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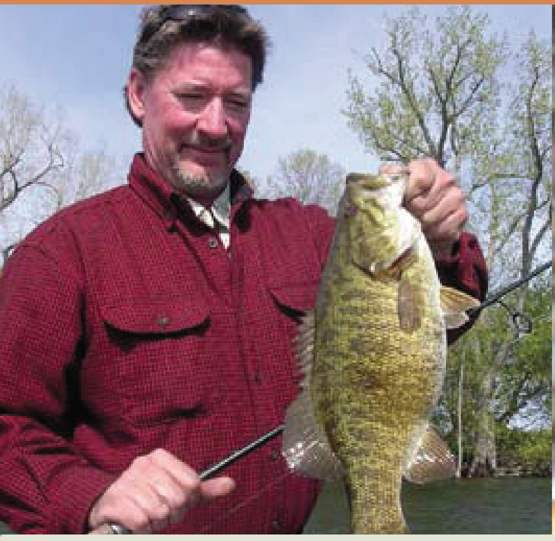
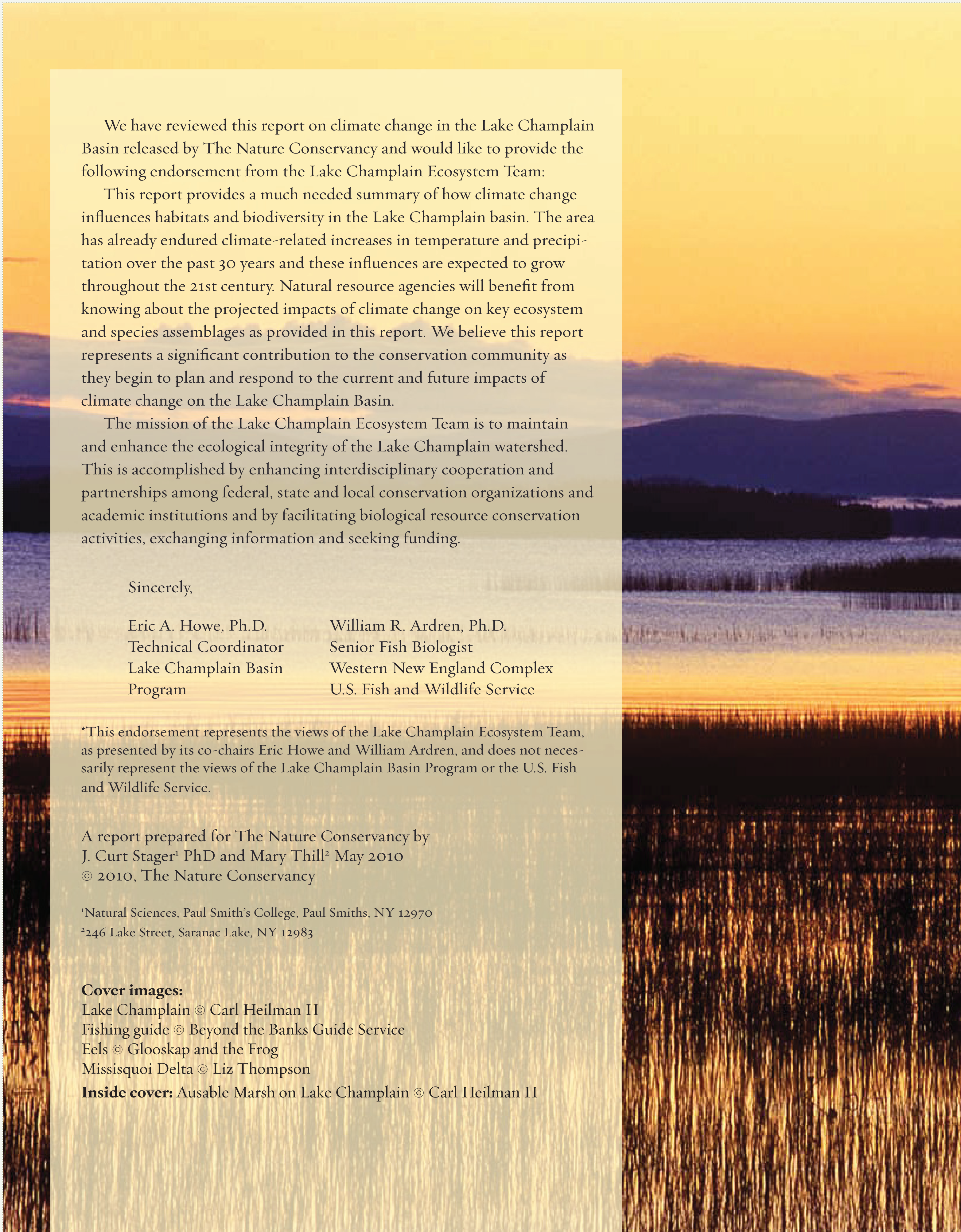
BY J. CURT STAGER AND MARY THILL

Climate Change in the Champlain Basin

What natural resource managers can expect and do





We have reviewed this report on climate change in the Lake Champlain Basin released by The Nature Conservancy and would like to provide the following endorsement from the Lake Champlain Ecosystem Team:

This report provides a much needed summary of how climate change influences habitats and biodiversity in the Lake Champlain basin. The area has already endured climate-related increases in temperature and precipitation over the past 30 years and these influences are expected to grow throughout the 21st century. Natural resource agencies will benefit from knowing about the projected impacts of climate change on key ecosystem and species assemblages as provided in this report. We believe this report represents a significant contribution to the conservation community as they begin to plan and respond to the current and future impacts of climate change on the Lake Champlain Basin.

The mission of the Lake Champlain Ecosystem Team is to maintain and enhance the ecological integrity of the Lake Champlain watershed. This is accomplished by enhancing interdisciplinary cooperation and partnerships among federal, state and local conservation organizations and academic institutions and by facilitating biological resource conservation activities, exchanging information and seeking funding.

Sincerely,

Eric A. Howe, Ph.D.
Technical Coordinator
Lake Champlain Basin Program

William R. Ardren, Ph.D.
Senior Fish Biologist
Western New England Complex
U.S. Fish and Wildlife Service

*This endorsement represents the views of the Lake Champlain Ecosystem Team, as presented by its co-chairs Eric Howe and William Ardren, and does not necessarily represent the views of the Lake Champlain Basin Program or the U.S. Fish and Wildlife Service.

A report prepared for The Nature Conservancy by
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I. Summary

The Champlain Basin has a long and varied environmental history that includes the slow climatic oscillations of Ice Ages, the comings and goings of countless species, and a period roughly 10,000 years ago when the valley was an arm of the Atlantic Ocean. Today, the region is entering a new phase of its history in which humans play a major role in determining what lives here and even what the local weather is like. Significant climatic changes, which most scientists agree are now driven primarily by human-generated greenhouse gases, are already under way in the Champlain Basin:

- Mean annual air temperatures warmed by 2.1°F (1.2°C) between 1976 and 2005, with the most significant seasonal warming during summer and autumn.
- Total annual precipitation during that time period was approximately 3 inches greater than it was during the preceding 8 decades.
- Freeze-up on Lake Champlain is happening two weeks later than in the early 1800s—that is, in the increasingly rare winters when ice covers the main body of the lake at all.

All credible projections indicate that temperatures here will become increasingly warmer on average for the rest of this century, even if greenhouse gas emission rates are greatly reduced.

However, climate is not the only factor to consider in predicting future ecological change in the Champlain Basin; how people influence the landscape will be at least as important. The goal of this report is to assess the patterns and ecological consequences of recent and future climatic change in the Champlain Basin, and to use that information to stimulate further research, informed planning, and adaptive management that can help residents of the watershed to maintain its diverse natural communities in a warmer future. The report focuses, in particular, on species and habitats of Lake Champlain and its associated shorelines, wetlands and tributaries.

Lake Champlain is one of the largest lakes in North America, and its watershed supports a high level of biodiversity. It is not yet as profoundly altered by invasive species as the Great Lakes, though several nonnative plant and animal species have recently arrived, and more are likely to arrive in the near future. Ongoing climate change is likely to affect many of these organisms and their habitats in important ways.

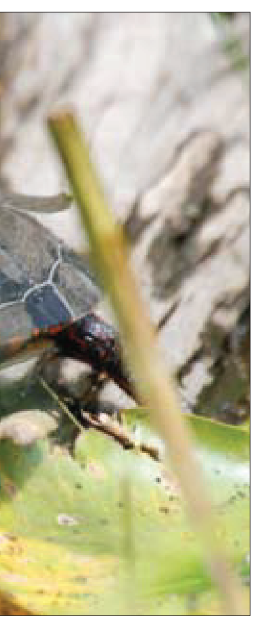
Predictive models point toward warmer and possibly wetter conditions in the northeastern United States in coming decades, but the exact magnitudes of those changes remain uncertain. We do not yet know, for example, how much greenhouse gas emissions will increase, and different climate models generate somewhat different predictions. Under such circumstances, the most effective strategy is to prepare for a realistic range of possible climatic futures rather than to focus too heavily on any particular one. In this report, we bracket that range by considering two 21st century carbon emissions scenarios described by the Intergovernmental Panel on Climate Change (IPCC, 2007): the relatively low-emissions scenario "B1" and the extreme scenario "A2." At present the world is on track to follow the A2 scenario unless greenhouse gas production is greatly reduced in the near future.

Most climate modeling to date has been global and regional in scope, but to be of the most practical use for watershed management such information must be more place-based and contextual, focusing on local scales. This report draws on peer-reviewed scientific literature, well-documented datasets, and decades of accumulated per-

sonal knowledge from scientists and natural resource professionals who study and manage species and ecosystems in the Champlain Basin. We also use a new Web-based forecasting tool, Climate Wizard, to generate watershed-scale climate projections specifically for the basin.

The weight of current scientific evidence presented in this report suggests that by the end of the 21st century:

- The range of anticipated additional warming is 1–6°F under a moderate emissions scenario and 6–11°F under an extreme (current path) scenario.
- The basin could receive as much as 10–15% (ca. 4–6 inches) more precipitation in an average year, with heavy storm events becoming more frequent.
- A larger fraction of winter precipitation is likely to fall as rain rather than as snow.
- Because of the warming, there will be less lake and river ice in winter and less snowpack in the watershed.
- Rising surface water temperatures may increase the stability and duration of warm-season stratification in Lake Champlain, potentially making the lake more susceptible to nuisance phytoplankton blooms and low-oxygen (“hypoxic”) conditions.



We have identified six key aquatic ecosystems and species assemblages that are potentially vulnerable to climatic change, drawing on The Nature Conservancy’s 2005 Conservation Action Plan for Lake Champlain (Munno et al., 2005):

1. Tributary systems

2. Wetlands and shorelines

3. Littoral zone

4. The deep lake

5. Native fish assemblages

6. Freshwater mussel assemblages

Changes in temperature, precipitation and ice cover do not necessarily have adverse impacts on all species and habitats directly, but the long-term direction of change in these factors is likely to magnify existing stressors on the conservation targets, including:

- **stormwater runoff and phosphorus pollution**
- **erosion and sedimentation**
- **nuisance cyanobacterial blooms**
- **deep-water hypoxia**
- **susceptibility to certain invasive species**
- **toxicity of pollutants such as methylmercury**
- **altered fish community composition and dynamics**
- **possibly lower and/or warmer stream conditions in summer and autumn**

The interaction of climate change with fragmented and heavily settled and farmed landscapes in the Champlain Basin has the potential to reduce lake and river water quality significantly and, in turn, the diversity and viability of local habitats and species.

Yet there are steps that scientists, managers and policymakers can take now in anticipation of such changes. Dealing proactively with climate change will ultimately be less costly and more effective than trying to respond after the fact.

