Editors | Charles R. Goldman
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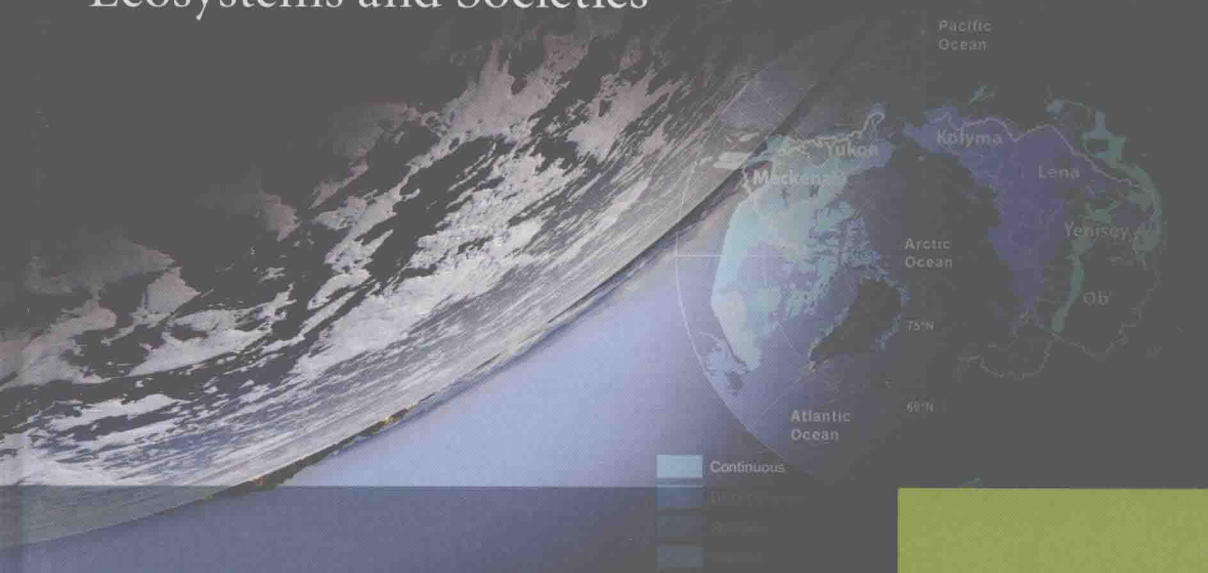
# Climatic Change and Global Warming of Inland Waters

## Impacts and Mitigation for Ecosystems and Societies

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# Climatic Change and Global Warming of Inland Waters

## Impacts and Mitigation for Ecosystems and Societies

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# Preface

The World Water and Climate Network (WWCN) was created during the Third World Water Forum in Kyoto Japan in 2003. Its objective is to gather and exchange science-based information on the current and future conditions of our limited surface freshwaters contained in the lakes and rivers of the world. Since then the impact of global climatic change and associated warming has resulted in WWCN sessions organized in conjunction with three international conferences in France, the United States, and China. A fourth session was held in conjunction with the meeting of the American Society of Limnology and Oceanography at Otsu, Japan, in 2012. An important feature of the WWCN activities has been to attract and provide advanced training and scientific exchange for promising young graduate students competitively selected from about ten different countries. Bringing them together for several days to attend student meetings and then to present their research at an international scientific conference provides a stimulating intellectual platform for them to exchange information and make contact with old and new generations of aquatic ecologists, limnologists, hydrologists modelers, and environmental engineers. The meetings take place at a very important and formative time in the students' career development. Following the WWCN in Nice, France in 2009 the editors recruited experienced scientists from the meetings to assemble information on the impact of climatic change on the world's inland waters culminating in a book that Wiley-Blackwell agreed to publish. The following chapters are the result of this initiative.

