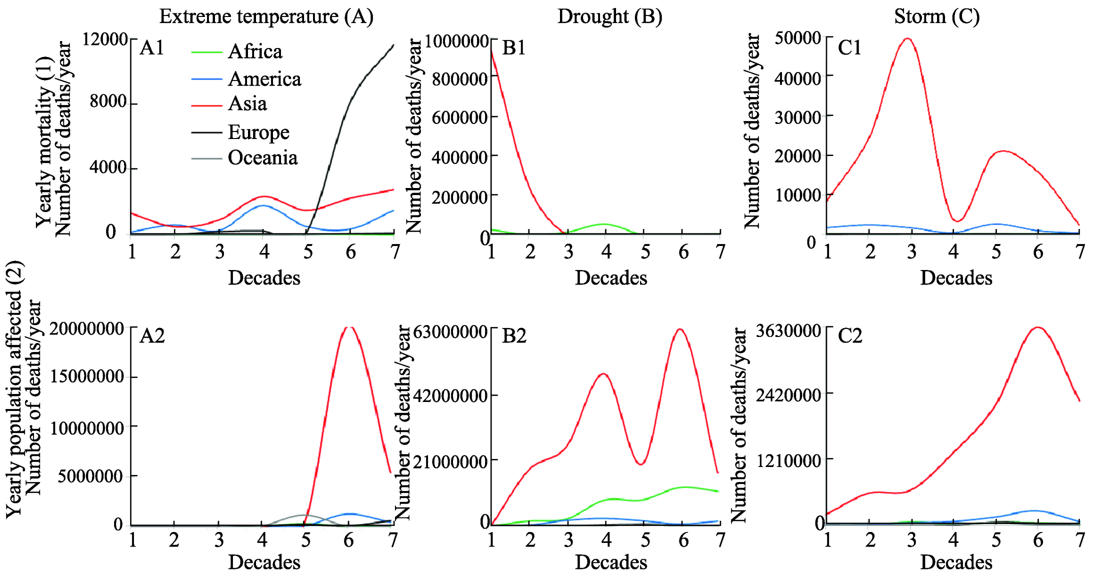

Figure 7. Graphs showing the average yearly mortality and population affected by **(A)** extreme temperature, **(B)** drought and **(C)** storm in each continent. The trends are represented based on successive decades since 1950 to 2015. The numbers on the axe of decades stand for: 1 = 1950–59; 2 = 1960–69; 3 = 1970–79; 4 = 1980–89; 5 = 1990–99; 6 = 2000–09 and 7 = 2010–15). Estimates are based on the information released by Emergency Events Database EM-DAT.

with two options — stay on their lands and endure the calamities with all the related uncertainty, or migrate to a different location. The consequences for either of the options are critical and result in family dislocations, population migrations, alteration of the political stability, and inter-communal conflicts due to pressure on resources (Raleigh, 2010; Reuveny, 2007).

5.2 Economic Implications

Beside its environmental and societal consequences, the impact of climate change on the hydrologic cycle is frequently accompanied by important economic damages. The estimate of these damages over the last decades is alarming. As an example, in this section we target floods in different continents. Then we examine the trend of average annual economic losses over different decades since 1950 and the results are displayed in Figure 8. Clearly, we can note a consistent increasing trend of losses for individual continents. However, the monetary losses related to climate changes are very disproportionate across the globe. The most important losses are located in Asia. Yet one may assume a link with the population or territory size. However, when we compare the estimates for Africa with Oceania, we can see that the yearly economic damage incurred in Oceania is 4.5 times greater than in Africa during 2000–2015, and so it is for different decades. Hence, we can infer that the more economically developed a region is, the greater is the economic damage caused by floods. Likewise, the same analysis may reveal similar patterns with drought, wildfire, typhoons, extreme temperature, storms and low precipitation. Figure 9 presents the magnitude of economic damages caused by extreme temperature, storms and drought during different decades over the period 1950 to 2015.