The final section of this report provides a list of recommendations for further research as well as mitigation and adaptation policies and practices for the watershed. In general, it is a call to strengthen existing regulatory and funding mechanisms rather than a call for new programs, because dealing with altered climatic settings will not require an entirely new suite of conservation tools. Many of the best adaptation strategies are already known and in use in the Champlain Basin: land conservation, river corridor and floodplain protection, pollutant control, water quality regulation, species monitoring, prevention of alien species invasions, best management practices, and the maintenance of vegetated lake and stream shoreline “buffer” zones. These time-tested and effective strategies will become even more important as natural resource and planning professionals seek to minimize threats that could be exacerbated by coming changes in 21st century climate.

II. Introduction

Despite the pervasiveness, importance and long-lasting nature of modern climate change, most natural resource management plans for the Champlain Basin do not yet take full account of it. Many of these blueprints were developed before there was widespread scientific consensus that human-driven climatic changes will present serious challenges to local ecosystems and communities for the foreseeable future. However, climate change is already having both subtle and readily visible effects on the basin, and more impacts are likely to come in the decades ahead. Anticipating these impacts and acting far enough in advance of them to mitigate or adapt to them effectively will require deliberate, well-informed and proactive management.

The goal of this study is to assess the patterns and ecological consequences of recent and future climate change in the Champlain Basin and to help stimulate research and management practices that can most effectively support diverse species assemblages and habitats in a warming future.

Physical setting

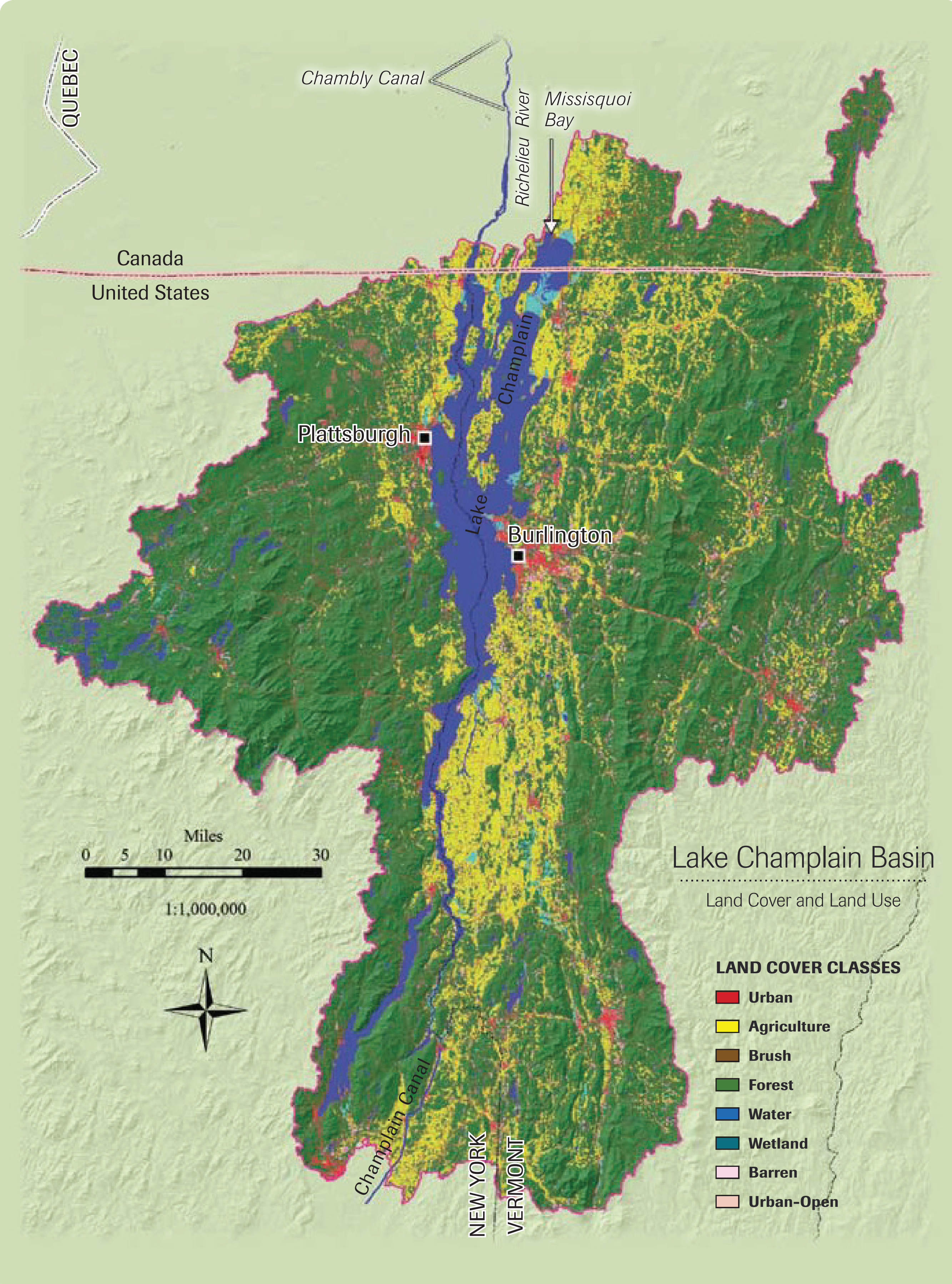
Lake Champlain is 120 miles (193 km) long from north to south, and up to 12 miles (19 km) wide (interrupted by a breakwater; the greatest open-water width is 8 miles), with a surface area of 435 square miles (1127 sq. km). Its maximum depth is 400 feet (122 m) and average depth is 64 feet (19.5 m) [LCBP, 2004; J.E. Marsden, personal communication]. Lake Champlain drains to the north via the Richelieu River into the St. Lawrence River; the Chambly Canal, opened in 1843, bypasses rapids on the Richelieu to allow navigation. The lake has also been connected since 1823 to the Hudson River via the Champlain Canal.

Lake Champlain's multi-state and bi-national watershed encompasses 8,234 square miles (21,326 sq. km), 56% of which lies in Vermont, 37% in New York and 7% in Quebec (Map 1). A little more than a half million people live within its boundaries. Dozens of rivers and streams, in eight major drainages, flow into Lake Champlain, carrying 90% of the water that enters the lake (LCBP, 2008). Excessive phosphorus loads causing "cultural eutrophication" (undesirable growth of aquatic plants and/or phytoplankton) come primarily (95%) from nonpoint sources, with 46% of that from developed land and a little more than a third from agricultural land (LCBP, 2008; Smeltzer et al., 2009). The watershed:lake area ratio is 18:1, and 78% of the basin is composed of natural cover, which includes forests, wetlands and open water.

As shown in a later section of this report, inter-annual fluctuations in lake levels are strongly influenced by changes in regional precipitation, which today averages more than 40–45 inches (100–115 cm) per year in the mountains and 30–35 inches (75–90 cm) at low elevations. Lake levels typically vary on the order of 3–6 feet (ca. 1–2 m) over the course of a year, with a mean elevation of 95.5 feet (ca. 29 m) above sea level. Observational records from Burlington, VT, show seasonal maximum levels occurring in April–May and minimum levels occurring in September–October (NOAA, 2006). Precipitation tends to be most abundant in summer and autumn, so the April–May lake level highs reflect snowmelt and runoff from frozen or water-saturated soils more than direct deposition in spring, and the autumn lows may largely reflect reduced soil moisture and greater evaporative and transpiration losses during the warmer months. The historical range of lake levels spans a record high of 101.9 feet above mean sea level, measured in April 1993, and a low of 92.6 feet, measured in December 1908 (USGS, 2006).

Map 1. The Lake Champlain watershed encompasses 8,234 square miles: 56% is located in Vermont, 37% in New York and 7% in Quebec. Including forests, wetlands and open water, 78% of the watershed is natural cover. Agricultural land accounts for 16% of the watershed. Six percent is developed land.

Data Source: Land Use / Land Cover for the Lake Champlain Basin, circa 2001, University of Vermont, Spatial Analysis Lab. Map by D. Farrell, The Nature Conservancy, Vermont Chapter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Richelieu River
Missisquoi Bay
Canada
United States
Lake Champlain
Plattsburgh
Burlington
Miles
0 5 10 20 30
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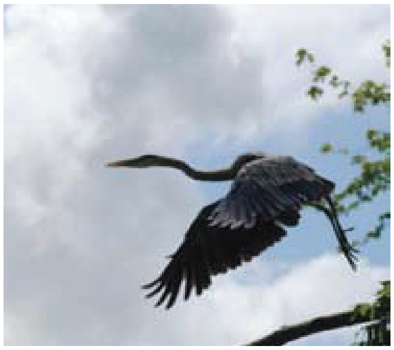
N
Champlain Canal
NEW YORK
VERMONT
Lake Champlain Basin
Land Cover and Land Use
LAND COVER CLASSES
Urban
Agriculture
Brush
Forest
Water
Wetland
Barren
Urban-Open

Paddler on Lake Champlain © Seth Lang Photography

APPROACH

The scientific community agrees, with a high level of confidence, that human-generated greenhouse gases are accumulating in the atmosphere and are causing significant changes in the global climate system, particularly during the last several decades (IPCC, 2007). Temperature and precipitation in the Champlain Basin have both increased significantly since the early 1970s, and similar changes can reasonably be expected to occur in the future as well.



Great blue heron © Elizabeth Collins

In this report, we examine what those changes have been, what they are likely to be and how they may affect physical and biological attributes of the watershed, with an emphasis on aquatic species and ecosystems. Also at issue is how to develop methods of natural resource stewardship that take into account expected shifts in temperature and precipitation. This document therefore offers basic insights into how key species and habitats within the Champlain Basin are likely to respond to future climatic changes, and how such information can help those involved in natural resource management, planning and regulation to make effective preparations for those changes.

III. Methods

Climate, or the "climate normal" for a particular location, is typically defined as the average weather conditions over a period of 30 years, a sliding window of time that is updated from year to year. For the purposes of this report only two climatic factors—temperature and precipitation—will be discussed in detail. Other factors, such as wind and humidity, are potentially important as well, but they are less thoroughly documented and are beyond the scope of this study. Table 1 summarizes mean climatic conditions in the Champlain Basin between 1976 and 2005, based upon records from eight weather stations in the watershed.

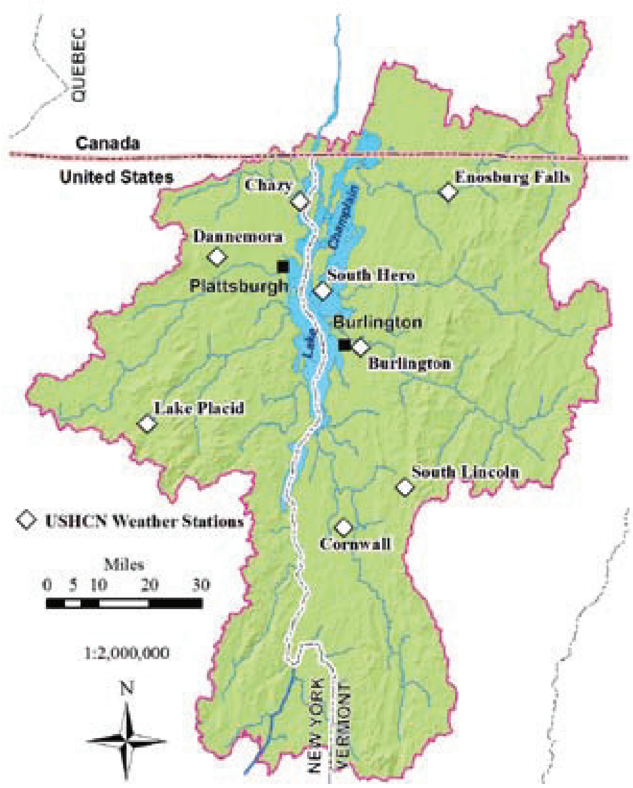
Table 1. Temperature and precipitation in the Champlain Basin 1976–2005, averaged from eight USHCN weather stations in the watershed.