Little doubt remains in the scientific community that the planet's climate is changing. Notably, the earth continued to gain heat during 2005–2010, a period marked by the strongest solar minimum recorded since accurate monitoring began. In other words, we now have irrefutable evidence that the sun is not the only important nor even perhaps the dominant factor forcing this climate change and that carbon dioxide, the classic greenhouse gas, is being joined by increasing amounts of methane. This gas is over 20 times as potent a greenhouse gas as carbon dioxide and will continue to increase as permafrost melts. Furthermore, analysis of ice cores indicates that the current, rapid rate of warming has not occurred in the last 800 000 years. Some natural and healthy scientific debate will doubtless continue on the exact role of human activity, especially regarding the large but practically unmeasured role of human-made atmospheric aerosols and the feedback loop of water vapor rising from the warming oceans. Major volcanic eruptions could temporarily reduce the global warming trend, as may have occurred following the Novarupta eruption on the Alaska Peninsula on

June 6, 1912, and as was recorded following the Mount Pinatubo eruption in 1991 from the ash blown into the atmosphere. Regardless of periodic volcanic events and the need for refinements of existing models, the evidence for anthropogenic warming is overwhelming. We need to accept the fact that, in the coming years, we face a dangerously warming world accompanied by rising sea levels and the damaging weather extremes that are already occurring. The evidence indicates that the globe is now warming at a rate sufficient to greatly alter the quantity and quality of fresh and marine waters and thus the lives of plants, animals and humans in the current century and beyond. In the chapters that follow we concentrate on the changes that have occurred and are likely to occur to our vital surface inland waters, both fresh and saline, as warming proceeds. We recognized that these changes vary considerably in different locations and have therefore selected authors from around the globe who are experienced with a wide range of different ecosystems. Where possible, recommendations for reducing the anticipated negative impacts of global warming on aquatic ecosystems are included.

The authors of the following chapters are limnologists, hydrologists, modelers and environmental engineers. We explore, through the contributions of these talented scientists from many countries, the impacts that climate change and the associated warming effect have had and are likely to have on lakes, rivers, wetlands, and their watersheds. The chapters, with input from 80 authors, are organized from northern latitudes to the more southern regions since the most extreme conditions of climatic change have already been well documented in the Arctic. In contrast the least impact of climate change for inland waters appears to be in the southern hemisphere where the temperature of New Zealand lakes has not measurably changed. Here the ratio of surrounding ocean to land mass is particularly great. Together with the many lake studies included in this book, three major river systems and their watersheds are included. We have, through selection of the contributors, been able to explore the subject in Siberia and other far northern region bordering the Arctic Ocean, Europe, Asia, Africa, the Middle East, and North and South America, New Zealand and Antarctica. Following the first 20 chapters on lakes and rivers are two unique chapters, 21 and 22, on the impact of global warming on society with the final three chapters dealing with possible mitigation of negative impacts. Chapter 25 presents a new technology that may prove helpful where oxygen depletion in lakes occurs as eutrophication is stimulated by increasing water temperatures.

Chapters 1 and 2 of the book deal with the physical-chemical and biological impacts of climate change on Arctic rivers and lakes. The aquatic resources of this region are vitally important to the indigenous people of the north who have depended on them for millennia and who now face the impacts of extremely rapid climatic change. The rivers of the far north have a profound influence on the Polar Sea, which receives them, since their volumetric contribution is relatively great when compared with the rivers discharging into the much larger world oceans. Chapter 2 is a comprehensive coverage of existent and future changes in the enormous number of large and small fresh water bodies to be found in the permafrost areas of the high arctic. Here conditions have already brought about extensive changes. Chapter 3 covers Lake Baikal, the oldest deepest lake in the world located in Russian Siberia. Its enormous volume of 24 000 cubic kilometers of largely unpolluted water is equivalent to all the water in the United States Great Lakes and may well turn out be Russia's most valuable natural resource. In this lake the annual period and extent of ice cover and thickness is already being

reduced with a variety of impacts on local conditions including the use of the lake's ice cover for north and south automotive and truck transport. Chapters 4 and 5 cover two major Chinese rivers, the Yellow and Yangtze, as well as their enormous watersheds. With the huge and growing population in the region dependent upon the water from these two great rivers it is not surprising that the Chinese government is attempting to predict their future water yield on the basis of existing studies. These efforts have underscored the necessity of collecting accurate longer term data to improve prediction on floods and droughts. This monitoring data is urgently needed for improving global water-resource management. This theme reappears in a number of chapters at a time when institutions and governments have been reducing funding for important research-driven data collection so essential for improving the predictive capacity of models used to plan for the future.

