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RESEARCH ARTICLE

GLOBAL CLIMATE CHANGE AND AQUATIC ECOSYSTEM: POTENTIAL IMPACTS AND CHALLENGES

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ABSTRACT

Global climatic changes have led to alteration in earth's capacity to sustain life. Melting of ice, rise in sea-level and increased ocean acidity have affected the entire aquatic ecosystem. Changes in water quality, as a consequence of storms, snow-melt, and periods of elevated air temperature exceeds the thresholds of tolerance, leading to altered distribution and phenology of species and productivity of aquatic ecosystems. Increased atmospheric carbon dioxide concentrations alter ocean chemistry which affects the ecosystem structure and functioning. This review focuses on the adverse effects of climate changes on species habitat and their extinction, deep sea biodiversity and the potential impacts of oxygen-deficient dead-zone expansion, alterations in river flow regimes and hydrological cycle, thereby acting as the biggest challenge. It further emphasizes the need for ability to moderate, cope up with and take advantage of the consequences of climate change while preventing the degradation of ecosystems and preserving our biodiversity.

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INTRODUCTION

An ecosystem is composed of biotic communities structured by biological interactions and abiotic environmental factors. Substrate type, water depth, nutrient levels, temperature, salinity, and flow are some of the important abiotic environmental factors of aquatic ecosystems. The amount of dissolved oxygen in a water body plays key role in determining the extent and kind of life the water body can hold. Aquatic flora and fauna needs dissolved oxygen to survive. Algae are a very important source of food for aquatic life and it depends on nutrient levels and relative abundance of nitrogen and phosphorus. However, if they become over-abundant, they can cause decline in fish due to their decaying (Vallentyne, 1974). Over-abundance of algae in the Gulf of Mexico produces a hypoxic region of water which is known as a dead zone (Turner and Rabelais, 2003). The salinity of the water body is also a determining factor in the kinds of species found in the water body. Increasing global climate change causes some species to be forced out of their habitats while some become extinct. Climate change is expected to result in warmer water temperatures, increased salinization, shorter duration of ice cover, altered streamflow patterns, and increased demand for water storage. These changes will alter the pathways by which non-native species enter aquatic systems by facilitating the spread of species during floods to new areas. Climate-driven change will thus modify the ecological impacts of invasive species by enhancing their competitive and predatory effects on native species and by increasing the virulence of some diseases (IPCC, 2007). Climate change is arguably the greatest emerging threat to global biodiversity and the functioning of local ecosystems. Experts in The IPCC Fourth Assessment Report assessed that human-induced warming had a discernible influence on many physical and biological systems. Regional temperature trends had already affected species and ecosystems around the world and climate change would result in the extinction of many species and a reduction in the diversity of ecosystems (Rosenzweig *et al*. 2007, Schneider *et al*. 2007). Many species are adapted to cold water habitat such as Salmon and cutthroat trout that need cold water to survive and to reproduce. Reduced glacier runoff can lead to insufficient stream flow to allow these species to thrive. Ocean krill prefer cold water and are the primary food source for aquatic mammals such as the blue whale. Alterations to the ocean currents, due to increased freshwater inputs from glacier melt affects existing fisheries upon which humans depend as well. Human activities are releasing giga tonnes of carbon to the earth's atmosphere annually (Brierley and Kingsford, 2009). Consequences of carbon emissions have led to biological changes, although the resistance and resilience of organisms and ecosystems is highly variable. Aquatic organisms have important role in cycling of carbon, nitrogen and other key elements. An aquatic ecosystem broadly falls into two categories (a) Marine ecosystem and b) Fresh water ecosystem.

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1. Climate changes within the ocean

Marine ecosystems cover approximately 71% of the Earth's surface and generate 32% of the world's net primary production. Marine ecosystems can be divided into many zones depending upon water depth and shoreline features. The oceanic zone is the vast open part of the ocean where animals such as whales, sharks, and tuna live. Organisms found in marine ecosystems include brown algae, dinoflagellates, corals, cephalopods, echinoderms, and sharks. Most marine locations experience narrower ranges of daily and annual temperature variation than their terrestrial equivalents. However, they exhibit physical variability which influences nutrient availability, physiology of dwelling fauna, productivity, larval dispersal, species migration, biodiversity and biogeography. The large fraction of the planet covered in deep waters guarantees that most carbon sequestration and significant nitrogen cycling in the ocean occurs here. The ocean absorbs approximately 25% of industrial CO_2 emissions and 93% of the heat (Sweetman *et al*., 2017).

