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Lakes and reservoirs as sentinels, integrators, and regulators of climate change

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Abstract

Climate change is generating complex responses in both natural and human ecosystems that vary in their geographic distribution, magnitude, and timing across the global landscape. One of the major issues that scientists and policy makers now confront is how to assess such massive changes over multiple scales of space and time. Lakes and reservoirs comprise a geographically distributed network of the lowest points in the surrounding landscape that make them important sentinels of climate change. Their physical, chemical, and biological responses to climate provide a variety of information-rich signals. Their sediments archive and integrate these signals, enabling paleolimnologists to document changes over years to millennia. Lakes are also hot spots of carbon cycling in the landscape and as such are important regulators of climate change, processing terrestrial and atmospheric as well as aquatic carbon. We provide an overview of this concept of lakes and reservoirs as sentinels, integrators, and regulators of climate change, as well as of the need for scaling and modeling these responses in the context of global climate change. We conclude by providing a brief look to the future and the creation of globally networked sensors in lakes and reservoirs around the world.

Aquatic ecosystems are an integral part of human existence on Earth. Both oceanic and inland waters provide a wide range of essential ecosystem services ranging from drinking water and food to transportation and recreation. They also add a less tangible but economically and spiritually invaluable aesthetic dimension to our lives. According to both the Millennium Ecosystem Assessment (MEA 2005) and the Intergovernmental Panel on Climate Change (IPCC 2007), inland waters and their associated ecosystem services are some of the most threatened by climate change and burgeoning human populations.

Global climate change is altering aquatic ecosystems in profound ways (Polunin 2008). One of the most visible examples at the planetary level is the recent and rapid melting of the Arctic sea ice. The extent of the Arctic ice at its minimum in September of 2007 was only 50% of that recorded during this same season from the 1950s to the 1970s (Stroeve and Serreze 2008), and further decreases in multiyear sea ice and ice shelves were recorded in 2008 (Fig. 1). The reduction in sea ice has created a fundamental shift in the associated ecosystems that influences fisheries and marine mammals such as seals and walruses, as well as polar bears and the hunting grounds of indigenous people in both the Arctic and Bering seas (Grebmeier et al. 2006; Stroeve and Serreze 2008). The Arctic Ocean may be totally open seasonally within the next few decades (Wang and Overland 2009).

These changes in the Arctic Ocean signal fundamental changes that are likely to extend to a wide range of inland global water resources. Lakes and reservoirs in particular form a network of environmental sensors that when properly interpreted can give us abundant information about the effect of climate change on water resources. Pronounced effects of climate warming are now being observed in many inland lakes and reservoirs, with potentially severe consequences for the ecosystem services that they provide (Vincent 2009; Williamson et al. 2009). Even the deepest and largest lakes in the world, from Lake Tanganyika in Africa (O'Reilly et al. 2003) to Lake Baikal in Siberia (Hampton et al. 2008; Moore et al. 2009), are experiencing dramatic climate-related changes. Some of the most visible of these changes are the drying up of lakes, ponds, and wetlands in response to decreases in precipitation, increases in evaporation, or both (Fig. 2) (Postel 2005; Smol and Douglas 2007*a*). Global warming trends have resulted in ice cover times that are on the order of 12 d shorter per 100 yr in lakes and rivers in the Northern Hemisphere (Magnuson et al. 2000). These changes in ice cover can result in positive feedback effects on the rate of water column warming (Fig. 3), and can be linked to important biological changes in lakes (Quayle et al. 2002; Smol and Douglas 2007*a*; Rühland et al. 2008; Antoniades et al. in press). Major changes in rainfall patterns are also predicted over the course of this century (IPCC 2007), and prolonged drought or flooding has striking effects on lake ecosystems, sometimes exacerbated by human activities in the surrounding catchment (Fig. 4).

The important point is that lakes and reservoirs comprise a large, geographically distributed network of ecosystems that can provide valuable information on both the patterns and the mechanisms of how terrestrial and aquatic ecosystems are responding to climate change (Figs. 5, 6) (Williamson et al. 2008). *Lakes and reservoirs are effective sentinels, integrators, and regulators of climate change.* This topic was the focus of a recent American Geophysical Union Chapman Conference (http://www.agu.