Champlain Basin 30-yr*	Annual (J-D)	Winter (DJF)	Spring (MAM)	Summer (JJA)	Autumn (SON)
Mean T (°F)	**44.5**	**19.2**	**42.2**	**65.8**	**46.4**
Mean P (in.)	**37.5**	**6.3**	**8.6**	**11.9**	**10.8**

** J-D is a full year, January through December; DJF is December, January, February; MAM is March, April, May; JJA is June, July, August; SON is September, October, November.*

In order to determine how climatic patterns within the Champlain Basin have changed in the recent past, we analyzed local weather records from the United States Historical Climatology Network (USHCN). Most weather datasets contain flaws due to gaps in coverage, changes in instrumentation, and inconsistencies in the number and timing of daily observations. Simply using their raw data for analysis therefore produces spurious results. The USHCN performs standardized adjustments that fill temporal gaps and that compensate for changes in methodology, urban development and other such biases (Menne and Williams, 2005, 2009; Menne et al., 2009). The database currently includes records from more than 1,200 stations in the lower 48 states, and it is produced and updated at the National Climatic Data Center in conjunction with the Department of Energy's Carbon Dioxide Information Analysis Center.

The eight USHCN stations located within the Champlain Basin are indicated on Map 2 and are also listed in Table 2, along with mean annual temperatures and total annual precipitation measured at each station for two time frames: the entire period of record (1895–2008) and a recent 30-year time interval (1976–2005) that has been selected for comparison to previous studies in the region. For our analyses, the records were averaged together to produce mean values for the basin as a whole. Trends were calculated through linear regression (Press et al., 1986) with the SigmaPlot™ program, using p-values of up to 0.05 to indicate statistical significance.



Map 2. The eight United States Historical Climatology Network weather stations located in the Champlain Basin.
Map by D. Farrell, The Nature Conservancy, Vermont Chapter

Table 2. Historical temperature and precipitation data from the 8 USHCN weather stations in the Champlain Basin.

STATION	Station elevation (feet)	Mean T* 1895-2008 (˚F)	Mean T 1976-2005 (˚F)	Mean P* 1895-2008 (in./yr.)	Mean P 1976-2005 (in./yr.)
VERMONT					
Burlington	330	45.2	45.5	33.6	35.7
Cornwall	345	45.3	45.0	33.5	36.0
Enosburg Falls	420	42.3	43.1	40.7	42.0
South Hero	110	53.3	53.8	30.1	32.4
South Lincoln	1341	41.3	42.0	42.5	45.4
NEW YORK					
Chazy	157	43.3	44.1	28.5	28.4
Dannemora	1340	41.1	42.0	36.6	40.1
Lake Placid	1940	39.9	40.1	39.1	40.3
CHAMPLAIN BASIN (combined)		44.0°F	44.5°F	35.6"	37.5"

*T = temperature, P = precipitation

Predicting future climate change on a local scale

Climate models that simulate complex interactions among air, ocean and land masses can provide useful insights into the general direction of future climate change. Such models allow us to predict basic air temperature and precipitation patterns on a broad, global scale (IPCC, 2007), but a growing number of investigations are now also increasing the resolution of those predictions to regional and local geographic scales.

The projections of future climatic conditions within the Champlain Basin presented in this report were generated through Climate Wizard, a new analytical tool developed by the Nature Conservancy, the University of Washington, and the University of Southern Mississippi (http://www.ClimateWizard.org) [Girvetz et al., 2009]. Climate Wizard is a Web-based analysis engine that allows users to study climatic data that have been downscaled from coupled atmosphere-ocean global climate models (AOGCMs). Sixteen AOGCMs are available to provide a range of possible outcomes, and users can analyze absolute and percentage changes in annual, seasonal or monthly climate conditions in graphic or map form. With the Climate Wizard custom analysis tool, a user can define a relatively small geographic area of interest and conduct site-specific analyses using both historical data and possible future conditions that are based on low (B1), moderate (A1B) and high (A2) carbon emissions scenarios. The Champlain Basin was selected for such custom analysis in this report, and each mapped grid cell in the model simulations of climatic conditions in the watershed measured approximately 14 x 10 kilometers (D. Farrell, personal communication).

IV. Findings: Temperature, precipitation and physical changes

A. Air temperatures: past and future

The planet as a whole warmed by 1.3°F (0.7°C) during the 20th century, with human-generated greenhouse gases driving most of that change since the 1970s (IPCC, 2007). However, the global trend does not necessarily represent climatic changes that have occurred at local scales; temperatures in some areas of the world have warmed faster or cooled slightly on average during the last half century. In our region, the Northeast Climate Impacts Assessment (NECIA) and other sources have found that the northeastern states as a whole warmed by 1.4°F (0.8°C) over the course of the 20th century (Frumhoff et al., 2007; Hayhoe et al., 2007; Jacobson et al., 2009). Between 1970 and 2000, regional average temperatures rose more rapidly (ca. 1.3°F in 30 years), with the bulk of the warming occurring in winter. By the end of this century, mean temperatures in the Northeast are expected to rise another 5–10°F (ca. 3–5°C), depending upon the models and emissions scenario under consideration (Hayhoe et al., 2007).

Regional warming here has been slightly faster than the global average, and the overall shapes of the rising temperature curves in most of the Northeast, including the Champlain Basin, differed somewhat from the global pattern during much of the last century (Figure 1). This highlights the importance of considering smaller geographic scales in addition to globally averaged conditions, and it also means that the selection of appropriate time frames for analysis must be undertaken with care.

Both the global and regional temperature records show a temporary high in the mid-20th century followed by a decade or so of cooling before the long-term rising trend resumed in the 1970s. However, the mid-century high occurred later here (ca. 1950s) than it did for the planet as a whole (ca. 1940s). Because of that pattern, records of temperatures in the Northeast that begin in the 1950s can produce surprisingly weak linear warming trends or even slight overall cooling at sites where the mid-century peak has not yet been exceeded by today's rising temperatures. Conversely, shorter time windows that begin in the relatively cool 1960s produce rising trends that are steeper than the century-scale average. How does one most reasonably select the proper time frame for determining how climate has changed in the recent past?

For this study, we selected the 30-year, 1976-2005 interval for most of our historical analyses for three reasons. First, 30 years is the standard period used for calculation of a region's current climate. Second, it represents a time frame that has been analyzed elsewhere in the region, so it provides opportunities for comparison. And finally, it represents conditions that have been clearly influenced by greenhouse gas buildups. Before the 1970s, additional factors such as solar variability and aerosol concentrations more strongly disrupted the global warming trend, but since then, only greenhouse gas concentrations have risen in concert with temperature (IPCC, 2007). Because greenhouse gas concentrations are expected to rise further in coming decades, the climatic record of the 1976–2005 interval provides a useful guide to the general nature of changes that are soon to come.

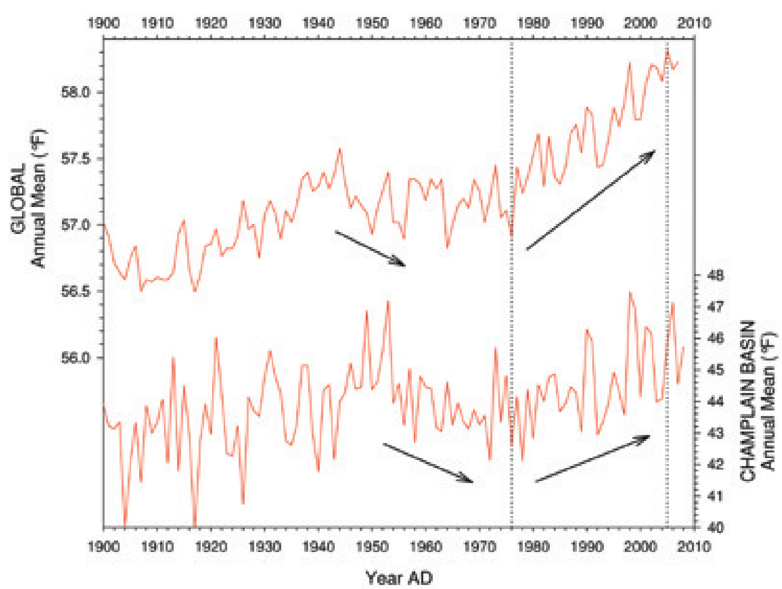
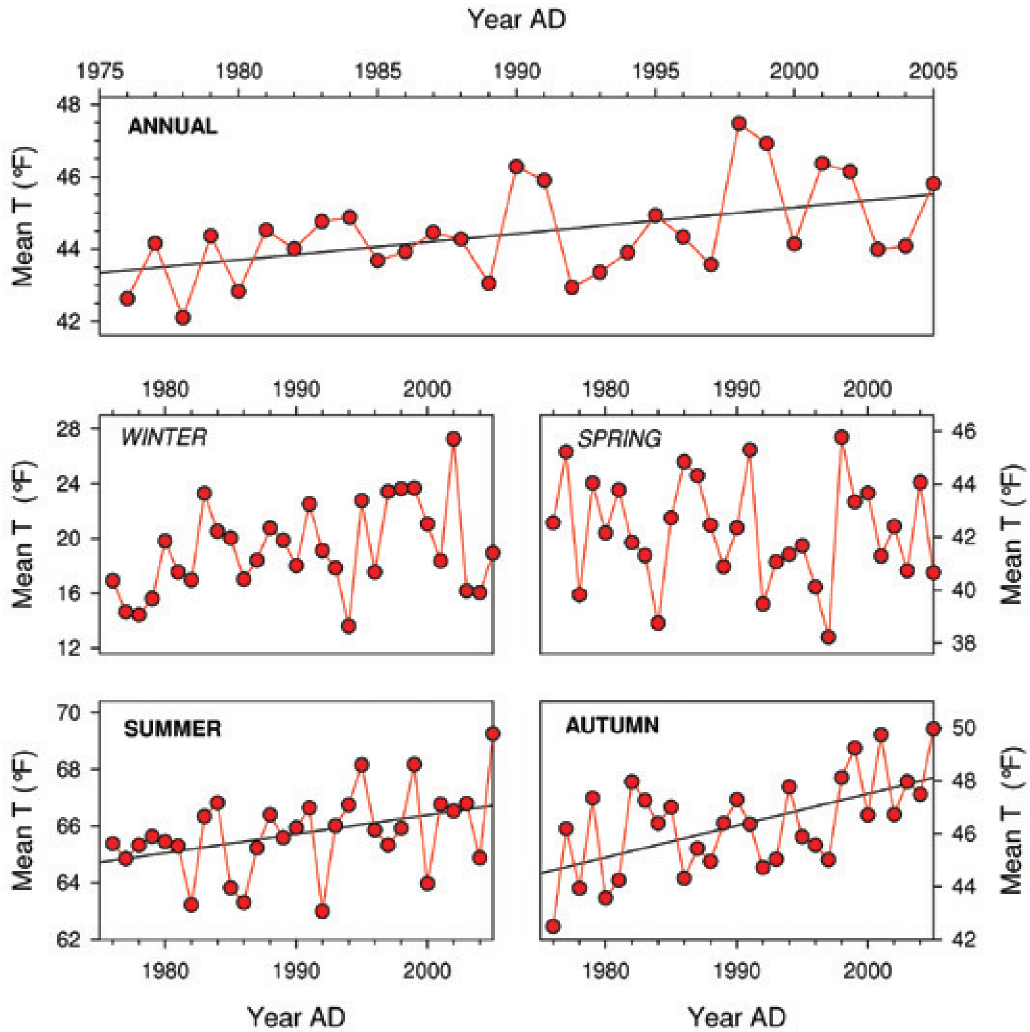


Figure 1. Global and Champlain Basin temperatures, 1900–2008. Dotted lines bracket the 1976-2005 time interval. Arrows indicate general directions of change over selected time intervals. Note the difference in timing of the mid-century warm periods in the two records; the global peak occurred a decade earlier than the one in the Champlain Basin.



In the Adirondack uplands, which mark the western border of the Champlain Basin, mean annual temperatures rose by 1.5°F (0.8°C) between 1975 and 2005, at a rate similar to that of the Northeast as a whole (Stager et al., 2009). Statistically significant warming occurred in June (+2.8°F, 1.6°C) and September (+4.7°F, 2.6°C), but no significant linear trends were found in the other months. December did display a prominent warming tendency, but it was statistically indistinguishable from random variability in that analysis.

