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# Ecological Responses of Freshwater Components to Climate Change Impacts: A Review

**Okorafor K. A**
Department of Zoology and Environmental Biology, University of Calabar, Calabar, Nigeria

## ABSTRACT

The impacts of climate change in the ecosystems are quite alarming. Ecological responses to such changes have also been conspicuous from the level of species, communities and even up to the ecosystems. Several researches have shown that freshwater components are vulnerable to climate change impacts. Change in climate affects aquatic species at various trophic levels, the physical and chemical environment that make up their habitat and the processes that act on and within freshwater ecosystems. Climate change directly affects a range of physical, chemical and biological processes in the aquatic systems. The extent and magnitude of the ecological consequences of climate change in freshwater ecosystems depends largely on temperature and alterations in water chemistry such as Nutrient Levels, Dissolved Organic Carbon (DOC), Dissolved Oxygen (DO) and Particulate Organic Matter Loading. Climate change is projected to cause significant alterations to aquatic biogeochemical processes, aquatic food web structure and dynamics, and biodiversity. This work reviews the responses of some freshwater components (biotic and a biotic components) to climate change impacts. Climate change has both direct and indirect consequences on the biota, structure and functions of freshwater ecosystems. Change in key physical and chemical parameters of freshwater can affect aquatic community and ecosystems attributes such as species richness, biodiversity range and distribution, and consequently alters corresponding food web structures and primary and secondary productivity levels. Climate change affects all life forms of freshwater ecosystems across the globe. The magnitude, extent, and duration of the impacts and responses are system- and location-dependent, and produce varying outcomes, including extinctions or species loss, genetic adaptations to new environments and alterations in species ranges and distributions. In view of the negative impacts climate change has on the ecosystems and the need to ameliorate such impacts, efforts aiming at or geared towards minimize anthropogenic activities leading to climate change would be desirable.

**Keywords:** *Review, Ecological Responses, Climate Change Impact, Freshwater Components*

## 1. INTRODUCTION

Climate change refers to the variation in the earth's global climate or in regional climate over time. It describes changes in the variability or average state of the atmosphere over time scales ranging from decades to millions of years (Emmanuel, 2005). These changes can be caused by processes internal to the earth, external forces (example, variations in sunlight intensity) or more recently human activities (anthropogenic).Climatic changes occur naturally over seasonal to millennial time scales, yet the unprecedented level of warming observed in recent decades threaten to undermine the functioning of natural ecosystems, especially when combined with the myriad additional anthropogenic stresses to which many fresh waters are subjected (Malmqvistetal., 2008). Climate change itself represents a complex amalgam of stressors, including changes in temperature (Webb et al., 2008), increased atmospheric $CO_2$ (IPCC 2007), and high frequency and intensity of droughts and extreme flow events (Barnett etal., 2005; Millyetal., 2006).Other stressors such as population growth, community preferences and management policies can be expected to interact in various ways with climate change (Dyer et al., 2013).

Change in climate have far-reaching impact, affecting aquatic species at various trophic levels, the physical and chemical environment that make up their habitat, and the processes that act on and within freshwater ecosystems (Wromaet al., 2006b). Large variations exist in the size, abundance and biota of two principal categories of freshwater ecosystems: lotic (flowing water; e.g., river, streams, delta and estuaries) and lentic (standing water; e.g., lakes, ponds and wetlands found across the globe (Prowse et al., 2006).Climate change directly affects a range of physical, chemical and biological processes in their aquatic systems.

The nature and severity of climate and weather have strong influence on the hydrology and ecology of freshwater ecosystems (Woo, 2000). These include extreme seasonality and severity in temperature extremes (that is long, cold winters and relatively short, warm summers, which persist long enough to limit biota because of physiological thresholds); high intra- and inter annual variability in temperature and precipitation, and strong seasonally driven latitudinal gradient in incident solar and UV radiation levels (Prowse et al., 2006).

The ecological consequences of environmental extremes are profound. For instance, overall annual productivity level of freshwater systems generally tends to be low because of low level of nutrient input, low temperature, prolonged period of ice presence compared to temperate aquatic ecosystems, and short growing seasons (Murray, 1998). Seasonal variations in arctic aquatic processes are relatively high, resulting in various adaptations in the organisms that thrive there. In animals, such adaptations include high rates of food consumption when it is available, rapid conversion of food to lipids for energy storage and later metabolism of stored lipids for over-winter maintenance, growth, and reproduction (Craig, 1989). Fish exhibit high migratory behavior to optimize life functions, resulting in movements among different habitats triggered by environmental cues (e.g., dramatic temperature change) that usually coincide with transition between particular seasons (Craig, 1989). Migratory organisms, such as waterfowls and mammals occupy a variety of habitats, both seasonally and over their lifetime (conservation of Arctic Flora and Fauna, CAFF, 2001).