Chapters 6 through Chapter 9 all involve conditions in Lake Biwa, the largest lake in Japan, which provides domestic water for over 14 million people and has undergone considerable eutrophication from nutrient input from its large urban and agricultural watershed. Chapter 6 deals with the human impacts on Lake Biwa and the additional stress of warming. Chapter 7 examines the changes in the plankton population as eutrophication has proceeded. Anoxic dead zones now occur in the near bottom waters as the biological oxygen demand of decaying plant and animal material exceeds the replenishment of oxygen from photosynthesis and seasonal mixing. Chapter 8 provides a numerical simulation of deep Japanese lakes and their future mixing as warming increases their water column stability and their resistance to complete mixing. Chapter 9 is a modeling paper with the potential to predict future lake conditions.

Chapters 10 and 11 take the reader to the Scandinavian lakes of Denmark, with Chapter 11 extending the coverage to a wide range of other lake types from different climate zones of the world. All of these studies underscore the increasing importance of eutrophication control. In the shallow phosphorus-rich Danish lakes, the warming effect has promoted dominance of the cyanobacteria, while in the deeper stratified lakes the dinoflagellates are dominant. These important changes in plankton dynamics should serve to revitalize the ongoing struggle by lake managers to slow or reverse the progress of eutrophication which, for years, has degraded the water quality of so many of the world's lakes. Chapter 12 concerns the mid-latitude lakes of Europe with the emphasis on the warming of Lake Geneva, where Professor Forel first gave birth to and named the field of limnology. Warming in this region has tended to promote more radical weather conditions as the atmospheric boundary layer has warmed. The author reports on the importance of ice breakup in Lake Constance as further evidence of progressive lake warming.

Moving to Canada, in Chapter 13 the author examines the wetlands of the prairie pot hole region. Warming is progressing there with definite increases in violent weather conditions and the threat that some of these small wetlands may dry up if rainfall is significantly reduced in the area. Chapter 14 takes the reader to the western United States and the half-century of data collected on the intensively studied Lake Tahoe located between California and Nevada, near the crest of the Sierra Nevada. In the earliest stages of eutrophication Tahoe's entire water volume has warmed a degree in 30 years with warming of the surface water occurring at an astonishing ten times as fast as the whole lake. Although still one of the world's clearest large lakes, it is likely to be subjected to more frequent floods, increased water shed erosion, sediment

transport, further eutrophication, and more frequent lowering of lake level below its natural rim.

Chapter 15 notes that, as the world's lakes warm, their biota and associated food webs are changed. The half-century of data at Lake Tahoe shows that, as it warms, it has become increasing vulnerable to invasion of non-native species and has, unfortunately, experienced the intentional and accidental introduction of a variety of warm-water fish and most recently the Eurasian clam. The phenomenon of invasive species is occurring across major landscapes as warm water plants and animals are gradually able to extend their northward range often displacing the endemic northern flora and fauna in their movement.

Chapter 16 concerns Lake Kinneret in Israel, an arid region where water demand for irrigation and municipal water supplies is intense and the threat of increased salinity is always present. Recent reductions in rainfall there may already mirror the expected impacts of climatic change. The authors report on major shifts in the dominant phytoplankton where, in recent years, serious cyanobacterial blooms have already altered the food web. This occurred in conjunction with inputs of organic carbon and nitrogen from degraded wetland peat.