(i) Reduction in Total Carbonate Alkalinity

Atmospheric CO_2 and ocean pH being inversely related poses a serious threat to many marine organisms and aquatic ecosystems. Over the past 200 years, the oceans have absorbed approximately half of the anthropogenically-generated atmospheric CO_2. The rate of decreasing pH is 0.1 units in the last 200 years and expected drop of pH is 0.3 to 0.5 units by 2100 (IPCC, 2007). Increased atmospheric CO_2 drives more CO_2 into the ocean where it dissolves forming carbonic acid (H_2CO_3) thereby increasing ocean acidity. Colder waters can accommodate more dissolved CO_2 and are therefore, more prone to acidification. Marine organisms, including tiny coccolithophores (phytoplankton), mollusks, starfishes, urchins as well as massive corals, require calcium carbonate for their skeletons, and for other carbonate rich structures like fish otoliths and are likely to suffer as increasing acidity reduces carbonate availability. Studies of the coccolithophore Emiliania huxleyi suggested thickening and wasting of calcareous shells and excretion of precipitated carbonates by teleost fish with rise in ambient CO_2 (Brierley *et al*., 2009).

(ii) Rise in Sea Levels

Sea level is likely to rise due to thermal expansion of ocean water and accelerated melting of glaciers. Migratory fishes (mullet and eels), turtles, red sea corals, some aquatic crustaceans and aquatic birds (flamingo, aquatic warbler, pelicans and swan goose) are vulnerable to such drastic changes (Fig 1). The threats are mainly due to destruction of spawning areas and nesting grounds for these species (Galbraith *et al*., 2002). One species that is vulnerable to climate-change-induced glacier loss is the meltwater stonefly (*Lednia tumana*). It is endemic species to glacial and snowmelt-driven alpine streams and candidate for listing under the Endangered Species Act (Fig 1) *L. tumana* inhabits a narrow distribution, restricted to cold, alpine streams directly below glaciers, permanent snowfields, and springs. Simulation models suggest that climate change threatens the future distribution of these sensitive habitats and the persistence of *L. tumana* through the loss of glaciers and snowfields (Muhlfeld *et al*., 2011).

(iii) Increase in Sea Temperature

The ocean depths are the most thermally-stable of earth's habitats, and the organisms living in it are the last ones to be affected by direct warming. As a result of thermal inertia temperatures will continue to rise for many decades even if carbon emissions were to cease immediately. Rise in temperature causes increased evaporation-surface and groundwater drought and longer ice free period leading to increased end of summer anoxia and macrophyte growth. In addition, it causes loss of wetlands, changes in time, intensity of precipitation events which results in winter thaw, floods, erosion, and sewer overflows. An important consequence of global warming is the sex ratios change among animals. Temperatures of 29.2°C produce a 1:1 sex ratio in sea turtle populations; including the green turtle, hawksbill turtle, leatherback turtle, loggerhead turtle and the olive ridley turtle (Sari *et al*., 2015). Higher temperatures will lead to the feminization of populations, which will affect breeding success and ultimately resulting in extinction of certain species. Polar bear's survival is dependent on sea-ice and less winter sea ice means that female polar bears have to go longer without food, which impacts their fat stores, and their reproductive success. Complete loss of summer sea-ice cover could force them to adopt a land-based lifestyle which causes risks due to competition with other predators and interactions with humans (GreenFacts, 2006). Harp seal, spotted seal and the ringed seal that rarely come to land depend on Arctic sea ice. Sea ice provides feeding ground as well as home for resting, giving birth and raising pups. Other species, such as the harbour and grey seals, are likely to expand their geographic spread if the Arctic has less ice coverage (GreenFacts, 2006). Some seabirds such as ivory gulls and little auks nest on rocky cliffs and fly out to the sea ice to fish through cracks in the ice and scavenge on top of the ice. The number of ivory gulls in Canada has already dropped by 90% over the last 20 years (Spencer *et al*., 2014). Walrus rely on sea ice to travel large distances on floating ice to feed over a wide area. Ice algae which grows at the porous bottom of sea ice, forms the base of the marine food web connected to sea ice. The melting of ice can affect the availability of physical habitats for algae, as well as the temperature and salinity of surface waters, potentially disrupting the whole food web. Climate change also poses other threats mainly increased risk of diseases, expansion of the geographic spread of species ranges thereby increasing competition between them.