Change in climate regimes, however they may be manifested, will only indirectly affect organisms of interest (Reistet al., 2006). That is the aquatic environment itself will be directly affected by changes in climate, but will modify and then transmit the influences in some fashion. For example, substantive shifts in atmospheric temperature regimes will affect water temperature but given the density differences between water and air and the influence of hydrodynamic factors on aquatic systems will be modified to some degree. In turn, change in atmospheric conditions will have indirect effects on biota present in aquatic ecosystems and thus may be ameliorated or partially buffered e.g., thermal extremes or seasonal timing shifted (Reistet al., 2006). In some instances, climate effect may be magnified or exacerbated, increasing the multiplicity of possible outcomes resulting from these changes. For example, streams networks amplify many environmental signals that occur at the watershed level and are concentrated in the stream channel (Dahm and Molles, 1992).

Fishes are ectotherms, thus for the most part; their body temperature is governed by that of the surrounding waters. In addition, fish species and individuals can behaviorally choose specific thermal preferenda (preferred optimal temperature) at which physiological processes are optimal, i.e., greatest net benefit is achieved for the individual (Wromaet al., 2006a). This is typically a thermal range that may be fairly narrow: temperatures outside this are suboptimal (i.e., net benefit is still attained but it is not the greatest possible), grading to detrimental (i.e., non-lethal but net energy is expended while in such conditions) and ultimately to lethal conditions (i.e., death ensue after some level of exposure) (Reistet al., 2006).

Fresh waters are particularly vulnerable to climate change because they are relatively isolated and physically fragmented within a largely terrestrial landscape, and they are also already heavily exploited by humans for the provision of 'goods and services' (e.g. drinking water and food; Woodward 2009). Furthermore, freshwater biodiversity is disproportionately at risk on a global scale, because while fresh waters cover only 0.8 per cent of the Earth's surface, they are home to an estimated 6 per cent of all species (Dudgeon et al. 2006). From an applied perspective, climate change has the potential to undermine many existing freshwater bio-monitoring schemes, which are based largely on responses to organic pollution with little consideration of the increasing influence of climatic effects (Woodward etal. 2009).

## 2. CAUSES OF CLIMATE CHANGE

Climate change could be caused by internal processes within the climate system and/ or external forces or more recently human activities (Emmanuel, 2005). The earth's climate is dynamic and always changing through a natural cycle. The changes that occur today have been speeded up because of man's activities. The causes of climate change due to natural occurrences could be as a result of volcanic eruption, continental drift, ocean current, earth's tilt and variation in the sun's output (Miller and Edwards, 2001). The natural processes leading to climate change as the name implies are strictly natural while those termed "artificial" are anthropogenic in origin. Figure 1 shows the natural factors that can influence the earth's climate.

### 2.1 Natural Causes of Climate Change

As aforementioned, the natural processes leading to climate change include: volcanic eruption, continental drift, ocean current, earth's tilt, variation in the sun's output, and change in the Earth' s orbit.

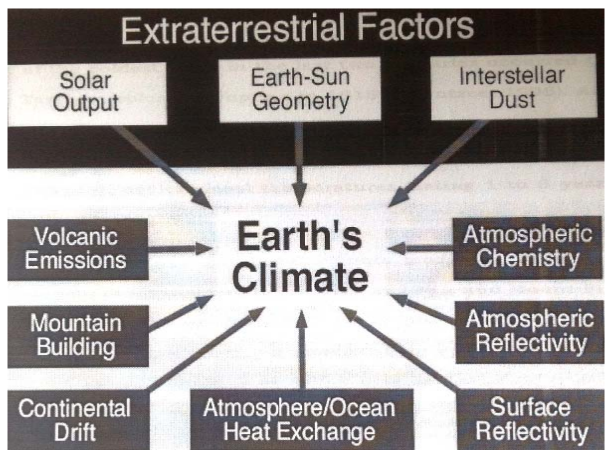


**Fig 1:** Factors that influence the Earth's climate (Source: keeling et al., 2006)

#### 2.1.1 Volcanic Eruption

For many years, climatologists have noticed a connection between large explosive volcanic eruptions and short climatic change. For example, one of the coldest years in the last two centuries was the year following the Tambora volcanic eruption which occurred in 1815 (Rowntree, 1998). Accounts of a very cold weather were documented in the year following this eruption in a number of regions across the planet. Several other major volcanic eruptions also showed a pattern of cooler global temperatures lasting one to three years after their eruption ((Rowntree, 1998).

In the last century, two significant climate modifying eruptions have occurred. El Chichon in Mexico erupted in April of 1920, and Mount Pinatubo went off in the Philippines during 1991 (Wellburn, 1994). Of these two volcanic events, Mount Pinatubo had a greater effect on the Earth's climate and ejected about 20 million tons of sulphur dioxides into the stratosphere (figure 4). Satellite data confirmed the connection between the Mount

VOL. 4, NO. 11, November 2014 ISSN 2225-7217
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Pinatubo eruption and the global temperature decrease in 1992 and 1993 (Miller and Edwards, 2001). The satellite data indicated that the sulphur dioxide plume from the eruption caused a per cent increase in the amount of sunlight reflected by the Earth's atmosphere back to space causing the surface of the planet to cool. Volcanic eruptions are still continuing leading to climate change. Recently Mount Etna, as seen from the town of Acireale, Italy, (fig. 3) spewed lava during an eruption on November 16, 2013 and mount Ontake in Japan erupted on September 27, 2014 (fig. 2).