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Fig. 1. Climate warming in the Arctic cryosphere. Record Arctic sea ice melt in 2007 was followed by additional loss of ice volume in 2008, including 23% loss of Arctic ice shelves (Mueller et al. 2008). This photograph, taken 20 August 2008, shows the dramatic calving and fracturing of the Ward Hunt Ice Shelf (Ellesmere Island, Canada), the largest ice shelf in the Northern Hemisphere. Photo credit: Denis Sarrazin, Centre for Northern Studies (CEN).

org/meetings/chapman/2008/dcall/) held at Lake Tahoe in September of 2008, and is also the subject of this special issue of *Limnology and Oceanography*.

Although the focus of this special issue is squarely on science, the intention is to have the product be of substantial value to environmental managers and policy makers dealing with climate-change issues. The results presented here are the efforts of individuals and groups of scientists and also four working groups that synthesized research to date in four principal areas involving lakes and reservoirs as (1) sentinels of climate change (Adrian et al. 2009), (2) integrators of climate change (Leavitt et al. 2009), and (3) regulators of climate change (Tranvik et al. 2009), as well as (4) modeling efforts to integrate lakes and reservoirs into a more quantitative framework including larger global climate models (MacKay et al. 2009). After a brief introduction to the landscape context of lakes and reservoirs, we briefly summarize here some of the highlights of the conference in these four major topic areas, and conclude with a view to the future and how lakes and reservoirs can help us to understand the effects of climate change.

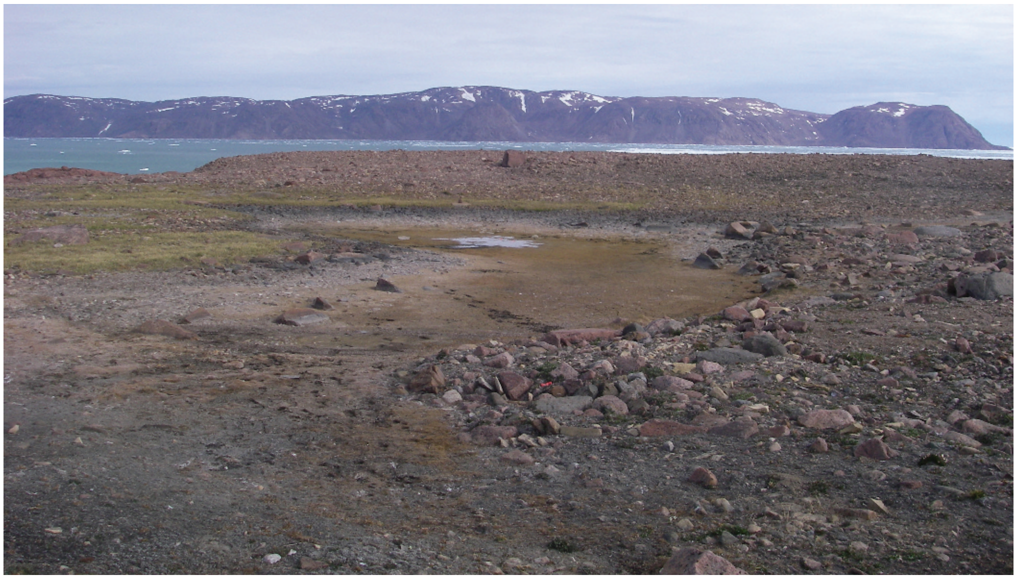

Fig. 2. Effects of climate change on water budgets. This photograph of Camp Pond on Cape Herschel (Ellesmere Island, Canada) was taken on 16 July 2007 just a few hours before it completely dried up as a result of increased evaporation due to warmer temperatures and longer ice-free conditions. Paleolimnological data indicate that many of the ponds at this site had been permanent waterbodies for millennia (Smol and Douglas 2007*b*).

Fig. 3. Climate effects on the North American Great Lakes. Effects observed to date include earlier ice melt, earlier onset of stratification, and warmer epilimnetic temperatures (Austin and Colman 2007). Future potential effects include changes in primary productivity (Brooks and Zastrow 2002), reduced lake levels, and contracted coastal wetlands. This image was acquired by the Aqua satellite, on 05 April 2004 (courtesy of National Aeronautics and Space Agency Goddard Space Flight Center).

Papers in this special issue use a variety of experimental, observational, paleolimnological, and modeling approaches to elucidate climate–lake linkages. Several papers examine climatic control of the physical structure (MacIntyre et al. 2009; Mueller et al. 2009; Verburg and Hecky 2009) and carbon chemistry (Catalan et al. 2009; Finlay et al. 2009; Weyhenmeyer and Karlsson 2009) of lake ecosystems. Climatic forcing of biological responses in lake ecosystems (Castañeda et al. 2009; Dröscher et al. 2009; Graham and Vinebrooke 2009; Wagner and Adrian 2009*a*; Winder et al.