Effects on Deep Sea Biodiversity: The deep sea is a major reservoir of biodiversity and it encompasses the largest ecosystems on Earth. Seafloor habitats may experience reductions in water column oxygen concentrations. Deep-sea ecological processes and characteristics, such as nutrient cycling, carbon sequestration, productivity, habitat provision, and trophic support, underlie the healthy functioning of ocean ecosystems and provide valuable ecosystem services to mankind (Thurber *et al*., 2014). Deep sea biodiversity is threatened by climate-driven change of species habitats and their extinction. Hawaiian bobtail squid, affected by increased oceanic CO_2 because they require very high amounts of oxygen supply to sustain their energy-demanding method of swimming (Fig 2). Not only are the surface-dwellers threatened by a dwindling nutrient supply, triggered by climate impacts but even tiny crustaceans in the deepest and darkest depths of the ocean floor feel the effects of climate change. Limacina helicina, a mollusc that is an important food source for juvenile North Pacific salmon, mackerel, herring, and cod, forms a calcium carbonate shell made of aragonite. Some echinoderms such as starfish are also at risk from ocean acidification (Fig 2).

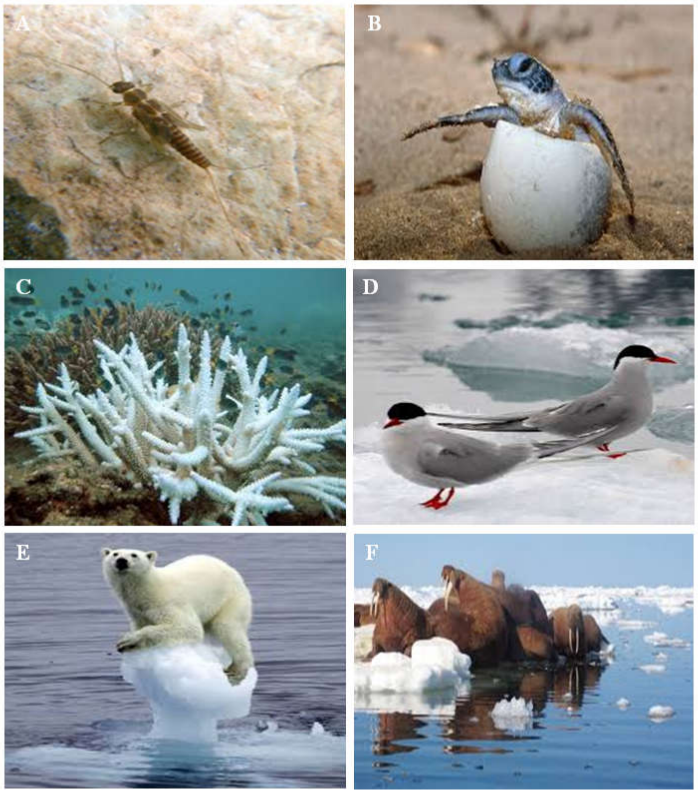

Fig 1. Impact of global climate change on various organisms of aquatic ecosystem (A) Nymph of *Lednia tumana*, meltwater stonefly is vulnerable to climate-change-induced glacier loss (Photo by Joe Giersch, USGS) (B) Increased sand temperatures affect sea turtle hatchlings by altering natural sex ratios, with hotter temperatures producing more female hatchlings. (Photo by Roger leguen) **(C) Red sea corals have a higher prevalence of bleaching due to climate change (D) Seabirds such as small auks are negatively affected by a decline in sea ice. (E) Polar bear's survival is dependent on sea-ice as they need it to travel from one region to another to hunt. (F) Walrus rely on sea ice for easier access to food**