The rapid effects of volcanic eruptions are dusts and gases being hurled up into the stratosphere where dioxide sulphur is rapidly oxidized to the sulphur ion ($SO_4^{2-}$) (Wellburn, 1994). These natural aerosols from volcanoes as well as those from wind-blown dusts of soils, land, and ocean emissions of biologically produced gases and see spray, have high albedo or reflectivity (Mackenzie and Mackenzie, 1995). The high albedo, otherwise known as reflectivity has a marked effect on the proportion of energy being reflected back into space. The greater the number of aerosol particles, the greater the amount of heat radiated planetary reflectiveness and this brings about a significant cooling within months. If the volcanic eruption is particularly great, this cooling effect can last for years (Kelly et al., 1996).

**Fig 2:** Smoke rising from Japan's Mount Ontake after its eruption on Saturday, September 27, 2014 (Source: online picture)

**Fig 3:** Mount Etna, as seen from the town of Acireale, Italy, spewed lava during an eruption on November 16, 2013. (Source: online picture)

**Fig 4:** Ash column generated by the eruption of Mount Pinatubo in Philippine islands on June 12, 1991. The strongest eruption of Mount Pinatubo occurred three days later on June 15, 1991. (Source: US Geological Survey, 1991)

### 2.1.2 Continental Drift

Scientists believe that the earth was a unified mass about 200 million years ago, and the continents were all part of one large landmass. Proof of this comes from the similarity between plant and animal fossils and broad belts of rocks found on the eastern coastline of South

America and Western coastline of Africa, which are now widely separated by the Atlantic Ocean (Cusbasch and Cess, 1990). The discovery of fossils of tropical plants (in the form of coal deposits) in Antarctica has led to the conclusion that this frozen land at some time in the past, must have been situated closer to the equator, where the climate was tropical, with swamps and plenty of lush vegetation (Cusbasch and Cess, 1990).

The continents that we are familiar with today were formed when the landmass began gradually drifting apart, millions of years back. This drifting also had an impact on the climate because it changed the physical features of the landmass, their position, and the position of water bodies. The separation of the landmass changed the flow of ocean current and winds, which affected the climate (Rowntree 1998). The drift of the continent continues even today.

#### 2.1.3 Ocean Current

The oceans are the major components of the climate system. They cover about 71% of the Earth and absorb about twice as much of the sun's radiation as the atmosphere or the land surface. Ocean currents move large amountof heat across the planet, roughly the same amount as the atmosphere. Nevertheless, the oceans are surrounded by landmasses, so heat transport through the water is through channels (World Meteorological Organization, 1999).

Winds push horizontally against the sea surface driving ocean current patterns. Ocean currents influenced certain parts of the world more than others. The coast of Peru and other adjoining regions are directly influenced by the Humboldt Current that flows along the coastline of Peru. The El Niño event in the Pacific Ocean affects climatic conditions all over the world (Walker, 1991).

The warming of the waters of the central and eastern pacific is what is called El Niño, while the cooling of the waters is called La Niña. The El-Niño Southern Oscillation (ENSO) phenomenon is one of the best-defined modes of so-called internal climate variability. It has the oceanic- El Niño and La Niña and an atmospheric- the southern Oscillation- Component (World Meteorological Organization, 1999). The temperature change is strongest in the zone ten degrees latitude on either side of the equator. It affects the regional energy balance, disrupting the atmospheric circulation and climate of much of the low-latitude zone, with effects extending well into middle latitudes during strong 'warm' or 'cold' events.

Walker (1991) named this see-saw the El-Niño southern Oscillation (ENSO) and Bjerknes (1991) first demonstrated a link between the southern Oscillation and sea surface temperatures in the Pacific Ocean and related the ENSO to weather events in the North Pacific and North America. He showed that an initial change in the ocean could affect the atmosphere in a manner that would in turn, include further change in ocean circulation, and reinforcing its initial trend and eventually resulting in an El Niño. Floods in Ecuador, Peru, southern United States and droughts in Southern Indian and southern Africa may have been consequences of the ENSO (Gates, 1993).

#### 2.1.4 Earth's Tilt

The Earth makes one full orbit around the sun each year. It is tilted at an angle of $23.5^0$ to the perpendicular plane of its orbital path. For one-half of the year when it is summer, the northern hemisphere tilts towards the sun. In the other half when it is winter, the earth is tilted away from the sun. If there was no tilt, we would not have experienced seasons (Kelly etal., 1992). Changes in the tilt of the earth can affect the severity of the seasons – more tilt means warmer summers and colder winters; less tilt means cooler summers and milder winters. This gradual change in the direction of the earth's axis, called procession is also responsible for change in the climate.

#### 2.1.5 Variation in the Sun's Output

Changes in the amount of energy emitted by the sun are major causes of climate variability. There is no doubt that on the longest time-scales of Earth's geological history, trends in solar output have played a major role in shaping the Earth's climate and will continue to do so in the future (Friis-Christensen and Lassen, 1991).