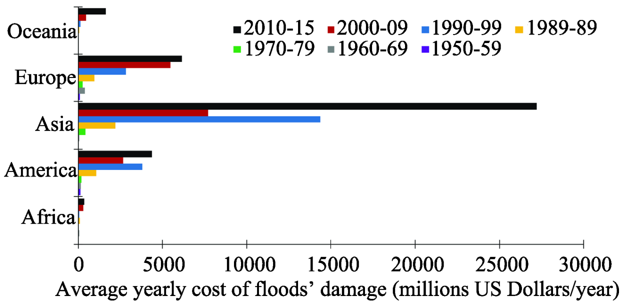

Figure 8. Average yearly cost of the damages caused by floods in each continent during different decades since 1950, including the current decade. Estimates are based on the information released by Emergency Events Database EM-DAT.

5.3 Other Societal Implications

It would be difficult to establish a complete list of all the social implications of climate change. Nonetheless, this paper aims to capture the most relevant implications. For this reason we find it relevant to report in

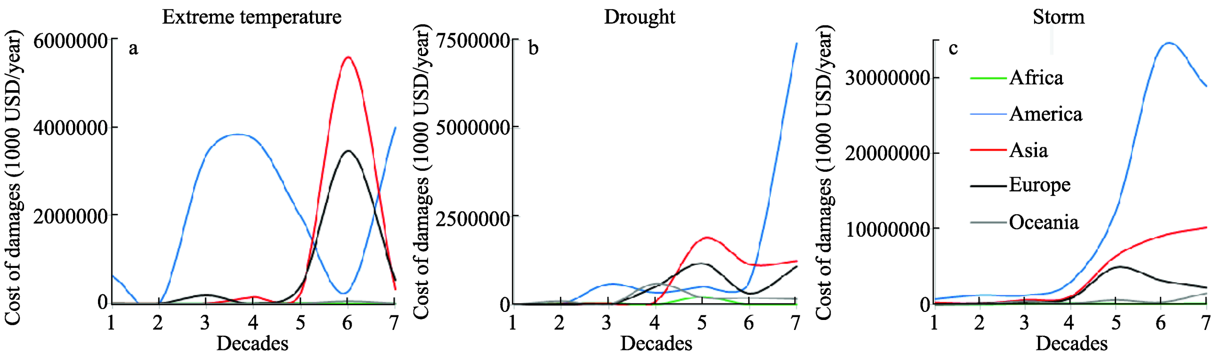

Figure 9. The magnitude of average yearly economic damages caused by extreme temperature, drought and storm in each continent. The trends are represented, based on successive decades, since 1950 to 2015. The numbers representing the decades stand for: 1 = 1950–59; 2 = 1960–69; 3 = 1970–79; 4 = 1980–89; 5 = 1990–99; 6 = 2000–09 and 7 = 2010–15. Estimates are based on the information released by Emergency Events Database EM-DAT.

this paragraph a few additional social implications, including energy demand and health. Actually, the fact that many communities depend on hydropower energy raises sustainability questions. Indeed, the rise of global atmospheric temperature has affected significantly the energy consumption in the society. Particularly, during summer seasons, the energy demand for cooling houses and buildings has increased across the globe (Isaac and Van Vuuren, 2009). Paradoxically, the amount of water available for hydropower dams is constantly depleting. In that condition, competition for water resources may envisage probable rationalization measures. However, in the long term, these measures may turn to compromising the well-being of society and the freedom to have access to water and energy.

Regarding human health, the resurgence of diseases is also viewed as a consequence of climate change. For instance, in the East Africa region, Hay *et al.* (2002) reported a resurgence of malaria in relation with climate change. In that case particularly, the rise of temperature, associated with local moist conditions, favors an ideal habitat for mosquito population. Subsequently, the exposure to mosquito bites increases, explaining the high number of people affected by the disease. Jhajharia *et al.* (2013) found increasing incidences of malaria with rising temperature in Rajasthan, India. Similarly, Kwak *et al.* (2014, 2015) found an increase in the occurrence of malaria and the shortening of annual time of occurrence in Korea as a result of climate change. Moreover, the rise of evapotranspiration is likely to increase air humidity which itself is a factor favoring germs transmissions. In summary, the hydrologic impacts of climate change are likely to depreciate social well-being in different manners.