In this study, we find that the Champlain Basin has also warmed since the mid-1970s. A statistically significant rise of 2.1°F (1.2°C) occurred between 1976 and 2005 (Figure 2), which suggests that the basin is warming even faster than the Adirondack uplands and the rest of the Northeast. In summer and autumn, respectively, significant warming of 2.0 and 3.6°F (ca. 1 and 2°C) occurred here, but spring temperatures displayed no reliable trend. Winter displayed a large increase (3.7°F, 2.1°C) but the linear trend was not statistically significant at the 5% level (though it was significant at the 10% level). This is in apparent contrast to the aforementioned strong winter warming that NECIA has reported for the northeastern states, but it is consistent with other recent analyses of weather records in northern New York and northwestern Vermont (Dello, 2007; Stager et al., 2009). These differences between local patterns and those found regionally and globally, as well as the variability of the trends over time, again illustrate the need for current, place-based analyses such as those presented here.

Figure 2. Temperatures averaged from eight USHCN weather stations in the Champlain Basin, arranged by season, 1976–2005. The only statistically significant linear warming trends were in the annual, summer and autumn records.

Sixteen AOGCMs were available to us for advanced watershed-scale analysis through Climate Wizard, which included the smaller set of models used previously by NECIA for their regional analysis of the Northeast (full descriptions of all models are archived on the Climate Wizard Web site). Differences in their design cause these models to produce a diversity of projections, especially for precipitation and for variations among seasons, but the general direction of temperature change is consistent among all of them. Table 3 summarizes the predictions for 21st century warming in the Champlain Basin produced by each of the models for low (B1) and high (A2) emissions scenarios.

Table 3: Temperature changes in the Champlain Basin projected by 16 atmosphere-ocean global climate models through Climate Wizard, covering the period 2010 to 2099. Left: moderate B1 emissions scenario. Right: extreme A2 emissions scenario. Shaded cells indicate the season with the greatest statistically significant change ($p \leq 0.05$). Dashes indicate no significant change. (Special thanks to C. Zganjar.)

B1 EMISSIONS SCENARIO					
MODEL	Annual (°F)	Winter (°F)	Spring (°F)	Summer (°F)	Autumn (°F)
BCCR-BCM2.0	3.2	2.8	3.7	4.6	2.0
CGCM3.1(T47)	4.1	5.0	3.4	3.4	4.7
CNRM-CM3	3.1	3.3	3.1	3.4	2.4
CSIRO-Mk3.0	3.2	4.1	3.0	3.0	2.3
GFDL-CM2.0	4.3	7.0	3.9	3.6	3.0
GFDL-CM2.1	3.5	3.1	2.8	4.3	3.9
GISS-ER	1.1	-	-	1.4	-
INM-CM3.0	3.1	3.5	2.7	2.4	3.5
ipsl_cm4	5.8	5.0	6.0	5.7	6.1
MIROC3.2 (medres)	5.3	5.9	5.5	5.8	4.1
ECHO-G	5.7	7.3	3.8	5.1	6.4
ECHAM5/MPI-OM	5.4	6.0	3.9	6.0	5.8
MRI-GCM2.3.2	3.0	3.1	2.8	2.8	3.3
NCAR-CCSM3	1.2	-	2.2	-	-
NCAR-PCM	2.8	2.7	3.3	2.3	2.5
UKMO-HadCM3	6.2	6.2	5.4	6.8	6.1

A2 EMISSIONS SCENARIO					
MODEL	Annual (°F)	Winter (°F)	Spring (°F)	Summer (°F)	Autumn (°F)
BCCR-BCM2.0	7.1	8.2	5.9	6.6	7.8
CGCM3.1(T47)	9.3	11.0	9.3	8.5	8.6
CNRM-CM3	8.0	9.2	6.7	7.7	8.6
CSIRO-Mk3.0	7.4	11.6	5.9	5.9	5.9
GFDL-CM2.0	9.6	10.7	8.3	10.4	9.2
GFDL-CM2.1	7.4	7.9	7.1	7.5	6.8
GISS-ER	6.1	7.7	6.5	5.1	5.2
INM-CM3.0	7.1	7.7	6.6	7.1	7.0
ipsl_cm4	11.0	11.2	11.3	9.9	-
MIROC3.2 (medres)	11.1	12.9	12.0	9.6	10.0
ECHO-G	9.0	9.7	7.7	9.2	9.5
ECHAM5/MPI-OM	8.7	9.6	8.8	8.4	8.3
MRI-GCM2.3.2	6.8	8.2	6.2	6.1	6.5
NCAR-CCSM3	9.0	9.9	8.2	10.1	8.0
NCAR-PCM	6.4	8.3	5.9	5.5	5.9
UKMO-HadCM3	10.0	8.7	8.7	12.7	9.6

In addition to summarizing future projections, we also screened the UKMO-HadCM3, PCM, BCCR-BCM2.0 and CGCM3.1 models by testing their ability to reconstruct known climatic conditions in the past, a process known as "hind-casting" or "back-casting." None of the models provided perfect reconstructions of the past five decades, over- or underestimating the magnitudes of trends and often misrepresenting patterns of short-term variability, but in general the models more accurately reproduced temperature than precipitation.

All of the models predicted a trend of rising annual mean temperatures throughout the rest of this century, although the magnitudes of change varied among models and emissions scenarios. Presumably, that unanimity in the basic prediction of future warming largely reflects the well-documented influence of rising greenhouse gas concentrations on global atmospheric temperatures. In the B1 scenario, emissions of heat-trapping gases are expected to be much lower than those in the A2 scenario, and therefore the modeled warming projections for B1, ranging close to 1–6°F (0.5–3.3°C), are lower than those for A2, which range close to 6–11°F (3.3–6.1°C).

The history of warming in the Champlain Basin during the 1976-2005 interval lends support to the approximate 6–11°F range of 21st century warming that is produced through most of the Climate Wizard model runs for the A2 emissions scenario. Although A2 represents an extreme situation relative to the B1 case, it represents a situation in which atmospheric CO_2 accumulation continues at gradually accelerating rates over the course of this century. Because the Champlain Basin has already experienced a warming of 2.1°F (1.2°C) during the last three decades, it is therefore reasonable to conclude that the A2 path might produce an additional warming close to what most models suggest by century's end; simply continuing the recent 30-year trend steadily for another nine decades would raise temperatures by another 6.3°F (ca. 3.5°C), within the modeled 6–11°F range that is predicted for the A2 scenario.

It is important, however, to remember that all projections of future trends come with the caveat that year-to-year fluctuations will also push temperatures well above or below the mean from time to time. Powerful short-term factors such as the North Atlantic Oscillation, shifts in stratospheric moisture content, volcanic eruptions and random movements of storm tracks will temporarily disrupt the more smoothly rising tide of greenhouse warming as they have always done in the past. As a result, changes from year to year will sometimes be more dramatic than the long-term trends and may even run counter to them for brief periods of time without negating the usefulness of those underlying trends for long-term climatic prediction.

Climatic "extremes" are also expected to become more common as the world warms (IPCC, 2007), but this does not necessarily mean that every aspect of variability will increase in the Champlain Basin. Record-breaking cold snaps, for example, may occur less often. Most of the thermal extremes might therefore appear in the form of record highs, which should naturally occur more often as the upper bounds of temperature variability rise along with the mean. Such changes could be experienced as increasingly frequent and memorable heat waves during the warmer months of the year and as deeper and/or more frequent thaws during winter.

In summary, mean annual temperatures in the Champlain Basin are likely to rise 1–11°F (roughly 0.5–6.1°C) by the end of this century, depending on which model simulation and emissions scenario is followed. One might also speculate that significant warming is most likely to occur during winter on the basis of three lines of reasoning. First, dominant winter warming is predicted for the Northeast and Champlain Basin by most, though not all, of the AOGCMs represented through Climate Wizard for the A2 scenario **(Table 3)**. Second, loss of cool, reflective snow and ice cover due to melting may tend to amplify winter warming in some locations, though the importance of this effect is likely to vary a great deal from site to site. And finally, winter weather in this region is strongly influenced by air masses that move down from higher latitudes where warming rates generally exceed the global average; the Champlain Basin might therefore be exposed to maximally warmed high-latitude air masses during the coldest periods of the year.

Such arguments, however, are only tentative, and when considering future climatic changes on a local scale it is wiser to anticipate a likely range of possibilities than to focus too heavily upon a single anticipated outcome. In addition, although the universal projection of annual-scale warming during this century is very likely to be correct, the consistency among climate model projections for seasonal-scale changes is much weaker **(Table 3)** due to inherent limitations in the ability of AOGCMs to simulate short-term climate conditions, especially on local geographic scales (Hayhoe et al., 2007; Schiermeier, 2010). Furthermore, because we do not yet know how greenhouse gas emissions will change in the future, we cannot be sure of exactly how much temperatures will rise, only that the general direction of change will be that of warming throughout the present century. The model simulations presented here nonetheless allow us to estimate the range of annual-scale warming in the Champlain Basin that is most reasonable to expect and prepare for.

B. Precipitation: Past and future

Precipitation is extremely variable in space and time, and future precipitation patterns are therefore more difficult to model and predict than temperature trends. However, broad-scale patterns of change are relatively easy to envision. As global warming continues, the amount and intensity of precipitation is expected to increase in much of the world as heat-driven atmospheric circulation systems strengthen, and as evaporation from warmer land and ocean surfaces raises the moisture content of the air (IPCC, 2007). NECIA predicted an increase of total annual precipitation in the Northeast by the end of this century, on the order of 10% or so (Frumhoff et al., 2007). In addition, more winter precipitation is expected to fall as rain rather than as snow as warming continues throughout this century (Frumhoff et al., 2007; Hayhoe et al., 2007).

Total annual precipitation in the Champlain Basin increased by about 3 inches during the early 1970s due to a rapid upward shift to a higher average baseline that has persisted to the present day **(Figure 3)**. But apart from this, there is little evidence of a direct correspondence between rising temperature and the amount of precipitation revealed

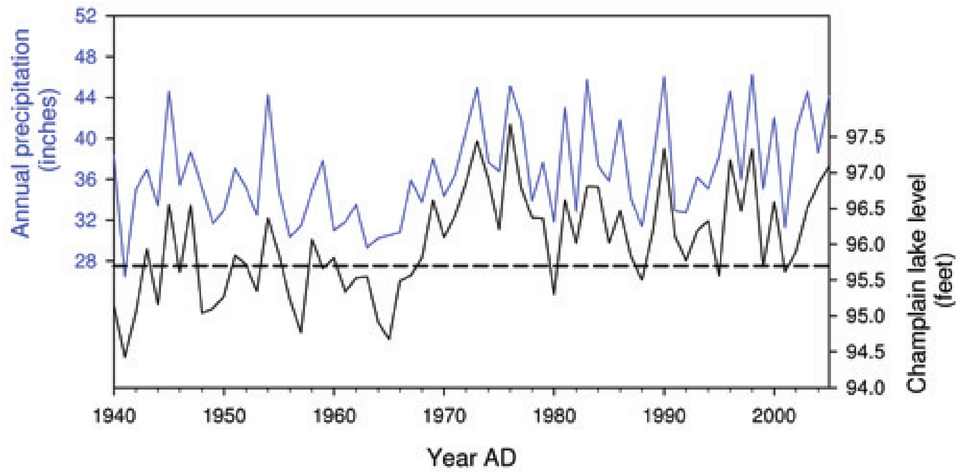
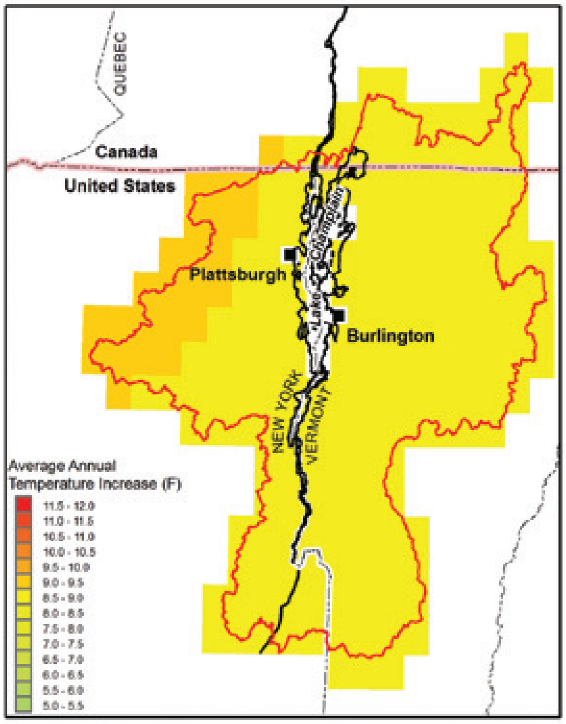


Figure 3. Total annual precipitation averaged from eight USHCN stations in the watershed vs. mean level of Lake Champlain since 1940. Note the prominent jump to higher precipitation and lake levels ca. 1970. The close similarity between these two records shows that precipitation is the dominant source of inter-annual variation in the level of the lake. The dotted line represents the average annual rainfall for the entire 20th century.