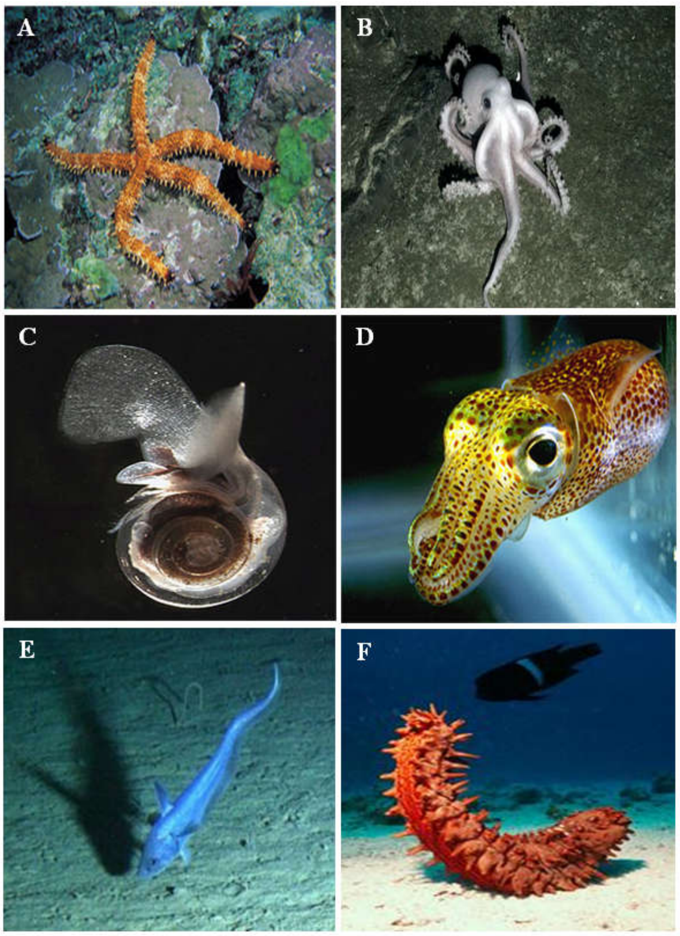

Fig. 2. Deep sea fauna of Aquatic ecosystem affected by global climate changes (A) Echinoderms such as starfish are at risk from ocean acidification. (B) Pale octopus found in the Southern Ocean (Photo courtesy Oxford University) (C) *Limacina helicina*, a mollusc that forms a calcium carbonate shell made of aragonite (Photo courtesy NOAA). (D) Bobtail squid, require very high amounts of oxygen supply to sustain their energy demanding swimming method (Photo by William Ormerod, courtesy Margaret McFall-Ngai and the University of Wisconsin-Madison) (E) Small grenadier fish over the seafloor (*Image: © 2007 MBARI)*** **(F) Sea cucumbers appear vulnerable to changes in climate** *(© SPL).*