Chapter 17 deals with the Amazon river, boasting a highly productive fishery, which, to a large degree, is based on Varzia lakes along its flood plain. These shallow lakes, which are important as fish nursery areas, are likely to be impacted by climate change as the dynamics of flooding may be altered. Chapter 18 concerns the African Great Lakes, which span the famous Rift Valley. Paleo-limnological proxies indicate that Lake Victoria is heating faster now than at any time in the last 2000 years. These are of enormous economic importance to Africa and have been intensively studied over the years. The author shows how mixing dynamic in the African lakes are testimony to their complexity and are greatly influenced by wind and ocean mixing conditions. Carbon dioxide accumulation in some volcanic African lakes has resulted in a serious threat to those humans and animals living downwind or at a lower elevation. The eruption of gas from volcanic Lake Nyos, in the Cameroon, for example, was responsible for the death of many local people and their cattle, and the lake is currently being degassed to prevent another eruption.

Chapter 19 considers New Zealand and the southern hemisphere, where temperatures are greatly moderated by the enormous water surface of the southern oceans. Studies of North Island Lakes Taupo and Rotorua indicate that, to date, there has not yet been detectable warming. Lake Taupo, like Lake Tahoe, may experience less frequent mixing should warming gradually overcome the influence of the surrounding ocean. Chapter 20 involves the extreme climate of Antarctica, a barren frozen land, which, like the northern polar region, is expected to undergo major changes with loss of sea ice and penguin habitat. Warming on the Alaska Peninsula has been 2.5 °C since 1945, which is reported to be five times faster than the global average. The highly sensitive coastal systems have low biological diversity and, as sentinel habitats, they are likely to show early response to even slight warming and may begin to be invaded by temperate zone species.

Chapters 21 and 22 consider some of the important societal aspects of water and climatic change. In the pasture lands of Mongolia, where Genghis Khan once raised an army of horseman that conquered much of the known world, the descendant herders of the already affected seasonal pastures conditions are forced to change their herding management or give up their ancestral life style. Climate change has altered

the availability of grazing and water supplies and severe sudden rainstorms are now more frequent. Chapter 22 deals with the growing problems associated with the many megacities that are emerging throughout the world as populations increase and more people are migrating to the cities. Only a few cities have taken the essential steps to meet some of the challenge of managing water, sewage and solid waste for the swelling numbers of inhabitants, which may double again by midcentury. The cities that have planned ahead are valuable examples of what can and must be done if a reasonable quality of life in large cities is to be maintained.

Chapters 23 and 24 provide recommendations for mitigating at least some of the global challenges facing our warming planet. Chapter 25 reports on an interesting technology for decomposing water into hydrogen and oxygen by electrolysis as a possible means of restoring oxygen to the depths of lakes impacted by eutrophication and climatic warming. The hydrogen produced can serve as a valuable by product of the process.

As noted above, Japan's Lake Biwa, an extremely important water source for Japanese citizens, is already threatened by a changing plankton community and an increase in the production of anoxic near bottom conditions fatal to some fish species. It would appear that our longstanding battle to reduce the greening of lakes by reducing nutrient loading may turn out to be one of the most cost-effective means of mitigating or at least reducing the negative impacts of lake warming. Strong evidence exists for the displacement of endemic species as movement of warm water species north increases because colder lakes and streams warm sufficiently to form more attractive habitat for invasion.

The editors hope that the following chapters will present ideas that will stimulate new approaches to what can and should be done to mitigate the more harmful aspects of climate change as we face the relentless warming of the planet and its effect on our vital and limited surface fresh water and related drinking water and food supplies. The impacts differ greatly in different regions of the world. Global conditions are inseparably linked to global atmospheric greenhouse gases, which can only be controlled by a rapid worldwide acceptance of alternative energy sources together with the emergence of a new carbon-based environmental ethic that drastically reduces greenhouse gas emission from controllable anthropogenic fossil fuel sources. This must be done before we pass a tipping point, or point of no return. Water, like air, is more essential than oil or any other commodity to life and is frequently contaminated or in very limited supply in many regions of the world. Climate change is altering the balance of rain, floods, and droughts, and our water-dependent food supplies essential to feed a dramatically and, in fact, frighteningly increasing world population. Current and anticipated shortages of unpolluted water are certain to be among the most serious challenges ever faced on earth by plants, man and animals alike.