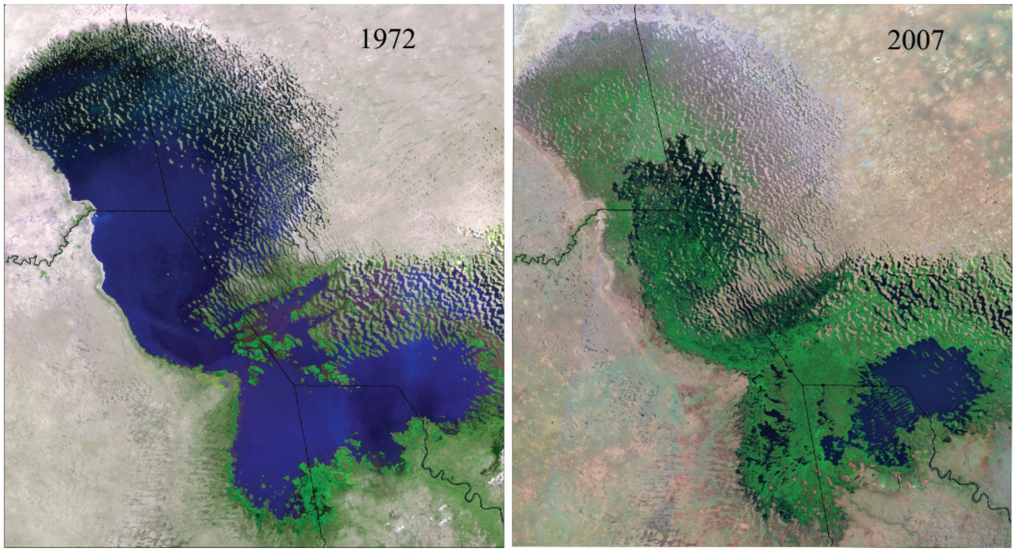

Fig. 4. Climate and catchment effects. Prolonged drought in the Lake Chad (northwest Africa) basin has led to a 20-fold contraction in lake area over the last few decades. This climate effect has been compounded by the increasing need to irrigate farmland (Coe and Foley 2001). Images courtesy of United Nations Environment Program (http://na.unep.net/AfricaAtlas/AfricaAtlas/).

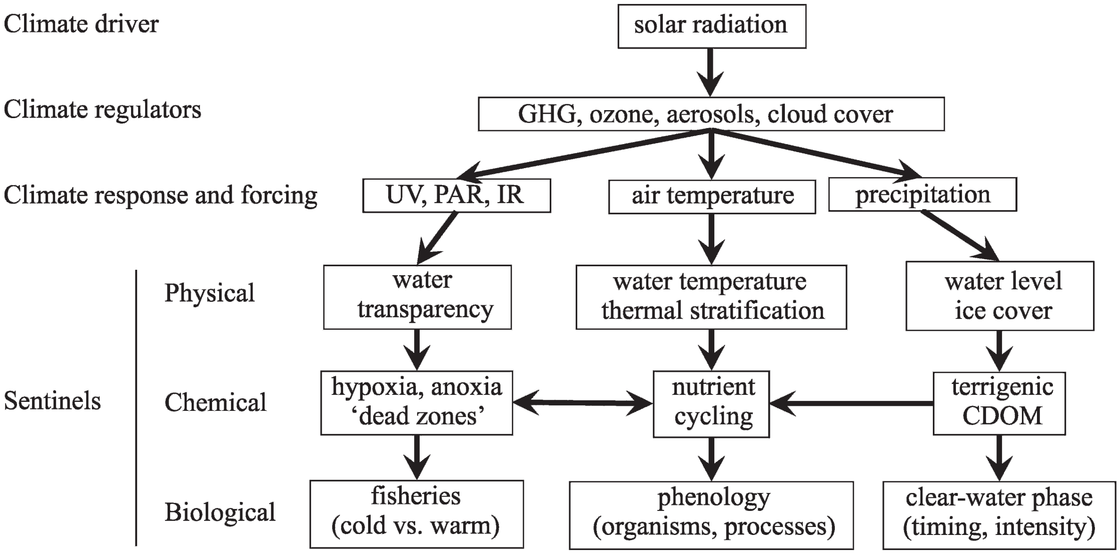

Fig. 5. Flow diagram of lakes as sentinels of climate change showing major climate regulators, climate response and forcing, and a few of the many physical, chemical, and biological sentinels that can be quantified in lakes as they respond to climate change.