6. Policies to Face the Climate Change Impact on Water Cycle

As reported earlier, the pressure on existing water resources for domestic use, industry, agriculture (husbandry and irrigation), and energy (hydropower) often results in serious socio-economic and political issues. Consequently, this reality exerts a substantial pressure on political leadership and policies. Now laws and regulations are being frequently introduced to improve water resources management. For instance, the use of groundwater in Texas, in the United States, is subjected to policies which have been reinforced over the years (Sophocleous, 2010). Likewise, the involvement of politics in water resource and climate change adaptation has increased all over the world. However, the consistency of this political implication does not appear to be the same in all countries. Especially in developing countries, climate change adaptation strategies are virtually present in the political agenda, but pragmatic strategies are poorly undertaken. Whereas progress is expected in the future, the awareness of hydrologic impacts of climate change has grown significantly during the last years. However, limited alternatives seem to emerge in terms of adaptation to water crisis. Historical solutions to water deficit (including groundwater pumping, diversion of streamflow, construction of reservoirs and dams) seem less sustainable for the environment and society. For example, the pressure on groundwater has resulted in serious depletion problems across the world. Likewise, streamflow diversion and reservoir construction represents a threat to aquatic life and to the local ecology. For sustainability purposes, it is critical to encourage and promote options which respect the environment and the ecosystems.

Some alternate solutions, such as water treatment and reforestation (for carbon sequestration), are environmentally friendly. While the alternative of treating waste water appears more promising to palliate water crisis in the long-term run, its main challenge remains the joint economic and quality efficiency. Today, water treatment options can hardly compensate quantitatively and qualitatively for water deficit. There is the actual reliance on groundwater, stream diversions, reservoirs and dams for the present needs of populations across the globe. Unfortunately, the potential amount of water which can result from waste water treatment may not be sufficient to compensate for the real needs of the society.

But the policies related to hydrologic changes impacts are not limited to the water crisis. Decision makers are highly concerned with risks and disasters management. Thus, the policies are formulated in order to better face the consequences of hydrologic hazards, such as floods, storms, drought, etc. Very often, these policies are devised to facilitate the functioning and viability of farming systems, industries, insurance companies and financial businesses (Nelson and Smith, 2008; Botterill, 2003). Policies in water resources are also established to protect the natural environment, the wildlife, and the aquatic life (e.g., protecting aquatic life by controlling point-source pollution). Overall, the implementation of policies in water resources management and climate change does not just impact water-use efficiency. In fact, these policies have increased the societal awareness of the climate change challenge and enticed public receptivity toward environmentally friendly practices and regulations. This particular point should receive more attention from policy makers at different stages of the society.

7. Synthesis and Conclusion

The analyses reported in this article cover several blind spots featuring the climate change impacts. First, we elucidate the phenomenon of climate change and provide its relevant features. Later, we emphasize particularly the impact of climate change on the hydrologic cycle, and then examine the related social considerations. Actually, it is quite difficult to describe the physical expressions of climate change impact on the hydrologic cycle without considering the main determinants. This is in part justified by the interactive functionality governing the components of the hydrologic cycle. Likewise, the social implications of the changes of the hydrologic cycle are numerous and very widely spread within the social system. Some effects are more of the sub-consequences of others. In that framework, discerning the primary causes of each social expression of climate change impact is essential. This is the guideline used in this paper. Specially, we distinguish different levels of the climate change impacts. We depict a hierarchical ordering based on physical and social expressions of climate change impact on the water cycle. The distinction made may be substantially used as an example for future studies or social assessment of climate change. We describe the main features of actual changes in the hydrologic system across the globe. Thus, we analyze different aspects of societal implications and the involvement of policies. In the case of hydrologic hazards (floods, droughts etc.), analyses of societal and economic implications indicate an important disparity, depending on the continents. We observe an increasing trend in the number of people affected, and the number of hazard occurrences in all the five continents (Africa, America, Asia, Europe, and Oceania). This trend is more of an expression of increasing severity of hydrologic hazards related to climate change. In terms of population mortality, migration and conflicts, developing countries are more vulnerable to these hydrologic hazards. Then, one understands the reason why developing countries are targeted as most vulnerable to climate change (IPCC, 2014). This is also true when we consider the climate change impact on hunger, environment and public health. However, the estimated economic losses related to the hydrologic impact of climate change appear to be more important in the developed countries.