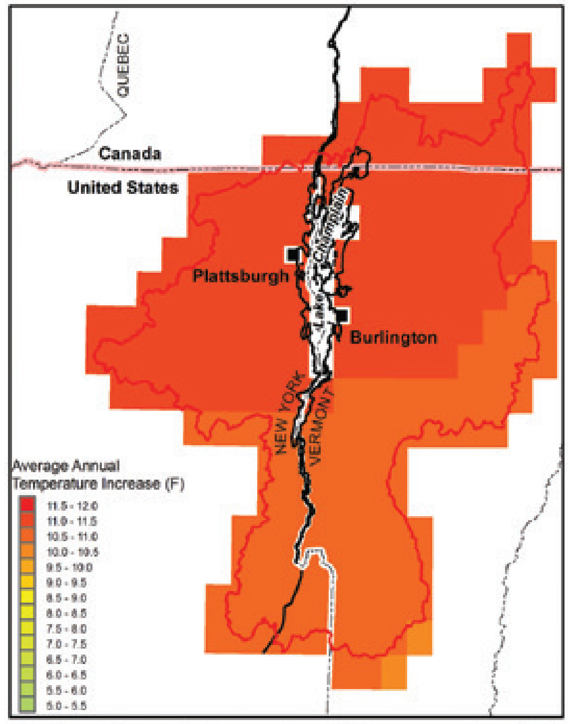
Table 4. Changes in total annual and seasonal precipitation in the Champlain Basin projected by 16 atmosphere-ocean global climate models through Climate Wizard, covering the period 2010 to 2099. Left: moderate B1 emissions scenario. Right: extreme A2 emissions scenario. Shaded cells indicate the season with the greatest statistically significant change ($p \leq 0.05$). Dashes indicate no significant change. Negative values indicate drying trend. (Special thanks to C. Zganjar).

B1 EMISSIONS SCENARIO					
MODEL	Annual (in.)	Winter (in.)	Spring (in.)	Summer (in.)	Autumn (in.)
BCCR-BCM2.0	-	-	3.0	-	-
CGCM3.1(T47)	-	-	1.44	-	-
CNRM-CM3	-	-	-	-	-
CSIRO-Mk3.0	-	-	-	-	-
GFDL-CM2.0	-	1.6	-	-	-
GFDL-CM2.1	-	-	1.6	-	-
GISS-ER	3.8	-	-	-	1.6
INM-CM3.0	-	-	-	-	-
ipsl_cm4	-	-	-	-	-
MIROC3.2 (medres)	5.5	-	2.1	-	-
ECHO-G	-	-	2.6	-	-
ECHAM5/MPI-OM	5.3	1.9	-	-	2.3
MRI-GCM2.3.2	-	-	-	-	-
NCAR-CCSM3	-	-	-	-	1.6
NCAR-PCM	-	-	-	-	-
UKMO-HadCM3	3.6	-	-	-	-

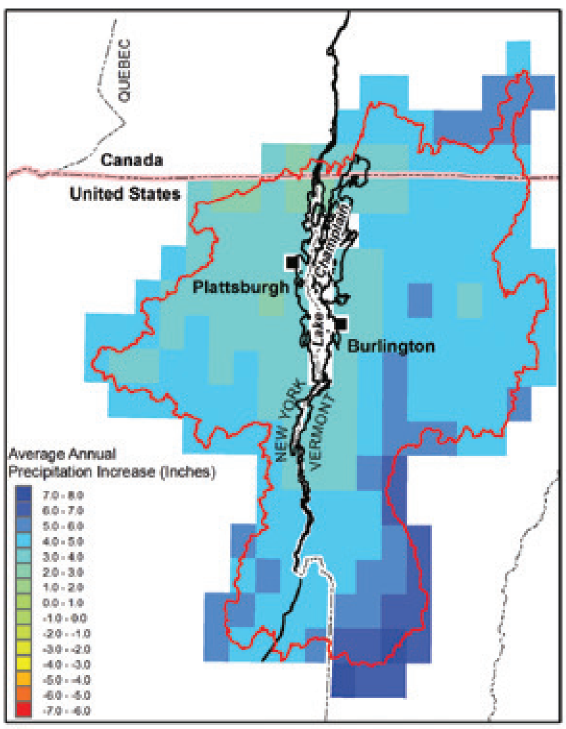
A2 EMISSIONS SCENARIO					
MODEL	Annual (in.)	Winter (in.)	Spring (in.)	Summer (in.)	Autumn (in.)
BCCR-BCM2.0	7.1	2.6	2.3	-	3.5
CGCM3.1(T47)	4.2	4.0	2.0	-1.4	-
CNRM-CM3	8.3	2.0	2.1	-	3.1
CSIRO-Mk3.0	5.9	-	-	-	2.0
GFDL-CM2.0	-	1.6	-	-2.2	-
GFDL-CM2.1	5.0	-	-	-	2.3
GISS-ER	9.9	2.4	3.9	1.7	1.8
INM-CM3.0	-	-	-	3.1	-
ipsl_cm4		-	-	-1.7	-
MIROC3.2 (medres)	-4.0	-	-	-2.3	-2.6
ECHO-G	4.4	2.2	3.4	-	-
ECHAM5/MPI-OM	4.9	-	-	-	2.5
MRI-GCM2.3.2	5.9	3.4	-	-	1.4
NCAR-CCSM3	4.6	2.4	-	-	-
NCAR-PCM	-	-	-	-	-
UKMO-HadCM3	4.0	2.0	-	-	-



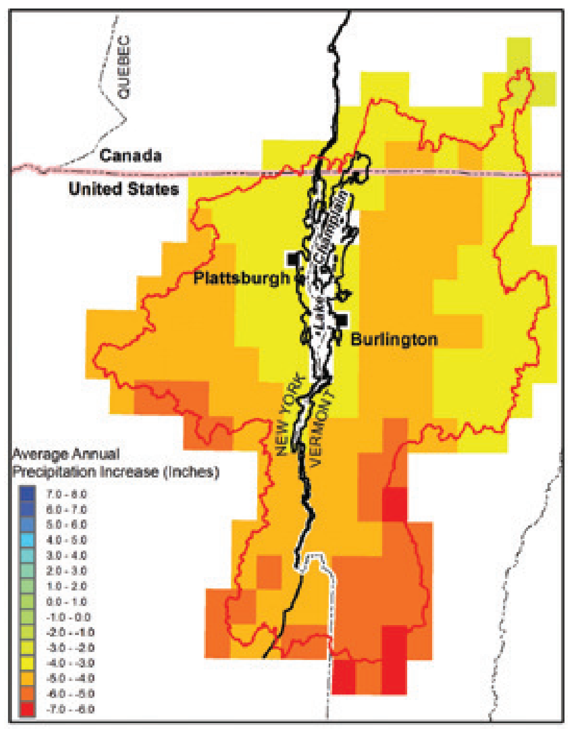
Predicted Change in Average Annual Temperature from 2010 to 2099--Model ECHO-G for Emissions Scenario A2.



Predicted Change in Average Annual Temperature from 2010 to 2099--Model MIROC3.2 (medres) for Emissions Scenario A2.



Predicted Change in Average Annual Precipitation from 2010 to 2099--Model ECHO-G for Emissions Scenario A2.



Predicted Change in Average Annual Precipitation from 2010 to 2099--Model MIROC3.2 (medres) for Emissions Scenario A2.

Map 3. Anticipated changes in temperature and precipitation between 2010 and 2099 AD in the Champlain Basin under the A2 emissions scenario, as projected by the ECHO-G and MIROC3.2 (medres) models. While all 16 climate models project warming trends under low or high future emissions scenarios (two models illustrated by maps a. and b.), modeled projections for precipitation are divergent (two models illustrated by maps c. and d.). Maps by D. Farrell, The Nature Conservancy, Vermont Chapter in the local weather records. There has been no apparent trend towards wetter or drier conditions in any season of the year since that shift upward during the early 1970s, despite the concurrent warming trend. A similar pattern also exists in precipitation and river discharge records from the Adirondack uplands (Stager et al., 2009), which occupy the western rim of the Champlain Basin.

Most, but not all, of the AOGCMs available through Climate Wizard predict little or no significant change in total annual precipitation in the Champlain Basin by century's end for the moderate B1 scenario. However, in the extreme A2 scenario, the majority of expected annual totals range between 4 and 6 inches higher than today (Table 4). Even more than with temperature, the amount of projected change within seasons varies a great deal between models.

The accuracy of these forecasts is impossible to ascertain in advance, but none of the four models tested through hind-casting were able to reconstruct the last five decades of precipitation history satisfactorily. All failed to reproduce the dry period of the 1960s, for example, none recreated the 1970s increase correctly, and the seasonal predictions listed in Table 4 vary too much to warrant much trust in any of them singly. This kind of problem is typical of many such models, which are apparently not yet capable of generating accurate, detailed predictions of long-term precipitation variability on local scales (for further discussion see: Frumhoff et al., 2007; Hayhoe et al., 2007; Sarewitz, 2010; Schiermeier, 2010). We are therefore far less certain of what the future holds for the Champlain Basin in terms of precipitation than we are for temperature.

However, the weight of evidence from climatological principles and modeling studies does suggest roughly 10–15% wetter conditions by 2100 if we follow a "non-intervention" A2 scenario (Frumhoff et al., 2007; Hayhoe et al., 2007). Furthermore, most of the AOGCMs used in this and previous studies show precipitation increasing more rapidly after mid-century, unlike the fairly steady warming trend that is consistently anticipated for the coming decades.

Split Rock shoreline on Lake Champlain © Carl Heilman II

Extreme precipitation

NECIA predicted that rainfall will become more intense and that periods of heavy rainfall will become more frequent in the Northeast during this century (Frumhoff et al., 2007). It also predicted that, under most emissions scenarios, the frequency of two-day periods with heavy downpours will increase by 8% by mid-century and 12–13% by 2100 AD. An elevated frequency of storms has already been reported for the 1980s and 1990s throughout the Northeast (Frumhoff et al., 2007).

Such analyses have yet to be performed for the entire Champlain Basin, but data from the Lake Placid weather station in the Adirondack sector of the watershed show that the mean number of storm events depositing more than 2 inches of precipitation within 48 hours doubled from 0.8 events per year in the early and mid-1900s to 1.5 per year after total annual precipitation increased in the early 1970s. This is probably not due to an increase in storm frequency but rather to an increase in the average amount of precipitation per event that pushed more storms above the 2-inch threshold; an analysis of weather records from eastern New York and western Vermont supports this interpretation (Dello, 2007).