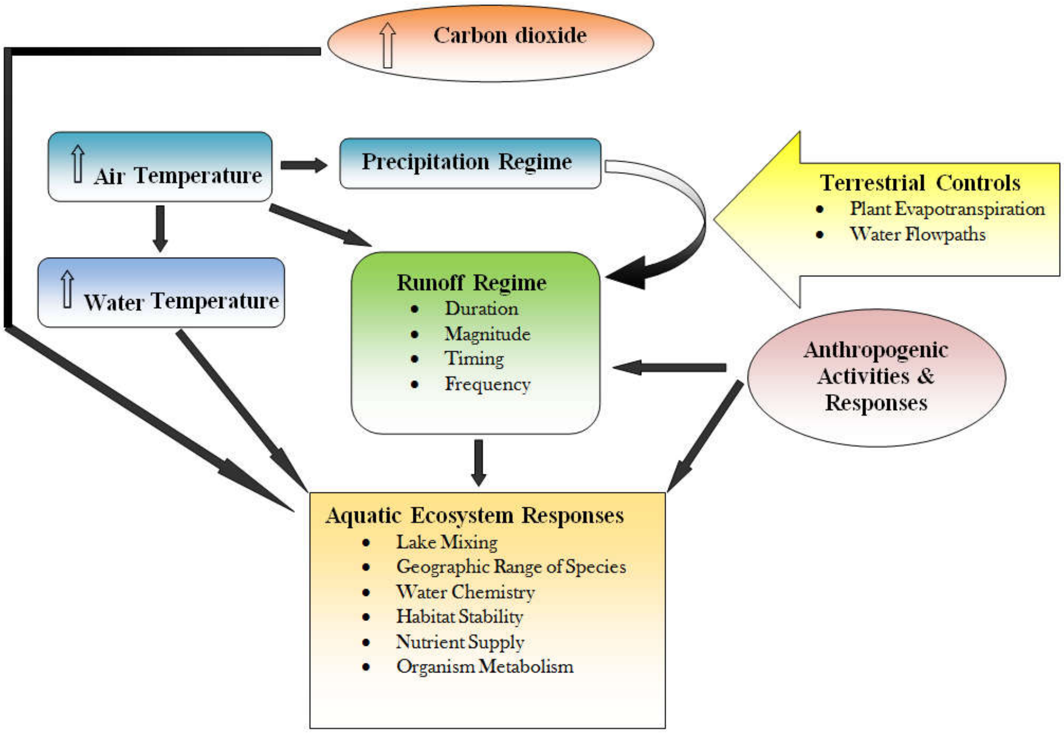

Fig. 3. Inter-relationship of CO_2, Climate and Aquatic Ecosystem responses

Table 1. Response of aquatic ecosystem due to changes in environmental factors

Environmental Factors	Observed changes	Aquatic ecosystem responses
Runoff	Annual increase, winter increase, increase in winter base flow due to increased melt and thawing permafrost	Geographic range of species
Streamflow	Earlier peak streamflow due to snowmelt	Geographic range of species
Snow melting	Warming driven earlier snow melting	Habitat instability
Drought	Decrease in annual daily streamflow due to dry and unusually warm summers, Increased evaporation with no altered patterns of precipitation	Altered productivity, altered metabolism
Water temperature	0.1-1.5°C increase in lakes	Altered productivity, water chemistry, organism metabolism
Water chemistry	Decreased nutrients from increased stratification, longer growing periods in aquatic bodies, increased catchment weathering and internal processing	Altered productivity
Floods	Increased catastrophic flood frequency due to earlier breakup of river ice and heavy rain	Lake mixing, nutrient supply

Elpidia minutissima, a sea cucumber survived when food was scarce, but it disappeared when disturbances leading to increased food supply took place (Ruhl and Smith, 2004). The scientists predict that seafloor-dwelling organisms will decline by over five per cent globally due to reduction in the food source of deep-sea communities. Studies demonstrated that animal communities on the abyssal seafloor are affected in a variety of ways by climate change (MBARI, 2009). Survival of several other deep sea-dwellers is affected by climatic variations leading to extinction of species thereby causing degradation of ecosystem (Fig 2).

Effects on Fish population: Fish body temperature is moderated by water temperature. Increasing sea temperatures can affect important biological processes of fish including growth, reproduction, swimming ability and behaviour. Reproduction is only possible in a narrow temperature range, and therefore could be affected by the forecast temperature rises associated with climate change. Temperature also influences the sex of fish, which may have an effect on population dynamics. Ocean acidification likely impacts fish reproductive processes. Fish eggs are more sensitive to pH changes than fish adults. There are also species of fish on the Great Barrier Reef that live in both freshwater and saltwater habitats and changes to the pathways between these two habitats will make moving between them difficult for these species. Climate warming allows the expansion of invasive coldwater species into new areas. For example, native bull trout (*Salvelinus confluentus*) appear to have a competitive advantage over non-native brook trout (*S. fontinalis*) in the coldest streams in the Rocky Mountains (Rieman *et al*. 1997). As these streams warm, brook trout are expected to achieve competitive superiority and thus displace native bull trout from one of their last remaining refugees from invasive species. Fish are often classified into thermal guilds based on temperature tolerance: coldwater species have physiological optimums <20◦C; cold water species have physiological optimums between 20 and 28◦C, and warmwater species have physiological optimums >28◦C (Magnuson *et al*. 1997). On this basis, coldwater temperatures can be viewed as a filter that prevents warmwater-adapted species from establishing self-sustaining populations. As water temperatures warm with climate change, the effectiveness of this filter will diminish, and warmwater species could spread to new areas and become established. There are evidences that some aquatic species have already responded to climate change. Shifts in the distribution of marine species have been documented (Perry *et al*. 2005).