The search of balance between economy, environment and society is now a challenge for political decision makers, since the implication of policies and regulations on climate change mitigation is real. Nevertheless, population safety and environment should always weigh more than financial considerations. Therefore, policies aiming to reinforce mitigation strategies should be designed accordingly by prioritizing societal and environmental benefits. Overall, the increasing public awareness of climate change seems to be a consequent and paramount benefit of all the research efforts directed at the concept. This awareness is a baseline for the effectiveness of mitigation and adaptation strategies in the communities.

Conflict of Interest and Funding

No conflict of interest was reported by the authors.

References

Barnett J and Adger W N, 2007, Climate change, human security and violent conflict. *Political Geography*, vol.26(6): 639-655. http://dx.doi.org/10.1016/j.polgeo.2007.03.003.

Becker A, Finger P, Meyer-Christoffer A, *et al*. 2013, A description of the global land-surface precipitation data products of the Global Precipitation Climatology Centre with sample applications including centennial (trend) analysis from 1901–present. *Earth System Science Data*, vol.5(1): 71–99. http://dx.doi.org/10.5194/essd-5-71-2013.

Blasing T J, 1985, Background: Carbon cycle, climate, and vegetation responses, in *Characterization of Information Requirements for Studies of CO_2 Effects: Water Resources, Agriculture, Fisheries, Forests and Human Health,* White M R (ed), DOE/ER-236. Washington D.C., U.S. Department of Energy, 9–22.

Botterill L C, 2003, Uncertain climate: The recent history of drought policy in Australia. *Australian Journal of Politics & History*, vol.49(1): 61–74. http://dx.doi.org/10.1111/1467-8497.00281.

Condit R, 1998, Ecological implications of changes in drought patterns: Shifts in forest composition in Panama. *Climatic Change*, vol.39(2–3)): 413–427. http://dx.doi.org/10.1023/A:1005395806800.

Ehrlich P R, Murphy D D, Singer M C, *et al*. 1980, Extinction, reduction, stability and increase: The responses of checkerspot butterfly (*Euphydryas*) populations to the California drought. *Oecologia*, vol.46(1): 101–105. http://dx.doi.org/10.1007/BF00346973.

Green C, 2004, The evaluation of vulnerability to flooding. *Disaster Prevention and Management: An International Journal*, vol.13(4): 323–329. http://dx.doi.org/10.1108/09653560410556546.

Hanjra M A and Qureshi M E, 2010, Global water crisis and future food security in an era of climate change. *Food Policy*, vol.35(5): 365–377. http://dx.doi.org/10.1016/j.foodpol.2010.05.006.

Hay S I, Cox J, Rogers D J, *et al*. 2002, Climate change and the resurgence of malaria in the East African highlands. *Nature*, vol.415(6874): 905–909. http://dx.doi.org/10.1038/415905a.

Huntington T G, 2006, Evidence for intensification of the global water cycle: Review and synthesis. *Journal of Hydrology*, vol.319(1–4): 83–95. http://dx.doi.org/10.1016/j.jhydrol.2005.07.003.

Huybers P, 2006, Early Pleistocene glacial cycles and the integrated summer insolation forcing. *Science*, vol.313(5786): 508–511. http://dx.doi.org/10.1126/science.1125249.

IPCC, 2014, *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge and New York: Cambridge University Press.

IPCC, 2013, *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge and New York: Cambridge University Press.

IPCC, 2007, *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC)*. Cambridge and New York: Cambridge University Press.

Isaac M and Van Vuuren D P, 2009, Modeling global residential sector energy demand for heating and air conditioning in the context of climate change. *Energy Policy*, vol.37(2): 507–521. http://dx.doi.org/10.1016/j.enpol.2008.09.051.

Ishii M, Shouji A, Sugimoto S, *et al*. 2005, Objective analyses of sea-surface temperature and marine meteorological variables for the 20th century using icoads and the Kobe collection. *International Journal of Climatology*, vol.25(7): 865–879. http://dx.doi.org/10.1002/joc.1169.

Jepma C J and Munasinghe M, 1998, *Climate Change Policy: Facts, Issues and Analyses*. New York: Cambridge University Press.