2009) is also a key focus of this issue, along with interactive effects of different components of climate change such as ultraviolet radiation (UVR) and elevated carbon dioxide levels (Sobrino et al. 2009) and the interactive effects of climate change and other disturbances such as nitrogen deposition (Hessen et al. 2009) and food-web dynamics (Manca and DeMott 2009). Investigations of climate–lake linkages in this special issue span lakes across arctic, alpine, boreal, temperate, semiarid, and tropical regions.

Lakes and reservoirs in the landscape—Lakes and reservoirs comprise only about 3% of the earth's total land surface area (Downing et al. 2006), yet they play a pivotal role as sentinels, integrators, and regulators of climate change. Relative to the surrounding drier terrestrial landscapes, lakes and reservoirs are hot spots of biological activity that both regulate and respond to climate change. Lakes and reservoirs are sentinels, conveying multiple signals of climate change. They are also integrators, as their sediments are archives of past responses

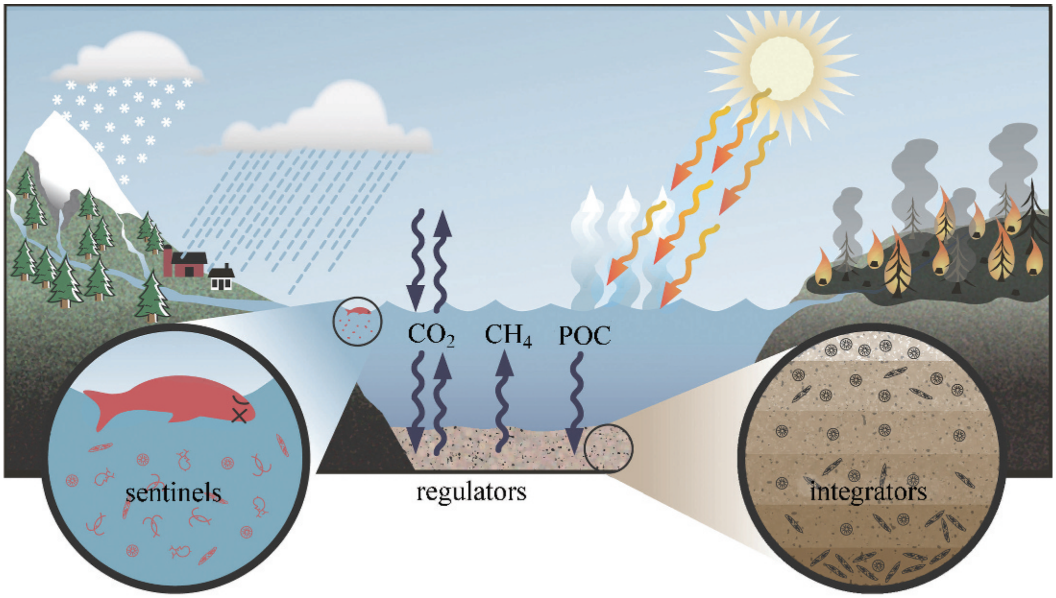

Fig. 6. Conceptual diagram of lakes as sentinels, integrators, and regulators of climate change. Lakes are sentinels because they respond very rapidly to changes in solar irradiance, precipitation, wind, hydrology, and a variety of atmospheric and terrestrial inputs. Lakes are integrators of climate change in that they store signals of change in their sediments—integrating changes not only within the aquatic ecosystem, but also changes in the surrounding terrestrial ecosystem and airshed. Lakes are regulators of climate change in that they (1) receive, process, and store large amounts of carbon from the surrounding terrestrial watershed as well as from the aquatic productivity within their shorelines, (2) are involved in active exchange of greenhouse gases with the overlying atmosphere, and (3) can alter regional climate by changing radiative forcing, cloud formation, precipitation, and evaporation.

to climate change in both surrounding terrestrial as well as aquatic ecosystems (Cohen 2003; Smol 2008). We need to learn more about how to read these signals and interpret the corresponding responses to, and records of, climate change.

As the lowest point in the landscape, lakes and reservoirs receive inputs from the surrounding terrestrial catchment as well as the upwind airsheds. Alterations in seasonal temperature and precipitation patterns as well as climate control of carbon flux into and out of lakes may play a central role in both the ecology of aquatic and terrestrial communities and ecosystems, and in global biogeochemical cycles. For example, long-term trends of changes in dissolved organic matter (DOM) have been observed in several regions around the world, but the mechanisms driving these changes are still poorly understood, actively debated, and likely to vary among geographic regions (Evans et al. 2006; Monteith et al. 2007). The chromophoric component of DOM is a major mediator of the effects of climate variability on lakes and reservoirs through its influence on UV and photosynthetically active radiation (PAR), thermal structure of the water column, carbon cycling, energy flow, primary and secondary productivity, and aquatic food-web structure (Williamson et al. 1999; Tranvik et al. 2009). Similar climate effects include changes in the flux of energy, water, and other dissolved substances that act as ecological subsidies among terrestrial, aquatic, and atmospheric domains.