It has been known for many centuries that the face of the sun exhibits dark patches, 'sunspots' and that the number of sunspots varies with a fairly regular cycle of around 11 years. Despite many studies, the evidence of the effect of this sunspot cycle on the Earth's climate is still controversial (Kelly et al., 1992). Sunspot cycle has been found in climate parameters, but the fluctuations are weak and tend to appear and disappear without reason (Rowntree, 1998). The 11-year sunspot cycle varies in strength on timescale of 80 years and longer, and these longer-term fluctuations have also been linked to climate change (Houghton, 2001).

**Fig 5:** The sun as seen at sunset. The sun is essentially the only source of energy for running the Earth's climate. Thus any change in its output will result in changes in the reception of insulation (rate of solar radiation) and the generation of heat energy, which drives the climate system. (Source: online picture).

### 2.1.6 Changes in the Earth's Orbit

The amount of radiation received from the sun and its distribution on earth vary according to the relative position between the sun and earth and this natural variation impact the climate of the planet, setting conditions for cooler-warmer periods of glacial-interglacial stage (Mackenzie and Mackenzie, 1995). According to Gate (1993), three characteristics of the earth's motion in orbit around the sun have been thought to influence the amount of radiation incident on the earth and its distribution with latitude. These are eccentricity, obliquity and precession.

The first cyclical variation, known as eccentricity, controls the shape of the Earth's orbit around the sun. The orbit gradually changes from being elliptical to being nearly circular and then back to elliptical in a period of about 100,000 years. The greater the eccentricity of the orbit (i.e., the more elliptical it is), the greater the variation in solar energy received at the top of the atmosphere between the earth's closest (perihelion) and farthest (aphelion) approach to the sun. The difference in the Earth's distance from the sun between the aphelion and perihelion (which is only about 3%) is responsible for approximately 7% variation in the amount of solar energy received at the top of the atmosphere (Gates, 1993). Obliquity involves the tilt of the earth's axis. The axis on which the earth spins is tilted at $23.5^0$-angle between the plane of the equator and the ecliptic. Obliquity varies from $22.1^0$ to $24.5^0$ with a periodicity of 41,000 years and this change affects the latitudinal distribution of solar radiation striking the earth.

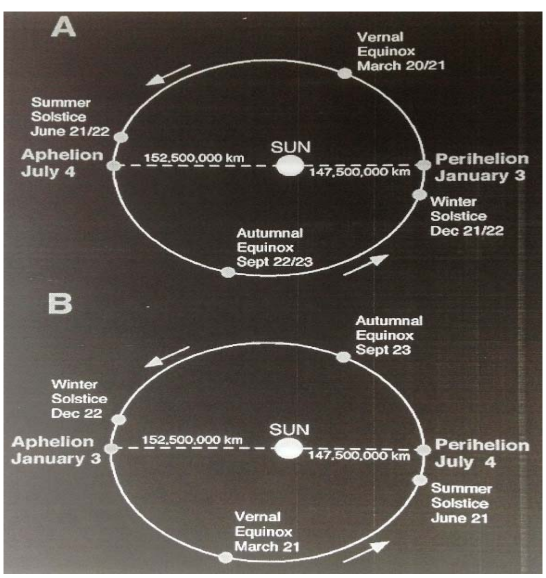


**Fig 6:** Modification of the timing of aphelion and perihelion over time (A=today; B=13,000 years into the future) (Source: Gates, 1993).

## 2.2 Anthropogenic Causes of Climate Change

Anthropogenic factors are acts by humans that change the environment and influence the climate. The biggest factor of present concern is the increase in carbon dioxide ($CO_2$) level due to emission from fossil fuel combustion, followed by aerosol (particulate matter in the atmosphere), which exerts a cooling effect (Ruddiman, 2003). Other factors which also impact climate including: land use, ozone depletion, animal agriculture and deforestation (Miller and Edwards, 2001).

The industrial revolution in the $19^{th}$ century saw the large-scale use of fossil fuel for industrial activities. These industries create jobs and over the years, people move from rural areas to the cities in search of jobs. This trend is continuing even today. More and more land that was covered with vegetation has been cleared to make way for houses. Natural resources are being used extensively for construction, industrial, transport and consumption. There is also increase in population. All this has contributed to a rise in greenhouse gases in the atmosphere. Fossil fuels such as oil, coal and natural gas supply most of the energy to run vehicles, generate electricity for industries, households, etc. The energy sector is responsible for about three-quarter (3/4) of the carbon dioxide emissions, one-fifth (1/5) of the methane emissions and a large quantity of nitrous oxide (Keeling and Whorf, 2006). In this modern era, rising carbon dioxide levels are implicated as the primary cause of global warming since 1950 (Ruddiman, 2003). According to the inter-governmental panel on climate change (IPCC, 2007), the atmospheric concentration of carbon dioxide in 2005 was 379ppm compared to the pre-industrial level of 280ppm. The US Geological Survey estimates that human activities generate 150 times the amount of carbon dioxide emitted by volcanoes (Ruddiman, 2003).

Methane is another important greenhouse gas in the atmosphere. About one-quarter (1/4) of all methane emissions are said to come from domesticated animals such as dairy cows, goats, pigs, buffaloes, camels, horses and sheep (Kelly and Wigley, 1992). These animals produce methane during the cud-chewing process. Methane is also released from rice or paddy fields that are flooded during the sowing and maturing period. Methane is also emitted during the process of oil drilling, coal mining and also from leaking gas pipelines (due to accidents and poor maintenance of sites). A large amount of nitrous emissions has been attributed to fertilizer application.