Although extremely wet events have become more common in northern New York in recent decades, severe droughts have not. The frequency and duration of rain-free periods in summer did not increase significantly at the Adirondack station of Wanakena during the last century (Stager et al., 2009). Nonetheless, other sources have predicted an increase in the frequency of summer droughts of 1–3 month(s) duration in the Northeast under a high-emissions scenario, with an average of one such dry spell occurring per year by 2100 (Frumhoff et al., 2007; Hayhoe et al., 2007). Little or no change in drought frequency was expected under a low-emissions situation. Considering the difficulties in modeling precipitation accurately (Table 4, Map 3), however, any such predictions should be considered tentative.

In summary, it seems reasonable to expect total annual precipitation in the Champlain Basin to increase by as much as 10–15% by the end of this century, though the models conflict in those projections more than they do for temperature. A 10-15% increase could translate to 4–6 inches (10–15 cm) more precipitation on top of the 37.5 inches (95 cm) that now fall in an average year. Most of the models also predict that the bulk of that increase will happen during the second half of this century. In addition, as temperatures rise in winter, more cold-season precipitation will likely fall as rain rather than as snow, although the scale of any projected warming would not completely eliminate all snow and ice cover from the watershed by 2100.

Although total annual precipitation is expected to increase during this century under an A2 emissions scenario, according to most models, it remains unclear how that increase will be distributed throughout the year. Some models foresee winters becoming wetter while most do not, some expect summers to become drier while others anticipate more abundant or unchanged summer precipitation, and some restrict all significant change to autumn (Table 4). It is also possible that the average intensity and frequency of heavy precipitation events could increase over time, and that short-term summer droughts could become more frequent as evaporation rates increase with warming, even if summer rainfall does not change much. This lack of consensus among model projections is unfortunate because the seasonality of precipitation can be even more ecologically important than the total annual amount. For example, a major increase in summer droughts might threaten the survival of fish in local tributaries even if precipitation became more abundant during the other seasons of the year. On the other hand, the mild summer wetting trends predicted by two of the models represented through Climate Wizard might, in theory, help to ameliorate such problems.

Finally, it is important to keep in mind that all of the climatic trends described here will be accompanied by potentially large short-term fluctuations from year to year and decade to decade. It is therefore wiser to prepare for a wide range of climatic conditions in the future than to expect a single, smooth pattern of change.

C. Physical effects of climate change on Lake Champlain

ICE COVER

Many lakes in the Northeast have less ice cover in winter than they once did, most likely due to warming (Frumhoff et al., 2007; Hayhoe et al., 2007). Earlier ice-out dates are commonly reported in the region, but the dates of lake freeze-up in and around the Champlain Basin are changing much more rapidly in response to several factors. Recent warming here has been more pronounced in autumn than in spring, and ice-out dates are also strongly influenced by winter snow cover, which complicates temperature-driven trends. For example, freeze-up at Mirror Lake, in the upper Adirondack watershed, now comes 12 days later than it did in 1910, but spring ice-out arrives only two days earlier and that smaller change is not statistically significant (Figure 4) [Stager et al., 2009]. As of 1980 Lake George froze a week later than it did in 1910 but, again, showed no significant change in ice-out date. Similar changes have also been documented among the Adirondack upland lakes of the SUNY College of Environmental Science and Forestry's Huntington Wildlife Forest in Newcomb, NY (C. Beier, personal communication).

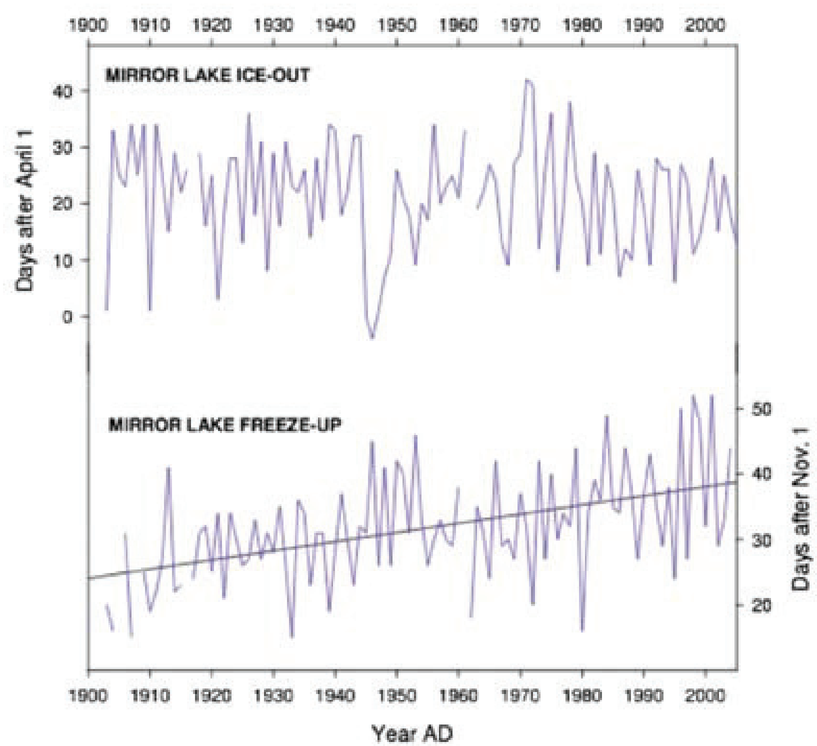


Figure 4. Changes in ice conditions on Mirror Lake, NY, 1903–2008, showing later freeze-ups but no statistically significant change in ice-out dates (after Stager et al., 2009).

But perhaps the most dramatic and widely recognized reduction of ice cover in the region has occurred on Lake Champlain. On average, the main body of the lake now freezes roughly two weeks later than it did during the early 1800s and about nine days later on average than in 1900—when it freezes over at all. The main lake remained open in winter only three times during the 19th century, but it did so 18 times between 1970 and 2007 (Figure 5; NOAA, 2007). A strong link between regional warming and ice cover shrinkage is further indicated by the short-term development of several ice-free winters during the warm 1950s, which was followed by a reduction in their frequency during the cooler intervening years before the 1970s warming trend resumed.

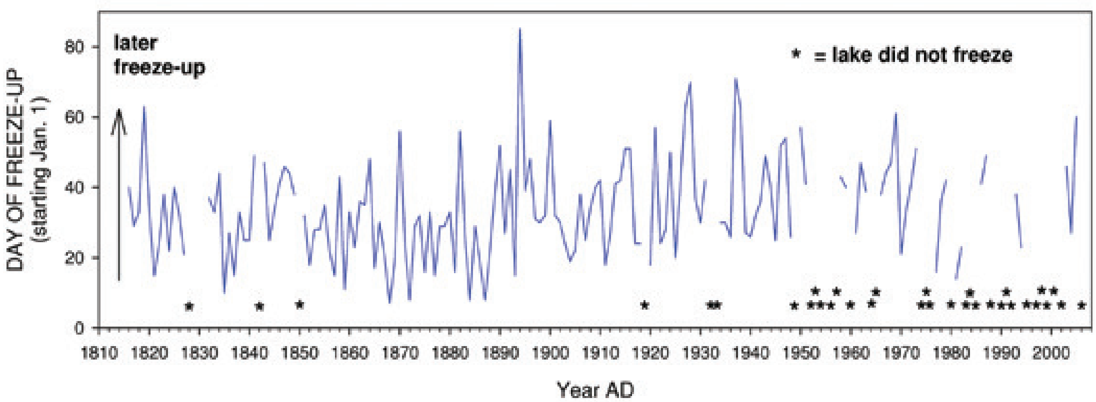


Figure 5. Lake Champlain freeze-up dates from 1816 to 2007. Asterisks indicate winters during which ice failed to cover the main body of the lake.

At present, open-water conditions in mid-winter are primarily limited to the main lake, and the shallower and more protected bays still freeze over every year. However, future warming is likely to make ice-free winters more common, to prevent more of the nearshore areas from freezing as well, and to reduce the longevity and thickness of ice when the lake does freeze over completely.

WATER TEMPERATURE

Many large northern-temperate-zone lakes have experienced dramatic warming during the past century, with summer surface-water temperature sometimes increasing more rapidly than overlying air temperatures (Hampton et al., 2008; Austin and Colman, 2007). This may seem counter-intuitive, but multiple factors can affect the rate of warming in a lake. Ice and snow cover shields underlying waters from local weather conditions and also reflects solar heat, keeping it from entering a lake. As a result, reduced ice cover and an earlier onset of summer stratification increase the period over which a lake heats up, thereby accelerating surface warming trends. In Russia's Lake Baikal, for example, mean surface water temperature in summer warmed 2.9°F (1.6°C) more than summer air temperature over the last 60 years (Austin and Colman, 2007).

Monthly surface temperatures in Lake Champlain measured at Colchester Reef between 2005 and 2007 (Vermont Monitoring Cooperative, 2010) showed a strong positive correlation (0.87) with monthly air temperatures. A moderately strong correlation with insolation (0.46) suggests that direct solar heating is also an important factor in the lake's heat budget. As regional warming continues and reflective ice cover shrinks during this century, Lake Champlain is therefore likely to warm as well.

STRATIFICATION AND MIXING

In the temperate zone, deep lakes such as Champlain normally become thermally stratified in summer as surface water (the "epilimnion") warms and becomes less dense than the underlying cooler water (the "hypolimnion"). In spring and autumn, when temperatures in the epilimnion and hypolimnion are similar, the lake mixes readily under the influence of wind and density currents. These two physical states—stratified and mixed—are associated with important ecological changes in the lake.

Under stratified conditions, buoyant cyanobacteria ("blue-green algae") such as *Microcystis* or *Anabaena* are often favored over other phytoplankton in the warm epilimnion, and the water is much cooler and denser in the isolated hypolimnion. In some lakes, especially in eutrophic ones, dissolved oxygen levels may also be reduced in the hypolimnion. Under twice-annual mixing conditions, a lake can "turn over" and erase stratification. At such times, oxygen is abundant at all depths, and nutrients from bottom sediments are carried up into the sunlit zone, where they can stimulate the growth of less buoyant phytoplankton such as diatoms and chrysophyte algae. The relationship between water column stability and cyanobacterial growth is well established in the ecological literature and is the basis of water quality control programs that use artificial water column mixing in small water bodies to inhibit such growth; for example, rapid changes in depth during artificial mixing have been shown to make the gas vacuoles in *Microcystis* collapse and lose their buoyant properties (Whitton and Potts, 2000). When and how a lake undergoes these seasonal changes can also profoundly affect fish and other animals by changing temperatures, oxygen concentrations and the kinds of food available.

To our knowledge, the most comprehensive records of temperature and dissolved oxygen profiles in Lake Champlain have been maintained by the Vermont and New York Departments of Environmental Conservation since 1992, but these contain potentially important informational gaps and, in particular, they do not fully cover the spring and fall overturn seasons. It is therefore unclear how the regional warming of the last three decades may have affected the thermal structure of the lake throughout the year. Ice cover reductions on Lake Superior are causing spring turnover there to begin half a day earlier per year, and the onset of autum turnover now comes two weeks later than it did 27 years ago (Austin and Colman, 2007). Observational records of water column temperatures are not complete enough to demonstrate whether the same thing is taking place in Lake Champlain; deep-water temperature measurements were apparently discontinued in the main lake after 2002, and sampling usually stops well before the autumn overturn begins.

Lake Champlain's thermocline also oscillates with the movement of an internal wave, or "seiche," that travels the length of the lake over four days with vertical amplitudes of 20 – 40 meters (Hunkins et al., 1998). Because the oscillation is primarily wind driven, it is unclear if a warmer epilimnion or potentially smaller hypolimnion would affect or be affected by the seiche (K. Hunkins, personal communication).

Nonetheless, continued warming and reductions of seasonal ice cover on Lake Champlain may well change the timing and duration of mixing and stratification episodes in the future, with stratified conditions becoming more prolonged between spring and autumn turnover periods. Such increased water column stability, in turn, could increase the risk of falling oxygen concentrations in the hypolimnion if cultural eutrophication reduces lake water quality in the future. Fortunately, there is no obvious sign of this problem developing yet in oxygen profile data from the main lake during the 1995 to 2009 field seasons.