Lakes and reservoirs as sentinels of present climate change—The primary mechanisms of climate forcing include changes in incident solar radiation (UV, PAR, and infrared), air temperature, and precipitation (Fig. 5). The responses of lakes and reservoirs as sentinels include changes in physical (water level, water transparency, water temperature, thermal stratification, and ice cover thickness and duration), chemical (DOM, oxygen, nutrient cycling), and biological (phenology, cold- vs. warm-water fisheries, clear-water phase [CWP]) characteristics (Fig. 5). Optical characteristics that integrate physical, chemical, and biological responses may also be effective indicators of climate change (Vincent et al. 1998). One particularly good optical metric of climate change is the intensity, duration, and timing of CWP events, an important seasonal period of high transparency driven by zooplankton grazing for visible wavelengths (Lampert et al. 1986; Sommer et al. 1986) and by photobleaching and zooplankton in UV wavelengths (Williamson et al. 2007). Climate-driven changes in ice-cover and DOM loading also have a controlling influence on underwater UVR, resulting in orders of magnitude greater changes in biological UV exposure than moderate ozone depletion in the stratosphere (Williamson et al. 1996; Vincent and Laybourn-Parry 2008). Incident UV exposure is particularly severe in tropical regions at high elevations (McKenzie et al. 2007), but even in very arid high-elevation tropical regions DOM concentrations may be quite high (Rose et al. in press), an interesting situation that clearly needs further investigation. A comprehensive summary of the sentinel responses of lakes is provided in the synthesis of the sentinels working group (Adrian et al. 2009), as well as in many of the individual papers in this volume. Here we provide a brief overview of the highlights of some of these and related studies.

By nature, the water level in lakes, and endorheic lakes in particular, is a sensitive sentinel of changes in hydrologic balance induced by changing temperature and precipitation. Projections of future evaporation rates on lakes in Africa suggest decreases in water level in endorheic lakes, as has been observed at Lake Chad (Fig. 4). Extraction of water from these arid regions by humans further aggravates this problem (Postel 2005). Warmer temperatures are expected to lead to longer periods of thermal stratification with warmer surface temperatures that can in turn influence the extent of hypoxia or anoxic "dead zones" (Sahoo and Schladow 2008), the intensity and phenology of thermal stratification, nutrient cycling, and food-web dynamics ranging from the phytoplankton (Wagner and Adrian 2009*a*) to zooplankton (Winder et al. 2009), to invertebrate predators (Manca and DeMott 2009) and fish (Fang and Stefan 2009).

In marine systems, climate-induced regime shifts have been recognized for some time (Mantua et al. 1997). Interestingly, biological responses may be more effective indicators than the actual climate variables themselves (Hare and Mantua 2000), and have important implications for commercial marine fisheries (Beaugrand et al. 2008). Climate-induced regime shifts have also been recognized in lakes where changes in phenology, and more specifically the timing of the CWP events, are altered by climate change (Scheffer et al. 2001). Arctic lakes are currently undergoing important regime shifts as warmer temperatures are leading them to transition from perennially ice-covered to annually ice-covered systems (Mueller et al. 2009).

Polar and alpine lakes are undergoing particularly rapid climate change (Bradley et al. 2006; Veillette et al. 2008; Mueller et al. 2009), and as such may be some of the most sensitive sentinels of climate change. Optical changes in UV and fluorescence in an alpine lake in the Sierra Nevada of Spain are effective sentinels of dust blown from the Sahara Desert (Mladenov et al. 2009). Annual and perennial snowpack and glaciers in some of these high-elevation and high-latitude regions can be viewed as "upside-down lakes" or perhaps more appropriately "upside-down reservoirs" as they play a critical role in long-term storage of drinking water for a major portion of the world's populations and their rapid melting threatens water supply in these regions (Bradley et al. 2006). Reduction in ecosystem services associated with hydroelectric projects, agricultural irrigation, and other industrial and recreational services will also result in substantial economic losses from the melting of these frozen montane reservoirs. Along these same lines the impoundment of rivers in reservoirs by humans is extensive enough to alter estimates of sea-level rise due to global warming, adding 0.55 mm yr^{-1} for the past 50 yr (Chao et al. 2008).