The anthropogenic influences on climate will not be properly understood without knowledge of the greenhouse effect and the associated global warming. Sunlight penetrating the atmosphere warms the earth's surface and the earth's surface radiates heat (infra-red wavelengths) to the atmosphere and some escape into space with certain gases in the atmosphere (the greenhouse gases) and water vapour absorbs some infra-red wavelength, re-radiating part of the wavelength towards the earth, creating what is known as "greenhouse

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effect"(Starr and Taggart, 1989). Thus the greenhouse gases such as Carbon Dioxide ($CO_2$), Methane ($CH_4$), Nitrous Oxide ($N_2O$), the Chlorofluorocarbons ($CFC_S$) and Tropospheric ozone ($O_3$) function in raising the equilibrium temperature of the earth's surface. Without the greenhouse gases, the mean temperature of the earth's surface with the present intensity of solar radiation would be -19$^0$C. However, with the greenhouse gases, the equilibrium temperature of the earth's surface is 15$^0$C, (Bolin, 1989).

However, today, increase in human activities such as agriculture, urbanization, industrialization, deforestation and resource exploitation has led to increase in earth's average temperature; a condition called global warming which leads to climate change.

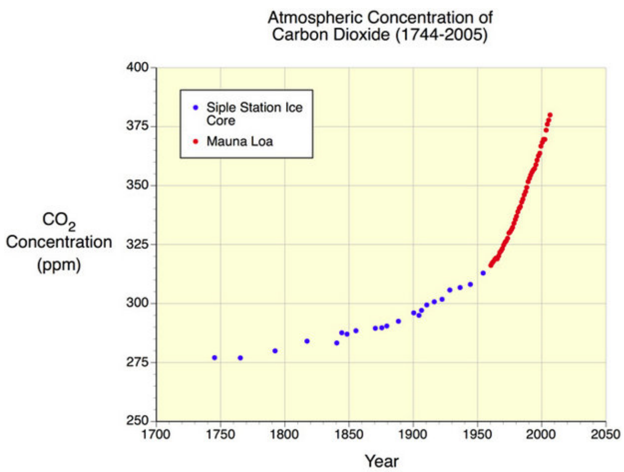


**Fig 7:** The graph above illustrates the rise in atmospheric carbon dioxide from 1744 to 2005. Note that increase in Carbon Dioxide concentration in the atmosphere has been exponential during the period examined. An extrapolation into the immediate future would suggest continued increases. (Source: Neftelet al., in Keeling et al., 2006)

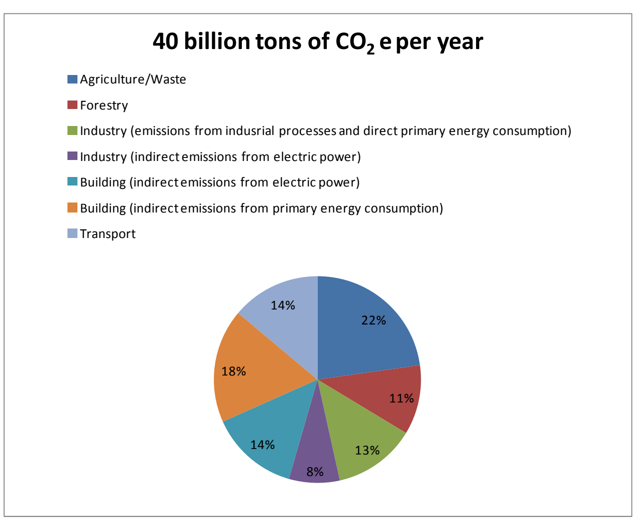


**Fig 8:** CO2 Equivalents Emissions by Key Sectors (Adapted from: IEA World Energy Outlook 2004, EPA).

# 3. RESPONSES OF FRESH WATER BIOTA AND ECOSYSTEM STRUCTURE TO CLIMATE CHANGE IMPACTS

There is ample evidence for ecological responses to recent climate change. Most studies to date have concentrated on the effects of climate change on individuals and species, with particular emphasis on the effects on phenology and physiology of organisms as well as changes in the distribution and range shifts of species. However, responses by individual species to climate change are not isolated; they are connected through interactions with others at the same or adjacent trophic levels. Also from this to more complex perspective, recent case studies have emphasized evidence on the effects of climate change on biotic interactions and ecosystem services (Gian-Reto, 2010).

The effects of climate change on biodiversity at large have already been observed and demonstrated in the past (Araújo and New, 2007; Thuiller, 2004) and are expected to increase in the future, according to predictive climate models and bioclimatic modeling. Very high extinction risks caused by global warming are predicted globally by Thomas et al. (2004). Species can respond to climate change in several ways. They can move to track climatic conditions, stay in place and evolve to the new climate, or they can become extinct. Although quick evolution is possible, movement that tracks climate is by far the most common response (Berteauxetal., 2004). Climate change is clearly altering the composition, diversity and functioning of many freshwater ecosystems. The trajectories of community change will be highly non-random, with certain taxa, especially those higher in the food web, typically being more vulnerable to local extinction (Ingsetal., 2009; Woodward 2009). Essentially, all organisms face the same options as the climate changes: adapt, migrate or perish. However, an organism's success in implementing the first two strategies will depend largely on its life history and dispersal traits in relation to habitat fragmentation and the rate at which its environment changes. For example, it has been suggested that very small organisms (e.g. protists) form panmictic populations, such that almost any given species can be found almost anywhere on the planet, if local conditions are suitable (Finlay & Esteban 2007).