Delta Park, Winooski River © Carl Heilman II

LAKE LEVEL

The level of a lake rises and falls in response to many factors, including surface inputs and outflow, evaporation, groundwater seepage, and manipulation or blockage of outlet channels. In the case of Lake Champlain, however, the primary climatic factors are the amount of precipitation that falls on the watershed, the melting of snow and ice, and the permeability of the ground. Lake levels are at their highest in spring, as narrow outlet morphology restricts the escape of excess water from snowmelt and rainwater running off frozen or water-soaked soils.

The 3-inch increase of annual precipitation in the watershed during the early 1970s was accompanied by a roughly 1-foot increase in mean lake level measured at the King Street Dock in Burlington (Figure 3). Some of that rise might have been related to outflow restrictions resulting from modification of the Chambly Canal 1971–1974 (M. Winslow, personal communication), but the extremely close correspondence between interannual variability in lake level and precipitation suggests that climate was also an important factor behind the change. If annual precipitation increases 4–6 inches by the end of this century as most models suggest under an A2 scenario, and if the relationship between precipitation and surface levels still follows its current pattern, then Lake Champlain could stand as much as 1-2 feet higher, on average, by 2100. Future warming is also likely to move the date of the snowmelt-driven lake level pulse earlier in the year. Meanwhile, heat-driven evaporation and possible summer rainfall reductions could intensify low stands in late summer and early autumn, producing a wider range of lake level fluctuations over the course of the year.

However, several factors in addition to the limitations of climate models complicate efforts to predict Lake Champlain's hydrological future with precision. Winter warming should reduce the amount of snow and ice on the ground, which could decrease the volume of water that is released in late-season melting events and distribute runoff more evenly through the colder months, thus allowing more of it to escape through the outlet by springtime. This might also leave water tables and soil moisture contents lower during subsequent warmer months even if total annual precipitation increases. In addition, summer warming is likely to increase evaporation from the lake and surrounding watershed. Modeling by Environment Canada suggests that the surface levels of the Great Lakes could decline by 8 inches to 8 feet (0.2-2.4 m) under a doubled CO_2 scenario (Mortsch and Quinn, 1996). As we seek to understand the likely balance between water inputs and outputs specific to Lake Champlain and its tributaries in a warmer, potentially wetter future, comprehensive hydrological modeling and monitoring in the watershed will become more important than ever.


LaPlatte Natural Area © Glenn Suokko

NUTRIENT LOADING

Cultural eutrophication is already a serious problem in Lake Champlain due to nutrient inputs from human activity in heavily settled and farmed portions of the watershed. Warming and possible wetting in the future are likely to aggravate the problem even if the nutrient sources themselves remain unchanged. As summer warming increases the stability and/or duration of stratified conditions in the lake, nuisance blooms of nitrogen-fixing cyanobacteria that are already stimulated by phosphorus inputs may become more frequent and abundant. And if more abundant or intense precipitation increases the delivery of phosphorus from soils and settlements to the lake, eutrophication will be enhanced even further.

V. Findings: Impacts on conservation targets

The Nature Conservancy's conservation action plan "Conserving Lake Champlain's Biological Diversity," completed in 2005, provides a framework for evaluating local environmental threats posed by climate change. Referencing key ecological attributes identified in the report, we focus on components of the Champlain Basin ecosystem that are potentially vulnerable to future changes in temperature and hydrology:

- **Tributary systems**
- **Wetlands and shorelines**
- **Littoral zone**
- **The deep lake**
- **Native fish assemblages**
- **Native mussel assemblages**

Management strategies that effectively address future climate-driven threats to these systems will help conserve Lake Champlain's full diversity of species and habitats.

Courtesy of J. Ellen Marsden

TRIBUTARY SYSTEMS

Tributary systems encompass a diversity of features, including headwaters and adjacent wetlands, floodplains and deltas. They are important sources of water, nutrients and sediment for the lake, and harbor a wealth of living things. Riverine habitats are important refuges for rare mussels and the basin's designated rare, threatened or endangered fish (including eastern sand darter, northern brook lamprey, American brook lamprey and stonecat). They also provide spawning grounds and nurseries for walleye, sturgeon, redhorses, quillback, Atlantic salmon and other predominantly lake-dwelling fish that spend part of their life cycle in running waters (R. Langdon, personal communication).

Future warming may alter the geographic ranges of aquatic species that currently live in the Champlain Basin, but predicting those changes is hampered by topographic variables as well as a lack of temperature tolerance data for many organisms. However, an analysis of baseline water temperatures from 1,700 U.S. Geological Survey stream-monitoring stations concluded that stream habitat for 57 cold- and cool-water fish such as brook trout and slimy sculpin could decline by as much as 50% in the United States as temperatures rise during this century (Eaton and Scheller, 1996).

Rising temperatures may also exacerbate late-summer low flows by increasing evapotranspiration through vegetation and evaporation from land and water surfaces. The U.S. Fish and Wildlife Service's New England aquatic baseflow policy currently defines 0.5 cfs/square mile as the August median flow of New England streams and also considers it to be the threshold required to maintain critical life cycle functions of many flora and fauna (Lang, 1999). In addition, reduced water volumes can increase the concentrations of toxic pollutants that collect in riparian wetlands (Environment Canada, 2009).

The quantity of precipitation that falls on a watershed over a given time period strongly affects stream discharge (Figure 6), but so do physical features of the landscape. The basin is heavily forested, which slows the rate at which water moves through it, but its fine-grained soils have generally low permeability, and many of the streams have steep gradients, features that tend to increase runoff rates.

The timing of precipitation and runoff is also important. Historically, the highest levels of stream flow in the watershed have occurred in spring under the influence of snowmelt, low evaporation rates and saturated ground. Discharge records maintained by the United States Geological Survey show that many rivers north of the 44th parallel have experienced progressively earlier winter/spring high flows during the 20th century (Hodgkins and Dudley, 2006a). This is consistent with regional warming trends and suggests that a similar change may be expected for Lake Champlain.

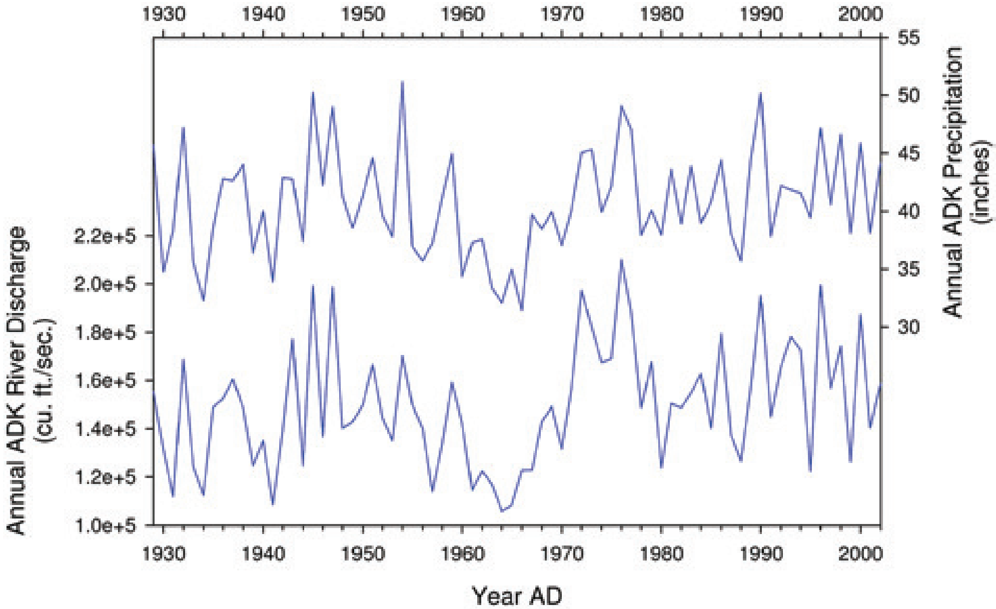


Figure 6. Annual river discharge (cubic feet per second) and total annual precipitation (inches) in the Adirondacks, 1929–2002 (after Stager et al., 2009).

As winters become warmer and snow is more often replaced by rain, river flow may become higher and more variable during the cold months of the year, increasing the magnitudes and frequencies of mid-season floods and ice jams. However, the overall reduction of snow cover might also reduce the volume of potential meltwater left to be released later on during spring floods.

In a warmer future, seasonal buildup of river ice should decrease, with important consequences for the ecology of river corridors. More frequent winter rains could increase the number of runoff pulses and ice releases throughout the season, but less snow and ice overall could also reduce the buildup of meltwater behind ice barriers and weaken spring flows. Furthermore, lighter ice loads and discharge volumes during early spring could reduce the scouring effects of fast-moving ice, which is central to the development and maintenance of riparian wetlands and "ice meadow" habitats.

Normally, high river flows spill into floodplains, which provide natural water-storage capacity and sustain riparian forests and wetlands (Opperman et al., 2009). But widespread channel modifications (e.g., straightening, dredging, armoring and berming) in the Champlain Basin, especially in the more agrarian regions of the valley, have largely eliminated river access to floodplains that would otherwise attenuate ice and high water flows during spring runoff and large storm events. The increase in stream power caused by the floodwaters that are now confined within their channels can result in greater channel incision and bank erosion. Lack of floodplain access also reduces sediment and nutrient storage functions at a watershed scale, because floodplains often store sediment and the nutrient pollution that may be bound to it (Vermont ANR, 2008). Projected increases in the intensity of storm events would be likely to further exacerbate these problems.

More than 20 Lake Champlain tributaries are considered "impaired," under state and federal standards, by stormwater pollution, which carries nutrients that cause undesirable plant and algae growth (LCBP, 2008; Vermont ANR, 2010). Heavier river discharge can also deliver more toxic pollutants, including agricultural chemicals and atmospheric contaminants, to riparian and lake habitats. Much is already being done to reduce sources of river-borne pollutants, but progress is offset by inadequate implementation of best management practices and by continuing landscape development. In 2002, for example, a phosphorus-loading budget was established for Lake Champlain as part of a New York/Vermont pollution control plan, but as of 2005–2006, streams still delivered more than twice the target amount of phosphorus (ca. 1,000 metric tons) into the lake (LCBP, 2008).

Records dating back to 1991 show a direct correlation between river flow and nonpoint phosphorus loading (LCBP, 2008), with the amount of phosphorus that is carried by local tributaries rising dramatically when flow rates and volumes increase (Smeltzer and Simoneau, 2008; Sullivan et al., 2009). Concentrations in Lake Champlain itself do not increase by the same proportion, for various complex reasons (LCBP, 2008), but anticipated increases in annual precipitation and winter runoff in the watershed suggest that nutrient delivery to the lake is likely to be enhanced by future climatic change.

LAKE-CONNECTED WETLANDS AND SHORELINES

Lake Champlain has 587 miles of shoreline encompassing beaches, rocky bluffs, talus slopes, and developed shorefront property as well as extensive wetlands (LCBP, 2004). There are 166 wetlands larger than 50 acres with a direct hydrologic connection to the lake, including marshes, silver maple/ash swamps, shrub swamps and floodplain forests that provide critical habitat for a rich diversity of wildlife (Munno et al., 2005).

Wetland plants and animals can be sensitive to changes in temperature or water supply. A rise in temperature may allow some kinds of invasive plants to colonize new locations or outcompete native species (see "Invasive species and climate change," page 32), and a change in the seasonality of precipitation can affect plants or animals whose life cycles require certain levels of water at specific times of year (Environment Canada, 2009). However, the likely impacts of climate-related changes on wetland organisms in the Champlain Basin during this century have yet to determined.

Least bittern © Benoît Jobin, Canadian Wildlife Service

The relationship between the seasonality of lake levels and the shoreline ecology of Lake Champlain is another area in need of further study. Long-term warming in winter may reduce snowpack and the magnitudes of lake level maxima in spring, which might change the amount of seasonally flooded shoreline habitat available to some organisms. Increased evaporation and/or a possible reduction of rainfall during summer might drop lake levels more than usual during the warmer months and thereby alter the distribution of shoreline habitats as well.