Effects on Coral Reefs: They have undergone major changes over the past 20 years, much of which has been associated with climate change (Bryant *et al*., 1998). These ecosystems form rich and complex food chains that support large populations of fish, birds, turtles and marine mammals. Light, temperature and the carbonate alkalinity of seawater decrease in a pole ward direction, making the formation of coral reefs more difficult at higher latitudes. Coral bleaching occurs when corals rapidly lose the cells and results in colonies turning from brown to white. Corals form the essential framework within which a multitude of other species makes their home. Fish that depend on corals for food and shelter may experience dramatic changes in abundance or go extinct. Mass mortality of coral reefs globally can lead to vulnerable impacts on thousands of other organisms.

Extent of oxygen-deficient dead-zones: At the very surface, the ocean is in intimate contact with the atmosphere, and the waters are oxygen-rich, but as one progress deeper into the ocean, the oxygen level drops lower and lower. With higher temperatures, the surface ocean acts like a cap that prevents oxygen from getting into deeper layers. As temperatures increase, that cap gets stronger and stronger. The extremely low oxygen region had a huge vertical range, from 110 to more than 3,000 meters (360 to 10,170 feet) below sea level. Today's oxygen minimum zones in the same region are much less extensive, extending from about 100 to 500 meters (128 to 1,640 feet) below sea level. Crab fishermen have reported that their catches are lower, and fishes are moving farther up in the water column because of expanded oxygen minimum zones. Algal Blooms which are blue-green algae (cyanobacteria) result due to excess of nutrients into waters and causes increased growth of algae and green plants. Such blooms help create low-oxygen areas called dead zones as the algae respire or decompose (Zielinski, 2014). Direct effects from depletion of O_2 levels and rising water temperatures may also impact embryonic survival rates of vulnerable deep-sea oviparous (egg-laying) elasmobranchs that currently deposit their capsules at the seafloor in very narrow oceanographic niches with distinct O_2, salinity and temperature conditions (Henry *et al*., 2016).

2. Climate changes within Freshwater Ecosystem

Freshwater ecosystems cover 0.78% of the Earth's surface and generate nearly 3% of its net primary production. Freshwater ecosystems contain 41% of the world's known fish species. Fresh waters are particularly vulnerable to climate change because they are relatively isolated and physically fragmented and they are heavily exploited by humans. Above about a 4 °C increase in global mean temperature by 2100 (relative to 1990-2000), Schneider *et al*. (2007:789) concluded, that many freshwater species would become extinct. Several other drastic effects of climate change on fresh water ecosystem include earlier breeding in amphibians (Beebee 1995), earlier emergence of dragonflies (Odonata) (Hassall *et al*. 2007), and compositional shifts of entire insect communities (Burgmer *et al*. 2007). The extreme events (floods and droughts), modify water quality through direct impacts of dilution or concentration of dissolved substances. More intense rainfall and flooding could result in increased loads of suspended solids (Lane *et al*. 2007) and contaminant fluxes (Longfield and Macklin 1999) associated with soil erosion and fine sediment transport from the land (Leemans and Kleidon 2002). Reduced dilution will increase organic pollutant concentrations, with increased biological oxygen demand (BOD), and hence lower dissolved oxygen (DO) concentrations in rivers (Prathumratana *et al* 2008; Van and Zwolsman 2008).

(i) Effect on Hydrologic cycle

As global temperatures have steadily increased at their fastest rates in millions of years, it's directly affected things like water vapor concentrations, clouds, precipitation patterns, and stream flow patterns, which are all related to the water cycle. Water evaporates from the land and sea, which eventually returns to Earth as rain and snow. Climate change intensifies this cycle because as air temperatures increase, more water evaporates into the air (Whitehead *et al*., 2009). Warmer air can hold more water vapor, which can lead to more intense rainstorms, causing major problems like extreme flooding in coastal communities around the world

(ii) Biological impacts

In the absence of disturbance, epilithic space was dominated by alga, *Gongrosira incrustans*. However, droughts consistetly reduced the dominance of the green alga, and crust abundance decreased, opening up space for a diversity of mat-forming diatoms. The invertebrate community structure also shifted in the most stressed treatments relative to the controls, with a decrease in large, rare species higher in the food web. In the warmer streams, the herbivore assemblage was dominated by large-bodied and very efficient grazers, in the form of the snail *Radix peregra*, whereas in the colder streams this niche was occupied by small chironomid midge larvae. This taxonomic change, represented by a functional shift in the community, in turn resulted in stronger top-down control of algal production in the warmer streams. More recently, it has been found that food chain length increased with a temperature change from approximately 5 to 25°C, with fish (brown trout, *Salmo trutta* L.) replacing invertebrates as the top predators in the warmer streams (Woodward *et al*., 2010).