Climate change is projected to cause significant alterations to aquatic biogeochemical processes, aquatic food web structure and dynamics, and biodiversity (Wromaet al., 2006b). The extent and magnitude of the ecological consequences of climate change in freshwater ecosystems depends largely on temperature and alterations in water chemistry such as nutrient levels, Dissolved Organic Carbon (DOC), dissolved oxygen and particulate organic matter loading (poffet al., 2002).This review section is focused on the responses of biological communities, biodiversity, aquatic food web structure and dynamics, primary and secondary productivity and aquatic birds and mammals to the impacts of climate change.

Climate change is very likely to have both direct and indirect consequences on the biota and structure and function of freshwater ecosystems. Change in key physical and chemical parameters at the landscape scale as described by Walsh et al., (2005) and Callaghan et al., (2005) are very likely to affect aquatic community and ecosystem attributes such as species richness, biodiversity, range and distribution, and consequently alter corresponding food web structures and primary and secondary productivity levels. The magnitude, extent, and duration of the impacts and responses will be system and location dependent. Projected effects on aquatic mammals and waterfowl include altered migration routes and timing: a possible increase in the incidence of mortality and decreased growth and productivity from disease and/ or parasites; and, probable changes in habitat suitability and timing or availability (Wromaetal., 2006b).

### 3.1 Responses of Biological Community

Climate change produces significant effects on the biodiversity of freshwater ecosystems and possibly initiates varying adaptive responses. As already mentioned in the introduction, the magnitude, extent, and duration of the impacts and responses are system-and location-dependent, and difficult to separate from other environmental stressors (Wromaet al., 2006b). Biodiversity is related to, and affected by factors including: the variability of regional and local climate, the availability of local resources (e.g., water, nutrients, trace elements, energy, substrates) affecting the productivity potential; the nature, timing and duration of disturbance regimes in the area (e.g., floods, catastrophic water loss, fire); the original local and regional stock" of species and their dispersal opportunities or barriers; the physiological capacity of individuals and populations to cope with new environmental conditions; the level of spatial heterogeneity (habitat fragmentation) and connections among aquatic systems; the intensity of biotic interactions such as competition, predation, disease, and parasitism; and the overall genetic variability and adaptive capacity of the species (IPCC, 2001; UNEP, 2003).

Climate change together with environmental stressors such as point and non-point-source pollution can synergistically contribute to the degradation of biological diversity at the species, genetic, and/or habitat-ecosystem levels (Conservation of Arctic Flora and Fauna-CAFF, 2001). There is growing evidence that climate change will contribute to accelerated species losses at regional and global levels (UNEP, 2003) and that the effects of alterations in the biodiversity of ecosystem structure and function are likely to be more dependent on given levels of functional diversity than on the total number of species (Chapin et al., 2000).

Changes in habitat characteristics driven by climate change are also likely to differentially affect specific populations of fish (Wromaet al., 2006a). For example, some aspects of life history variation of Dolly Verden fish on the Yukon north slope in the U.S.A. appear to be particularly associated with inter-river variation in groundwater thermal properties e.g., egg size is larger and development time is shorter in rivers that have significant groundwater warming, and reproduction occurs annually in these warmer rivers because sea access allows for earlier feeding, compared to reproduction every two years or less often in colder rivers; (Stands rang, 1995). Thus, climate change effects that mimic this natural local inter population variability are likely to result in similar shifts in populations presently occupying colder habitats.

An overarching issue affecting the responses of freshwater biota to rapid climate change is "adaptive capacity" (Wromaet al., 2006a). To survive such a challenge, aquatic biota must have the inherent capacity to adapt (i.e., have sufficient genetic capacity at the population level to evolve at the required rate); acclimate (i.e., the phenotypic ability at the population and/or individual level to survive in the new conditions); and/or move (i.e., emigrate to more optimal situations; (Klein et al., 2005). High levels of diversity in many organisms imply that some evolutionary compensation for rapid climate change is possible. Taxa with short generation time (e.g., zooplankton) will be able to evolve more rapidly (Wromaetal., 2006a) than those with longer generation time (e.g. fish). Wilson et al., (1996) suggested that previous events that reduced genetic diversity may have limited their capacity for such rapid evolution. This will probably further hamper responses by such taxa and, with the projected rapid rate of climate change and other factors (e.g., competition from new colonizers), is likely to result in an increased risk of local extirpation and/or extinction.

Many organisms have enzymes with different thermal optima to allow them cope with changing environmental conditions (Huntington et al., 2005). Such capacity could possibly counterbalance the increased risk of extinction. Taxa that are capable of emigrating to new areas have additional options to cope with rapid climate change, although access issues are likely to preclude such movements to suitable conditions (Flanagan et al., 2003). Clearly, significant changes in aquatic biodiversity are very likely to result from climate change, and biota have varying capacities to cope with the rate of this change.