The likelihood of future conflicts over increasingly limited sources of water now and in the future could cause immense human suffering through major and minor wars, famine, pestilence, and death. These were once portrayed as the "Four Horsemen of the Apocalypse." Unfortunately, these four symbolic riders of the world's skies are now joined by a fifth, representing global warming and pollution of water supplies from the combination of industrial, agricultural, and domestic sources. The long conflict over Kashmir has much of its basis in the immense importance of its water-yielding mountains to both India and Pakistan. There is much to be done in a timeframe that now appears to be becoming ever shorter through the biologically mitigated feedback

loops that will further accelerate the rate of global warming. Examples from the Arctic include the loss of albido as the ice cap melts and the melting of permafrost with carbon dioxide and methane release from activation of bacterial decomposition. The release of methane, which as we have seen is a far more potent greenhouse gas than carbon dioxide, will accelerate further melting and the associated release of gas to the atmosphere. Atmospheric deposition is influencing the nutrient and pollution loading of our surface waters and their watershed and should provide the motivation to bring world governments together in combating it. During a recent summer, half the dust falling on Lake Tahoe, according to the research of Drs Snyder and Cahill (personal communication), had travelled across the Pacific from China. It is the hope of the authors and editors alike that the chapters contained in this volume will bring further attention to the seriousness of climatic change to the future of our civilization. In offering some suggestions for mitigating some of the negative impacts of climatic change we hope to inspire some new and promising research, management, and political action before irreparable damage is done to our inland waters. These after all form our global life support system and to a great extent their condition and availability will determine the quality of life for this and future generations.

The editors are indebted to Ms. Ayaka Kawai Tawada for her expeditious, skillful and always cheerful coordination and tracking of the various stages of the manuscripts and correspondence with the authors—our work was made easier and more efficient with her help.

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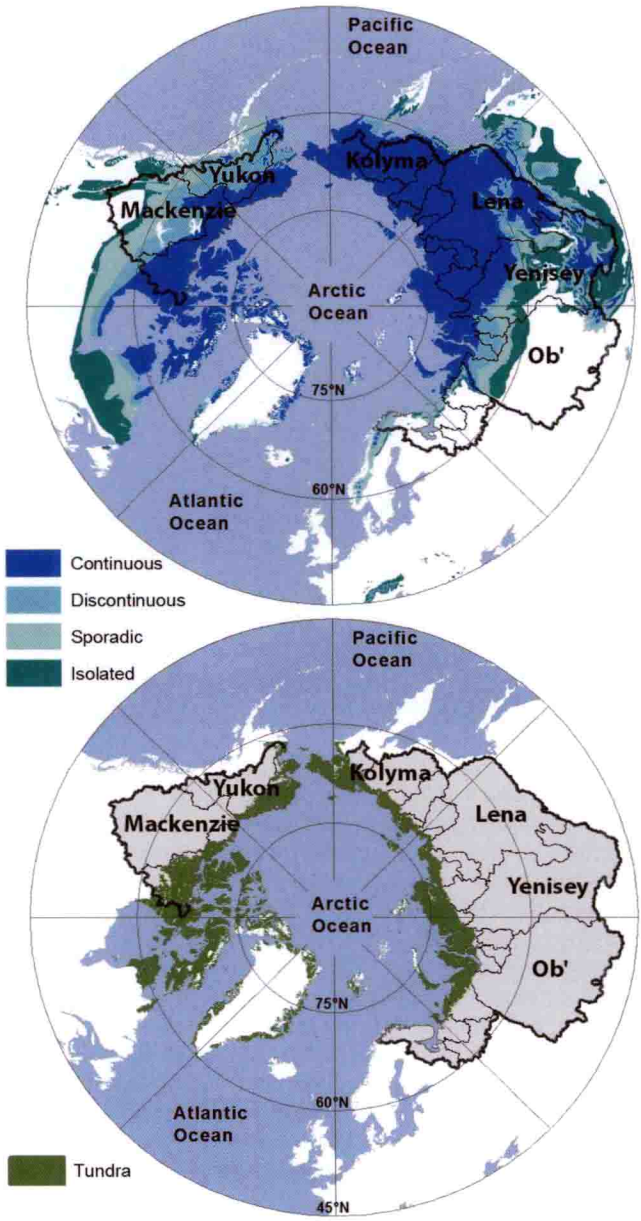


**Plate 1.2** Distribution of Arctic permafrost (upper panel) and tundra (lower panel). Continuous permafrost indicates that >90% of the land surface is underlain by permafrost, discontinuous indicates 50–90%, sporadic indicates 10–50%, and isolate indicates <10% of the region contains permafrost.