(iii) Alteration in River Flow Regimes

The magnitude, frequency, duration, and timing of floods, droughts, and intermittent flows (i.e., the flow regime) are primary drivers of ecological structure and function in aquatic ecosystems (Fig 3). Climate change affects freshwater ecosystems not only by increased temperatures but also by altered river flow regimes (Doll and Zhang, 2010). River flow characteristics such as long-term average discharge, seasonality, and statistical high flows are impacted more strongly than dam construction and water withdrawals. Flow regime is a primary determinant of the structure and function of rivers and their associated flood plain wetlands, and flow alteration is considered to be a serious and continuing threat to freshwater ecosystems (Poff and Zimmerman, 2010). Climate change modifies patterns of precipitation, evapotranspiration, and runoff (Poff *et al*. 2002). Increases in air temperature will cause concomitant increases in river temperatures and rates of evapotranspiration (Fig 3). Climate models predict increases in the variability and intensity of rainfall events; a pattern already observed over the last century (Frederick & Gleick 1999). This will modify disturbance regimes by changing the magnitude and frequency of floods. Table 1 summarizes the response of aquatic ecosystem to changes in environmental factors.

Major Challenges faced due to Global Climate Change

The major challenges faced due to climate changes is that these changes may combine with other anthropogenic stressors (e.g., fishing, mineral mining, oil and gas extraction) to further impact deep-seafloor ecosystems leading to augmented societal implications. The deep sea provides a diversity of ecosystem services to our global society which is likely to expand in the coming decades. Ecosystem is mainly influenced by human activities, and can be exacerbated by climate change. At the same time, a number of co-occurring stressors are likely to impact the ecology of deep-sea communities and the ways in which these communities influence the long-term carbon cycle. Long time continuous monitoring in different regions is still required and more efforts should be taken to separate the impacts of climate change from human activities based on the data, although it is complicated (Jun *et al*, 2010). Specific and practical adaptation options and positive ways to enhance adaptability should be proposed to decision-makers. As society makes critical decisions about the use and conservation of deep-ocean ecosystems, it is important that we recognize the vulnerability of life on the ocean floor to climate-related stressors, and the direct influence that the surface climate can exert on the world's largest biome.

Adaptation measures to decrease risk of aquatic ecosystem

Adaptation options should improve the ability to moderate, cope with and take advantage of the consequences of climate change. Moreover, because of uncertainty of future climate variability, management responses should be built in flexibility to ensure that current coping strategies are consistent with future climate change. Adaptation measures to decrease risk of aquatic ecosystem include reduction of overall water use and the harvest of vulnerable species, protection and restoration of key habitat features such as wetlands, riparian and shoreline buffers, reducing contaminants and nutrient additions along with elimination of the movement of non native species.

Conclusion

Climate change occurs due to natural and anthropogenic influences over evolutionary and ecological time scales. Oceans are a mosaic of habitats that support life and are huge reservoirs of nutrients and gases, including CO_2. Since ocean currents redistribute heat around the planet they have major impact on atmospheric circulation, regional weather patterns and rainfall distribution. Changes in ocean circulation bring fundamental physical changes, with major accompanying biological ramifications. There are numerous interactions between climate, physical water characteristics and aquatic life that should not be ignored. Increased CO_2 affects species differentially means that it is likely to drive substantial changes in the species composition and dynamics of aquatic ecosystems. It is expected that by 2040, some sensitive marine ecosystems such as coral reefs and ice-covered polar seas would be lost and other unexpected consequences may arise. The pressing need is for an international initiative to save world's ecosystem and prevent all living organisms from the colossal destructive effects of climate changes.

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