### 3.2 Responses of Food Web Structure and Dynamics

The impact of climate change on the structure and dynamics of aquatic food web remains poorly understood (Kalff, 2002 cited by Wromaet al., 2006b). Many of the insights as to how food webs will respond (directly or indirectly) to climate change effects have been obtained from either descriptive studies or a selected few manipulative/experimental studies where ecosystem-level or food web manipulations were conducted and response variables measured (Kalff, 2002). Research on microbial food webs of more temperate aquatic systems shows that in the absence of heavy grazing pressure on bacteria by macro-zooplankton or benthic macro-invertebrates, the principal role of the microbial food web is the degradation (respiration) of organic matter (Kalff, 2002). Hence, the microbial food web is a significant source of energy to plankton, being largely responsible for recycling nutrients in the water column and thereby helping to sustain plank tonic and benthic primary production and tertiary consumers in the food chain.

Projected increase in water temperature and input of Dissolved Organic Carbon (DOC), Particulate Organic Carbon (POC), and Dissolved Inorganic Carbon (DIC) arising from climate change are very likely to affect the structure and functional dynamics of the microbial food web, and are likely to increase rates of carbon processing. Pienitzet al., (1995) showed that the same abiotic parameters, along with Lake Morphometryexplained the greatest percentage of variance in diatom community composition in North-western Canada. Furthermore, diatom community structure was highly correlated with DOC gradients in Siberian and sub-arctic Quebec lakes (Lotteret al., 1999). Hence, concomitant changes in the phytoplankton component of the food web probably will cascade through the ecosystem.

Increasing temperature has the potential to alter the physiological rate (e.g., growth, respiration) of individuals, and the vital rates and resulting dynamics of populations (Beisneret al., 1997). Beisneret al., (1996) investigated the influence of increasing temperature and food chain length on plankton predator prey dynamics and found out that the predator-prey system is destabilized at higher temperatures (i.e., the macro-zooplankton herbivore, Dalphniapulex always become extinct), irrespective of the complexity of the food web (i.e., whether a two or three-level food web was involved). The low productivity that has been observed in many arctic lakes may limit the presence of fish predators and may result in systems where algal biomass is controlled by expensive zooplankton grazing (Flanagan et al., 2003).

### 3.3 Responses of Primary and Secondary Productivity

Primary and secondary productivity relationships in aquatic ecosystems are highly susceptible to structural and functional alterations resulting from changes in climate, although the direction and absolute magnitude of the responses are likely to be difficult to project (Vincent and Hobbie, 2000). Increase in temperature increases lake primary productivity. Brylinski and Mann (1973) analyzed lake productivity in 55 lakes and reservoirs from the tropics to the Arctic, and found that the best abiotic variables for estimating productivity to be latitude and air temperature. Arctic lakes, although relatively unproductive, will probably experience a significant increase in productivity as climate changes (Callaghan et al., 2004). If temperature and nutrient loads increase, it is likely that phytoplankton will no longer experience temperature-induced photosynthetic rate inhibition, and growth rate will probably become more similar to those in the temperate zone, thus allowing for a greater accumulation of algae (Callaghan et al., 2004). If algae are heavily grazed by herbivores at present because of a lack of predation, higher-level predators are likely to invade as the productivity of the system increases. Subsequent increased predation of the grazer community would permit an increase in algal biomass. In addition, the projected increase in nutrient concentration would augment those changes, making increase in productivity even more dramatic (Callaghan et al., 2004).

Dissolved Organic Carbon (DOC) fluctuation also triggers productivity response in freshwater ecosystems. High DOC levels can differentially affect measured primary productivity by influencing light penetration (More DOC leads to darker water), affecting turbidity, and adding carbon for processing (Wromaet al., 2006b). For example, benthic diatoms and total diatom concentrations increased significantly during conditions of high DOC concentrations and low water transparency, whereas plank tonic forms decrease (Pienitz and Vincent 2000). In southern Indian lake, northern Manitoba, Heckyet al., (1984) found that high DOC concentrations decreased light penetration sufficiently to cause a switch from nutrient to light limitation of primary production. In shallow tundral ponds, over 90% of algal primary production was by benthic algae (Stanley, 1976), although this level of productivity is very likely to decline if there is appreciable DOC-related light reduction. Productivity of freshwater zooplankton is very likely to rise in response to increases in primary production. At Toolik Lake, a 12-fold increase in primary production yields a less than 2-fold increase in primary production (O'Brien etal., 1992). This enhanced production is very likely to result in an increase in the abundance of secondary producers, as observed in Alaska, where the abundance of micro zooplankton (rotifers, protozoan) rose with increased primary production (Rublee, 1992).

