CLIMATE CHANGE

Sentinels of Change

Lakes and reservoirs provide key insights into the effects and mechanisms of climate change.

Craig E. Williamson,[1] Jasmine E. Saros,[2] David W. Schindler[3]

Given the vast and complex landscape of Earth's surface, where do we look for signals of how climate change influences ecosystems? Lakes and reservoirs are an important part of the answer. Although they make up a small percentage of Earth's surface, lakes and reservoirs act as sentinels by providing signals that reflect the influence of climate change in their much broader catchments (*1*). The sediments of inland waters integrate these signals over time, and the deposition of terrestrially derived carbon and outgassing of greenhouse gases make them hot spots of carbon cycling and, thus, climate change regulation. Furthermore, given that freshwater is one of Earth's resources most jeopardized by changing climate (*2*, *3*), being able to detect changes that are detrimental to water quantity or quality is critically important.

Lake levels are highly visible signals of change in water quantity, with records that can span many decades (*4*). For instance, declining levels in closed-basin prairie lakes in North America indicate that at some time in this century, climate change may render these areas much drier than they have been since the late 19th century (*5*). Many of these changes are caused by long-term, cyclic climatic changes driven by ocean circulation patterns (*4*). For example, levels in smaller lakes in Wisconsin rise and fall with those of the nearby Laurentian Great Lakes, suggesting climate oscillations as a common driver (*6*). Lake sediments also store signals that are proxies for prehistoric climate change. The height and position of beach ridges that can be dated are similarly useful in deducing the state of water supplies in past millennia.

Some of these indicators are worrisome. For example, the Laurentian Great Lakes are often viewed as vast reservoirs for solving future water shortages in other parts of North America. But recent studies show that their water balance is precarious, with water renewal rates of less than 1% per year (*7*). In much of North America, the 20th century now appears to have been the wettest in the past millennium or more, with droughts up to several decades long commonplace in earlier centuries (*8*). Water levels in the Great Lakes have been fairly stable in the past century, varying by less than 2.1 m, but proxy data suggest that climate-driven hydrologic imbalance led the connecting rivers and Niagara Falls to dry up between 8770 and 8290 years ago, leaving the Great Lakes as separate basins (*7*). Pollen and seeds in dated lake sediments have shown that between 3000 and 8000 years ago, grasslands around Lake Winnipeg extended well north of the present tree line; the climate in the catchment seems to have been very similar to 20th-century Medicine Hat, Alberta, one of the driest parts of the Canadian Prairies (*9*).

Lakes as sentinels. Alpine lakes, such as Lake Oesa in the Canadian Rockies pictured here, produce and store signals of climate change. Scientists are using these signals to determine how climate influences both terrestrial and aquatic ecosystems and to elucidate the role of inland waters in regulating climate change.

Other recent studies have elucidated the role of lakes as regulators in the global carbon cycle. Over 90% of the estimated 304 million lakes worldwide are small (less than 0.01 km^2) (*10*) and shallow, with ample nutrients, light, and water to make them optimal environments for high levels of biological productivity. Much of the carbon reaching lakes originates in the vegetation and soils of their catchments. About twice

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[1] Department of Zoology, Miami University, Oxford, OH 45056, USA. E-mail: craig.williamson@muohio.edu [2] Climate Change Institute and School of Biology and Ecology, University of Maine, Orono, ME 04469, USA. E-mail: jasmine.saros@maine.edu [3] Department of Biological Sciences, University of Alberta Edmonton, Alberta, Canada T6G 2E9. E-mail: d.schindler@ualberta.ca

as much terrestrial carbon is received by inland waters as reaches the world's oceans (*11*). Calcareous catchments also release considerable carbon to lakes as bicarbonate and carbonate. In total, inland waters may bury about four times as much carbon as do the oceans (*10*).

Much of the organic carbon received by lakes is mineralized and emitted to the atmosphere as carbon dioxide or methane. According to recent studies, inland waters—including eutrophic reservoirs and saline lakes as well as running waters—emit roughly as much carbon as is absorbed by the world's oceans (*10*, *12*). These contributions are given little consideration in global climate models. Including lakes and reservoirs in models may shift estimates for many landscapes to greater sources of carbon dioxide.

The dissolved organic carbon originating from terrestrial systems is usually colored and serves important functions in lakes. For example, it attenuates both damaging ultraviolet radiation and the longer wavelength solar radiation that regulates the thermal structure and physical habitat of the lake, thus changing nutrient and contaminant cycling. Dissolved organic carbon can be flocculated, contributing to carbon sedimentation, or mineralized through photolytic and biological processes (*13*). Widespread regional changes in dissolved organic carbon concentrations in inland waters remain poorly understood (*14*).

The biodiversity of many freshwater habitats is gravely threatened. During the 20th century in North America alone, 123 species of freshwater animals were recorded as extinct, with 49% of mussels, 23% of gastropods, 33% of crayfishes, 26% of amphibians, and 21% of freshwater fishes imperiled by the end of the century (*15*). The Laurentian Great Lakes are in the process of an "invasional meltdown" (*16*), due largely to species imported in the ballast water of Eurasian ships. Reservoirs and other human-made impoundments, including constructed ponds and wetlands, are 2.4 to 300 times as likely to harbor invasive species as natural lakes (*17*). They accelerate the spread of invasive species by decreasing the distance to the nearest "stepping stone" of water (*17*). The Three Gorges Dam has allowed the spread of 55 invasive species throughout its 58,000 km^2 catchment, including the water hyacinth, regarded by many as the world's worst invasive species (*18*).

Lakes also serve a sentinel function for many of the changes to forests and wetlands caused by a warming climate. For example, a 74 to 118% increase in the area burned by forest fires in Canada is predicted to result from increasingly severe dry weather by the end of the century (*19*). After a fire in the catchment of Moab Lake, Jasper National Park, Canada, increased nutrients and mercury caused changes in food web structure that resulted in greatly increased mercury concentrations in fish (*20*).

The outlook for lakes and reservoirs and the ecosystem services that they provide is bleak. Yet records from these inland waters may provide the insights necessary to address the dual challenges of climate change and increased human domination and their effects on lakes and the larger landscape. Global lake observatory networks that monitor and integrate these signals are needed in combination with experimental studies if we are to decipher all the information contained in the waters and sediments of lakes.

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