Jhajharia D, Chattopadhyay S, Choudhary R R, *et al*. 2013, Influence of climate on incidences of malaria in the Thar desert, northwest India. *International Journal of Climatology*, vol.33(2): 312–325. http://dx.doi.org/10.1002/joc.3424.

Kondrat′ev K I, Krapivin V F and Varotsos C, 2003, *Global Carbon Cycle and Climate Change*. Berlin Heidelberg: Springer Science + Business Media.

Kwak J, Noh H, Kim S, *et al*. 2014, Future climate data from RCP 4.5 and occurrence of malaria in Korea. *International Journal of Environmental Research and Public Health*, vol.11(10): 10587–10605. http://dx.doi.org/10.3390/ijerph111010587.

Kwak J, Kim S, Kim G, *et al*. 2015, Scrub typhus incidence modeling with meteorological factors in South Korea. *International*

Journal of Environmental Research and Public Health, vol.12(7): 7254–7273. http://dx.doi.org/10.3390/ijerph120707254.

McLeman R and Smit B, 2006, Vulnerability to climate change hazards and risks: Crop and flood insurance. *The Canadian Geographer/Le Géographe canadien*, vol.50(2): 217–226. http://dx.doi.org/10.1111/j.0008-3658.2006.00136.x.

Mithen S and Black E, (eds) 2011, *Water, Life and Civilisation: Climate, Environment and Society in the Jordan Valley*. Cambridge: Cambridge University Press.

Nelson R, Howden M and Smith M S, 2008, Using adaptive governance to rethink the way science supports Australian drought policy. *Environmental Science & Policy*, vol.11(7): 588–601. http://dx.doi.org/10.1016/j.envsci.2008.06.005.

Parmesan C and Yohe G, 2003, A globally coherent fingerprint of climate change impacts across natural systems. *Nature*, vol.421(6918): 37–42. http://dx.doi.org/10.1038/nature01286.

Raleigh C, 2010, Political marginalization, climate change, and conflict in African Sahel states. *International Studies Review*, vol.12(1): 69–86. http://dx.doi.org/10.1111/j.1468-2486.2009.00913.x.

Reuveny R, 2007, Climate change-induced migration and violent conflict. *Political Geography*, vol.26(6): 656–673. http://dx.doi.org/ 10.1016/j.polgeo.2007.05.001.

Rohde R, Muller R A, Jacobsen R, *et al*. 2013, A new estimate of the average Earth surface land temperature spanning 1753 to 2011. *Geoinformatics and Geostatistics: An Overview*, vol.1(1): 1–7. http://dx.doi.org/10.4172/2327-4581.1000101.

Rothrock D A, Percival D and Wensnahan M, 2008, The decline in arctic sea-ice thickness: Separating the spatial, annual, and interannual variability in a quarter century of submarine data. *Journal of Geophysical Research: Oceans*, vol.113(C5): C05003. http://dx.doi.org/10.1029/2007JC004252.

Sohoulande Djebou D C, Singh V P and Frauenfeld O W, 2015, Vegetation response to precipitation across the aridity gradient of the southwestern United States. *Journal of Arid Environments*, vol.115: 35–43. http://dx.doi.org/10.1016/j.jaridenv.2015.01.005.

Sophocleous M, 2010, Review: Groundwater management practices, challenges, and innovations in the High Plains aquifer, USA—lessons and recommended actions. *Hydrogeology Journal*, vol.18(3): 559–575. http://dx.doi.org/10.1007/s10040-009-0540-1.

Tu J Y, Chou C and Chu P S, 2009, The abrupt shift of typhoon activity in the vicinity of Taiwan and its association with western North Pacific-East Asian climate change. *Journal of Climate*, vol.22(13): 3617–3628. http://dx.doi.org/10.1175/2009JCLI2411.1.

Viollet P L, 2007, *Water Engineering in Ancient Civilizations: 5,000 Years of History*. Florida: CRC Press.

Walther G R, Post E, Convey P, *et al*. 2002, Ecological responses to recent climate change. *Nature*, vol.416(6879): 389–395. http://dx.doi.org/10.1038/416389a.

Westerling A L and Swetnam T W, 2003, Interannual to decadal drought and wildfire in the western United States. *EOS, Transactions American Geophysical Union*, vol.84(49): 545–555. http://dx.doi.org/10.1029/2003EO490001.