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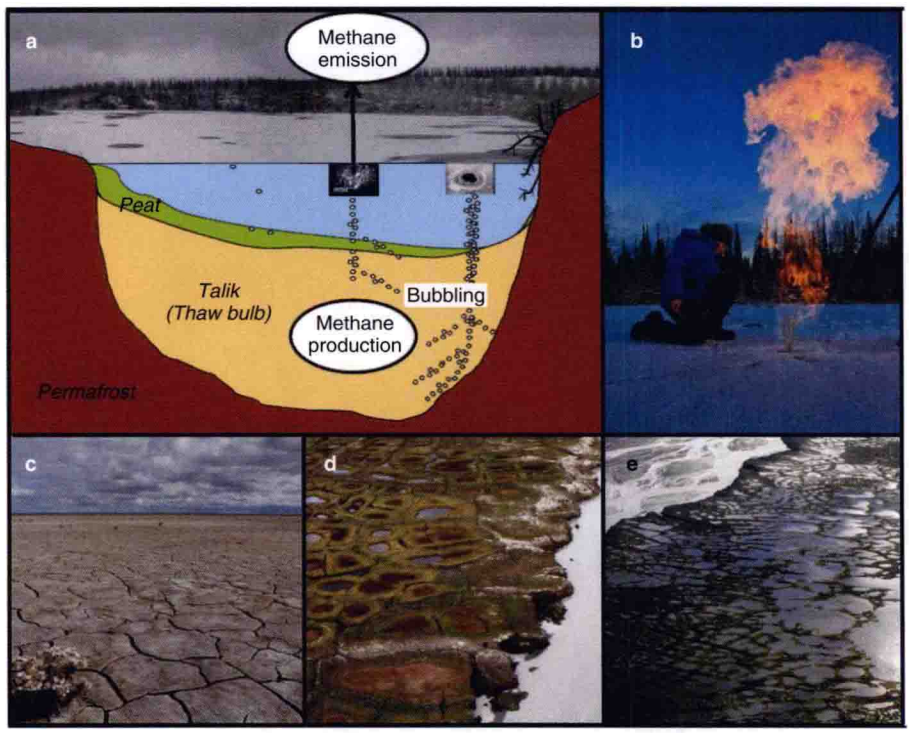


**Plate 2.2** Arctic thaw lakes in the changing Arctic. (a) These waterbodies are biogeochemical hotspots on the tundra in which soil and lake organic matter is broken down by microbial activity in the thaw zone beneath the lake, resulting in the liberation of methane and carbon dioxide. Large quantities of these gases are released to the atmosphere via bubbling, which can produce and maintain holes in the ice. Modified from Walter *et al.* (2007). (b) The methane can accumulate as gas pockets beneath the ice, such as here in an Alaska lake where the gas has been vented through a hole made in the ice and then ignited. Photocredit: Todd Paris, November 2009; from Walter Anthony *et al.* (2010). Reproduced with permission. (c) In parts of the Arctic, thaw lakes are expanding in number and size, while in other areas, such as here in the Nettilling Lake region of Baffin Island, landscape erosion has resulted in complete drainage of some waterbodies. Photocredit: Reinhard Pienitz, August 2010. (d) Long-term as well as interannual variations in climate strongly affect the water balance and persistence of lakes on the permafrost. Many of these polygon ponds on Bylot Island, Canada evaporated to dryness in a warm, low precipitation year. Photocredit: Isabelle Laurion, July 2007. (e) The Bylot Island polygon ponds were numerous and extensive during a preceding cool, wet year. Photocredit: Isabelle Laurion, July 2005.