Although climate warming is anticipated to be most severe in polar and alpine regions, tropical lakes are also experiencing warming trends. For example, in the great lakes of Africa warming has increased shallow water (100 m) temperatures more than that of deeper waters (1000 m), increasing thermal stability (Verburg and Hecky 2009).

Reduced mixing increases nutrient limitation of phytoplankton productivity and hence increases in water transparency similar to the effects of climate warming on ocean ecosystems. Climate also influences lakes in more temperate zones. For example, in Lake Maggiore, one of the largest and deepest lakes in Italy, climate change drove an earlier onset of thermal stratification and expansion of a low-light refuge from visual predators that led populations of the invertebrate predator *Bythotrephes longimanus* to increase 10-fold within a 5-yr warming period (1988–1993) (Manca and DeMott 2009). First appearance of the *Bythotrephes* population also shifted from August to May, and *Daphnia*, the principal prey of this invertebrate predator, showed significant declines. A study of over 1000 boreal lakes along latitudinal and elevation gradients that examined the relationship between dissolved organic carbon concentration and temperature revealed that of 14 meteorological, catchment, and morphometric and atmospheric variables, the length of the growing season (when air temperatures exceed 0°C) had the greatest explanatory power (Weyhenmeyer and Karlsson 2009).

Lakes and reservoirs as integrators of past climate change—The sediments of lakes and reservoirs integrate effects of climate variability on terrestrial and aquatic ecosystems over decades to millennia through the deposition and preservation of diverse materials derived from land, lake, and atmosphere. Lakes act as transducers and transformers of energy and mass inputs to catchments and the lake surface in a way that leaves signals of climate change in their sediments, providing information on changes in UV, temperature, and precipitation over past decades to millennia (Leavitt et al. 2009). Lake sediment records have revealed the effect of changes in energy influx on lake ecosystems over various timescales. In the Arctic, paleolimnological studies reveal that warming has led to changes in diatom community structure over the last century (Smol et al. 2005). Reconstructions of UVR over the past 100,000 yr in coastal ponds of Antarctica, where terrestrial sources of dissolved organic material are lacking, reveal the ongoing importance of UVR influx in controlling algal abundance and community structure in these lakes (Hodgson et al. 2005). Algal molecular biomarkers and compound-specific carbon isotopes from the sediments of Lake Malawi were used to reconstruct trends in air temperature and wind direction in East Africa over the last 23,000 yr, revealing a marked shift in the dominant wind direction and subsequent lake mixing patterns at the onset of the Holocene (Castañeda et al. 2009).

Alteration of mass inputs to lakes in the form of water volume, particulates, and solutes may in fact be much more important than the temperature and thermal structure changes that are often associated with climate change (Leavitt et al. 2009). For example, Catalan et al. (2009) reconstructed CO_2 concentration and saturation in a lake in the Pyrenees from diatom-inferred alkalinity and pH, and linked changes in lake water CO_2 to duration of ice cover and subsequent changes in algal productivity.

As such strong integrators of local, regional, and global changes, however, one major difficulty in using lake sediments in climate studies is deciphering climate signals from those driven by disturbance (e.g., land-use change, atmospheric deposition) and lake ontogeny (McGowan et al. 2008). Simpson and Anderson (2009) begin to address this problem by developing a new modeling approach using additive models to decipher the relative contributions of different forcing variables on changes in sedimentary diatom species composition through time.

Lakes and reservoirs as regulators of future climate change—Though comprising only on the order of 3% of the world's land surface area, lakes and reservoirs are true hot spots of carbon storage, processing, and greenhouse gas production (Williamson et al. 2009). Lakes and reservoirs deposit more organic carbon in their sediments annually than do the world's ocean sediments (Dean and Gorham 1998). Many lakes contain CO_2 and other greenhouse gases at concentrations above air equilibrium, and act as major conduits for the transfer of terrestrial carbon to the atmosphere (Cole et al. 2007). Recent estimates suggest that the rate of deposition of fixed organic carbon in lakes and reservoirs exceeds that being deposited in the world's oceans. As such, lakes and reservoirs may account for a substantial portion of the "missing carbon" sink resulting from anthropogenic fossil fuel burning and hence contribute in important ways to the regulation of global climate change (Cole et al. 2007). One portion of the carbon cycle in lakes and reservoirs that remains poorly understood in this respect is the role of photobleaching by UV and longer wavelengths and how it influences the production, biolability, and hence processing of organic matter by microbial autotrophs, heterotrophs, and mixotrophs.