### 3.4 Responses of Freshwater Birds and Mammals

Populations and community-level responses of freshwater birds and mammals result from combination of direct and indirect climate change impacts. These include changes in winter severity, seasonal snow and ice distribution, and depths; timing and peaks of lake, pond and wetland productivity; predator prey dynamics; parasite-host interactions; habitat quality and distribution; and fire frequency, intensity and distribution (Wromaet al., 2006a). Prowse et al., (2006) projected that coastal land areas (and associated estuarine and freshwater habitats) are likely to experience dramatic temperature increase and changes in their hydrologic regimes. Such changes are likely to produce significant alterations in the quantity and quality of existing coastal estuarine and delta habitats, thereby affecting associated communities of birds and aquatic mammals.

It is therefore probable that changes in freshwater and estuarine habitats will result in altered routes and timing of migration (Callaghan et al., 2004). Breeding ground suitability and access to food resources are likely to be the primary driving forces in changes in migration patterns. Changes in water regimes are very likely to dramatically alter the quality and quantity of aquatic habitat, leading to local changes in the distribution of birds and mammals, and at larger scales, are likely to affect overall habitat availability and quality of aquatic habitats for successful breeding, and in the case of waterfowl nesting (Gratto-Trevor, 1997). Many of the projected responses are likely to result from changes in temperature and precipitation. For example, Boyee and Miller (1985) showed that water depth have a significant positive effect on the annual production of juvenile whooping cranes (Grusamericana), and suggested that increase in summer temperatures are likely to create drier conditions in whooping crane nesting marshes over the long term, decreasing production of young and slowing the annual population growth rate.

Many shorebirds (e.g., sandpipers, plovers, snips, godwits, curlews) also depend on water levels and the persistence of shallow wetlands. For instance, most North American species of shorebirds breed in the Arctic, with ten species that are common to the outer Mackenzie Delta (Gratto-Trevor, 1997). These species depend on invertebrate prey during reproduction, and hatchlings are highly dependent on mosquitoes and Chironomids which are the preferred foods of developing young. According to Gratto-Trevor (1994), any changes in timing and availability of staging site are likely to have detrimental effects on the success of hatchlings. Therefore, most species are very likely to be adversely affected by loss of shallow wetland habitat as ponded areas dry in response to rising temperatures and a potential decline in precipitation.

Climate change possibly produces an increased incidence of mortality from disease and/or parasites in bird and aquatic mammal populations (Poffet al., 2002). As temperatures rise, southern species of mammals and waterfowl are likely to shift northward. These species will probably carry with them new diseases and/or parasites to which northern species are not adapted (Wromaet al., 2006b).

## 4. CONCLUSION

The nature and severity of climate and weather have a strong influence on the hydrology and ecology of freshwater ecosystems. These include extreme seasonality and severity in temperature extremes; high intra- and inter-annual variability in temperature and precipitation; and strong seasonality driven latitudinal gradients in incident solar and ultraviolet (UV) radiation levels. The ecological consequences of these environmental extremes are low overall annual productivity level of freshwater systems because of low level of nutrient input, changes in temperatures, prolonged periods of ice presence compared to temperate aquatic ecosystems, and short growing seasons.

Climate change is projected to affect runoff, water levels, river - and lake - ice and thermal regimes, causing significant alterations to biogeochemical processes, including carbon dynamics; aquatic biodiversity and adaptive capacities; aquatic food web structure and dynamics and corresponding levels of primary and secondary production; and, the range, distribution and habitat quality/quantity of aquatic mammals and waterfowl.

Climate change affects all life forms of freshwater ecosystems across the globe. The magnitude, extent, and duration of the impacts and responses are system - and location - dependent, and produce varying outcomes, including local and/or regional extinctions or species loss; genetic adaptations to new environments; and alterations in species ranges and distributions, including invasion by southern species. Climate change will also produce probable changes in quality and quantity of aquatic habitat for freshwater visitors such as freshwater mammals and waterfowl. Some projected effects at the individual, population and community levels include: altered migration routes and timing; a possible increase in the incidence of mortality and decreased growth and productivity from disease and/or parasites; and, probable changes in habitat suitability and timing of availability, very likely leading to altered reproductive success.

The impact of climate change on freshwater fisheries could be easily masked by or attributed to other anthropogenic influences, such as deforestation, over-exploitation and land use change. Now, global climate change appears to represent an additional stressor to the suite that includes pollution, over-fishing, water diversion, and introduction of non-native fishes. Large-scale human activities like water diversion, land-use changes, and deforestation often have dramatic and rapid impact on fish populations while the effects presently attributable to climate change exist in the background and may go unnoticed. However, even though the effects of climate change have not yet manifested themselves through large and widespread fish kills, the sub lethal effects experienced by the world's fish populations have been and will be detrimental. Temperature increase resulting in decreased dissolved oxygen level, changes in disease transmission, changes in toxicant stresses, and alterations to hydrographs all contribute to the decreased productivity of fish populations. Furthermore, human response to a hotter planet will lead to secondary effects on fisheries. For example, increased demand for water will lead to further water diversion, and increased waste heat loading that will exacerbate existing environmental challenges.

In view of the negative impacts climate change has on the ecosystem and the need to ameliorate such impacts, efforts aiming at minimize the release of greenhouse gasses into the atmosphere would be desirable. This can be done by avoiding deforestation, bush burning, gas flaring, etc. Afforestation, reforestation, modification of automobile engine-exhaust gas recirculation, use of solar power instead of fossil fuel-using generators should be encouraged.

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