In recent years a controversy has developed on how "green" hydroelectric projects really are; the greenhouse gases (GHG) produced per unit energy by these impoundments rival those produced by traditional power plants based on fossil fuels (Rudd et al. 1993; Giles 2006). The ratio of carbon emission to energy produced of tropical reservoirs varies greatly among regions. When relatively biomass-poor savannahs are flooded there tends to be a lower ratio of GHG emission to energy produced than when biomass-rich forests in the Amazon are flooded.

Recent development of powerful geographic information tools has led to more comprehensive estimates of the role of smaller lakes and impoundments as well as saline lakes in global carbon cycling (Downing et al. 2006; Duarte et al. 2008). These studies reveal an inordinate importance of smaller lakes: of an estimated 300+ million lakes worldwide, greater than 90% are less than 0.01 km^2 in surface area. Including these smaller lakes and impoundments in global estimates has increased the estimated surface area of lakes from 1.8% to over 3% of land surface area (Downing et al. 2006). Thaw lakes on permafrost soils have been identified as an especially abundant class of small waterbodies that are strong CO_2 and methane emitters, with potential effects on global climate (Walter et al. 2006; Vincent and Laybourn-Parry 2008). Saline lakes, which comprise about one-fifth of the total lake surface area on Earth, have a rate of gas exchange that is more than double that of freshwater lakes with the same partial pressure of CO_2 (Duarte et al. 2008).

Scaling and modeling the role of lakes and reservoirs in climate change—Climate effects on aquatic ecosystems range from the molecular-level response of UV-induced DNA damage and temperature-dependent enzyme kinetics to direct and indirect food-web responses at the population, community, and ecosystem levels. The timing of the response of lakes to climate change ranges over timescales of days (thermal stratification in response to storm events) to millennia (sediment records). On a regional scale great lakes play an important role in modulating regional climate patterns, which influence terrestrial ecosystems as well.

Tools for examining these responses may range from the use of the ways that stable isotope ratios are altered by climate effects on biochemical pathways to remote sensing and satellite imagery approaches to quantifying the distribution and abundance of lakes and large-scale regional or global responses. Sophisticated scaling and modeling approaches are required to integrate these disparate levels of response of lakes to climate change at local, regional, and global scales (MacKay et al. 2009). To really understand the role of lakes as sentinels, integrators, and regulators of climate change, broader-scale assessment of key regulating variables such as ice cover (Mueller et al. 2009) and DOM (Kutser et al. 2005) is necessary, and techniques such as remote sensing are being successfully developed to do this.

Integrating the role of lakes into global climate change will require the development of fully coupled atmosphere–land surface–lake climate models (MacKay et al. 2009). A workshop on ''Parameterization of Lakes in Numerical Weather Prediction and Climate Modelling'' was held 18–20 September 2008, in St. Petersburg (Zelenogorsk), Russia. One of the biggest challenges in modeling the role of lakes and reservoirs into global modeling efforts is integrating the numerous smaller lakes and impoundments as well as larger lakes into the models. Rather than entering individual lakes into climate models, one approach might involve using representative landscapes that are composed of different densities of water surface with appropriately adjusted eddy flux estimates. Because many lakes in the terrestrial landscape are sources of CO_2 and are not figured into climate models, they may shift these landscapes to greater sources of CO_2.

Linkages and interactions among themes—Lakes and reservoirs are simultaneously serving as sentinels, integrators, and regulators. As such there are many interactions among these different ''chapters'' of these encyclopedias and archives of information on climate change that these systems provide. Two of the many possible examples are given here. The first example deals with the multiple effects of predicted increases in thermal stability predicted by climate models and observed under climate warming scenarios in both inland waters and oceans (Lopez et al. 2008; Stramma et al. 2008). Data from systems ranging from small Arctic to large, deep tropical lakes demonstrate that warming increases thermal stability and decreases mixing (MacIntyre et al. 2009; Verburg and Hecky 2009). Increased stability leads to oxygen depletion and the creation of hypoxic or anoxic dead zones that have many far-reaching consequences. Anoxia enhances regeneration of limiting nutrients such as phosphorus that can in turn generate more severe cyanobacteria blooms (Lopez-Urrutia 2008; Wagner and Adrian 2009*a*). Climate-driven reductions in oxygen are predicted to increase summer kill of cold-water fish in more southern areas of the United States, but decrease or eliminate winterkill in more northerly areas (Fang and Stefan 2009).

The second example of the complex and interactive effects of lakes as sentinels, integrators, and regulators of climate change deals with the effects of construction of impoundments and reservoirs. As climate change forces regional changes in hydrologic balance, the construction of artificial impoundments, canals, and other waterways will be necessary to redistribute water to human populations and agricultural areas. On the bright side, the presence of more reservoirs will likely increase carbon burial, potentially reducing global warming (Tranvik et al. 2009). Anoxic conditions in these same reservoirs, however, are likely to increase the contributions of inland waters to outgassing of methane, a greenhouse gas that is about 25 times more potent than CO_2. Anthropogenic impoundments are altering the landscape with other important consequences: they are 2.4–300 times more likely to harbor invasive species and they are accelerating the spread of invasive species by decreasing the distance to the nearest stepping-stone of water (Ding et al. 2008; Johnson et al. 2008; Rahel and Olden 2008).

Where do we go from here?—We need to begin ''reading'' and interpreting more effectively the encyclopedias of information that lakes and reservoirs are providing us as sentinels, integrators, and regulators of climate-change effects on both terrestrial and aquatic ecosystems. There are two approaches that are likely to be particularly fruitful. One is the implementation of local, regional, and perhaps most importantly global networks that collect data on the sentinel, integrator, and regulator aspect of inland waters (Williamson et al. 2008). The Global Lake Ecosystem Network (GLEON) is a grass-roots organization that is creating a network of scientists and sensors that are focused on using lake metabolism as a key regulator of response to climate change (http://www.gleon.org/). A cogent case has been made for the value of such long-term monitoring to decipher signals and effects of environmental change in a variety of ecosystems from terrestrial to oceanic (Lovett et al. 2007; Smetacek and Cloern 2008).

Although GLEON has been growing rapidly and holds great promise, there are two major challenges to the effectiveness of lakes as a truly global network. One is the fact that the technical expertise as well as the limnologists themselves are highly concentrated in North America and Europe. For example, although great efforts have been made by both the conveners of the Chapman Conference that preceded this special issue and by the leaders of GLEON to recruit a broad international group of scientists and students, 73% of GLEON members are from North America and Europe, and 96% of the scientists at this conference were from these two continents. With a few exceptions (Lewis 1987), tropical lakes are particularly under-represented. For example, in spite of the great importance of the African rift lakes, less than 2% of GLEON members are from Africa. Although there were investigators at the Chapman Conference with expertise on African lakes, there was not a single scientist from Africa. Another challenge to the development of a truly global lake network is the fact that there are major geographic regions of the world where few or no lakes even exist (Downing et al. 2006). Given that lakes are warming, more studies of warm tropical lakes are needed if we are to understand the effects of climate warming on the sentinel, integrator, and regulator properties of lakes.

An alternative to "waiting" for long-term trends to develop through broad-scale networks is to take advantage of extreme or episodic climate "events" (Jentsch et al. 2007). Such events may include climate events such as floods, droughts, heat waves, and cyclic oscillations driven by the multiple global or large-scale regional climate oscillations such as the Pacific Decadal (PDO), North Atlantic (NAO), and El Nino Southern (ENSO) oscillations. Studies of climate oscillators have been particularly helpful in understanding the effects of climate (Straile and Adrian 2000; Wagner and Adrian 2009*b*). For example, the timing of the spring CWP in shallow prairie lakes is strongly correlated with water temperatures exceeding 16°C and *Daphnia* grazing activity on diatoms. Heat income and certain aspects of the CWP are inversely correlated with the winter index of the NAO as well as with later winter to early spring precipitation (Dröscher et al. 2009). Space-for-time substitution studies that examine variations in lake or reservoir processes across elevation gradients or latitudinal gradients are another potentially fruitful alternative (Weyhenmeyer and Karlsson 2009).

A major caveat to the use of lakes as sentinels and integrators is the potentially confounding effects of other anthropogenic forcing of changes such as eutrophication and acidification, which may both alter sentinels such as transparency, paleosignals such as diatoms, and key regulators such as anoxia, which influences C deposition and GHG emission. Paleolimnological approaches that test hypotheses by carefully selecting sites along gradients of interest, comparing inferences from sediment records to historical climate data, or coupling sediment records with experiments that are explicitly designed to provide mechanistic information do, however, hold promise (Leavitt et al. 2009). As in any scientific approach, carefully designed experiments and cautious interpretation of the data will be necessary as we harvest the volumes of information that lakes and reservoirs provide as sentinels, integrators, and regulators of climate change.

Acknowledgments

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