Lakeshore wetlands may either gain or lose acreage if mean or seasonal lake levels change during this century, depending upon availability of unoccupied ground upslope. Wetlands can accommodate rising lake levels only to the extent that their inland migration is not limited by topography, seawalls or other development. Some marginal wetlands may be at risk of being pinned against immovable barriers if the lake rises substantially in the future.

Reductions in the extent and duration of ice cover during this century are likely to expose Lake Champlain's shorelines to wave action for longer periods of the year, thereby potentially increasing annual erosion rates even without concurrent changes in lake levels or wind activity. However, vegetated buffer zones can help to resist wave erosion while enhancing shoreline habitat and absorbing stormwater and pollutants. Such buffers also contribute plant detritus to littoral habitats, which can provide shelter, food and/or colonization sites for aquatic invertebrates and fish as well as reptiles, amphibians, birds and mammals (Connin, 2003).

Artificial shoreline "hardening" by retaining walls and other structures resists wave erosion, too, but it restricts the natural movements of water, substrates, vegetation and wildlife (Connin, 2003). As a result, fish diversity and abundance tends to decline along deforested and walled shorefronts (Trial et al., 2001). Shoreline hardening may increase or creep inland if lake levels and the frequency of strong storms rise, but at present, guidelines and oversight are inconsistent from one town and state to the next, and conservation is not always a required design consideration. For instance, code-enforcement officials from the heavily developed lakeshore communities of Colchester, VT, and Willsboro, NY, report an increase in shoreline hardening during the past decade, but mandatory building setbacks differ between locales (100 feet from 95.5-foot normal water level in Colchester, and 50, 75 or 150 feet from 99.8-foot mean spring high water level in Willsboro).

LITTORAL ZONE

The littoral zone is the relatively shallow, biologically rich near-shore portion of the lake, where sunlight easily reaches the bottom. It encompasses slightly more than half of Lake Champlain's surface area, and includes beds of submergent vegetation, rocky or soft bottoms, and river deltas. Although compromised by invasive zebra mussels, the littoral zone still supports the lake's most biologically productive and diverse communities of plankton, plants, vertebrates and macroinvertebrates.

Major Ecological Impacts to Watch For

TRIBUTARY SYSTEMS

- Earlier spring high flows, ice jams and flooding
- Decrease in snowpack and ice, resulting in more meltwater flow in winter but possibly less severe conditions in spring
- Lower, warmer and less oxygenated tributaries in summer
- Less habitat for cold-water species
- Changes in the timing of spawning
- Increased nutrient inputs from potentially enhanced precipitation and increased intensities of rainstorms
- More erosion and siltation
- Physical disruption of streambed habitat for fish eggs and invertebrates

Fragile papershell © Darby Creek Association

WETLANDS AND SHORELINES

- Possible changes in average lake levels
- Changes in the acreage of lakeshore and riparian wetlands
- More extensive artificial hardening of lakeshores in response to water level changes, resulting in blockage or degradation of breeding and spawning habitat
- Sensitivity of wetland plants and animals to warming and changes in hydrology
- Possible larger array of invasive wetland plants

NEARSHORE AND OFFSHORE LAKE HABITATS

- Decreased ice cover
- Warmer surface temperatures
- Longer and more extreme summer thermal stratification
- Increased likelihood of nuisance cyanobacterial blooms
- Lower oxygen content at depth
- Changes in the timing of plankton growth and community structure
- Decreased water quality from enhanced nutrient and sediment inputs

FISH ASSEMBLAGES

- Plankton-based food web changes in fish communities
- New invasive species
- Temperature-driven shifts in the locations and extent of habitats
- Competitive advantages to warm-water over cold-water species
- Potential dominance of alewives over smelt with negative effects on the health of predators such as lake trout and Atlantic salmon
- Impaired habitat quality from increased nutrient inputs, sedimentation and prolonged thermal stratification
- Spawning affected by changes in the timing, temperature and/or volume of seasonal stream flow
- Increased methlymercury in food webs

NATIVE MUSSELS

- Sensitivity to changes in temperature, oxygen content, toxins, sedimentation and hydrologic regimes
- Altered host-fish availability
- Increased damage from pollutants that interfere with calcium assimilation
- Possible competition with new invasive mollusks

Because the littoral zone's shallow waters are readily influenced by wind, ice cover and air temperatures, it experiences dramatic thermal changes throughout the year. It tends to be warmer than the main lake during the summer and generally retains ice longer in winter and spring. The littoral zone also receives phosphorus inputs directly from streams, which, in combination with the upward stirring of nutrients from bottom sediments, makes this habitat more susceptible to eutrophication than deeper portions of the lake.

Climate-driven changes in the phenology, composition and abundance of plankton communities in Lake Champlain could have complex repercussions throughout the food web, not all of which are yet fully understood. Among the chief concerns are the responses of cyanobacteria (formerly known as blue-green algae). Cyanobacterial blooms are common in the lake's shallow bays, and some can produce dangerous nerve and liver toxins that make them unpalatable and potentially dangerous to larger organisms, including humans. Warmer temperatures often encourage the growth of certain cyanobacteria because gas bubbles in their cells help to keep them afloat in the relatively shallow, heat-stabilized epilimnion while less buoyant phytoplankton sink out below the sunlit zone where photosynthesis can occur. Phosphorus pollution also tends to favor some cyanobacteria, such as *Anabaena* and *Aphanizomenon*, over other taxa because they can fix their own nitrogen from air that has dissolved in the lake. In a warmer, potentially wetter future, stronger and more persistent summer stratification and heavier phosphorus loading from stream discharge are likely to increase the prevalence of cyanobacterial blooms in Lake Champlain, especially in the littoral zone. Therefore, effective management of phosphorus sources will probably become more important than ever.

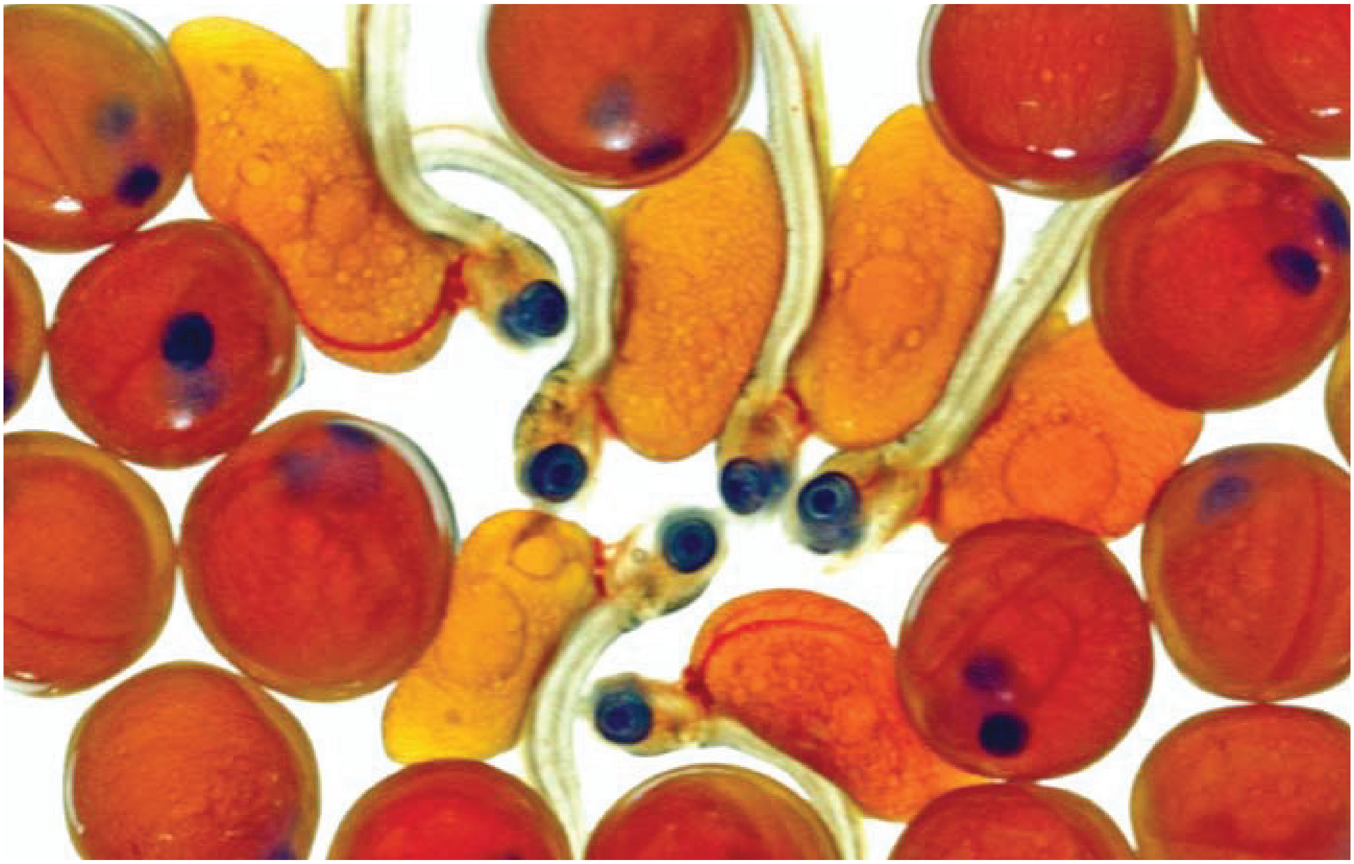
Water temperature has also been linked to the timing of phytoplankton and zooplankton emergence from resting stages in temperate zone lakes (De Stasio et al., 1996). Shrinking ice cover and warmer conditions in eutrophic Lake Müggelsee, Germany, are causing diatoms and *Daphnia* to appear in the spring plankton a month earlier than 25 years ago (Adrian et al., 2006), and laboratory studies suggest that late-season warming could cause zooplankton that normally overwinter in resting stages to emerge in autumn rather than spring (Chen and Folt, 1996). Other studies have found that warmer water and heavier sedimentation tend to favor rotifers over crustacean zooplankton in some lakes (Dupuis and Hann, 2009); a similar biotic shift in Lake Champlain might make nuisance phytoplankton even more abundant because of reduced grazing pressure from micro-crustaceans (Kirk and Gilbert, 1992). Any such climate-driven changes in the abundance and composition of zooplankton communities could have major impacts on the lake's food web, particularly among juvenile fish that depend on microscopic prey, but exactly which species would be helped or harmed by such changes remains to be determined.

The nearshore zone is also important to waterfowl, mammals, amphibians and reptiles. One example is eastern spiny softshell turtles (*Apalone spinifera*), which are rare in Lake Champlain and are thought to occupy only a small region in the northeastern sector of the lake. This turtle species is declining throughout much of its range and is listed as "threatened" in Vermont. One of the factors that determines where spiny softshell turtles overwinter is the destructive scouring action of ice on soft, shallow lake bottoms. Reduced ice cover in the future might therefore benefit softshell turtles by allowing them to hibernate in a wider selection of shallow-water sites in the lake.

THE DEEP LAKE

The deep-water benthos and pelagic zones, encompassing 80% of the lake's volume and 45% of its surface area (Munno et al., 2005), are home to diverse fish and invertebrate communities. This section of the lake is mainly oligotrophic, with generally clear water, low nutrient concentrations, abundant dissolved oxygen at all depths, and periods of thermal stratification in summer alternating with fall and spring turnovers. The great size and depth of the lake provide some measure of ecological resilience and relative stability, but it is not altogether immune to the effects of climate change.

The epilimnion of the main lake typically extends down 30–50 feet (ca. 9–15 m) during the summer months, and its late-summer temperatures generally range close to 66–73°F (ca. 19–23°C) as do the local air temperatures; in contrast, the dark, cool hypolimnion averages close to 41–46°F (ca. 5–8°C) in summer (Long-term water quality…[2003]). Dissolved oxygen concentrations during summer are often higher near the bottom of the main lake (ca. 11–12 mg/L) than in the epilimnion (ca. 8–10 mg/L) despite the absence of photosynthesis at depth, perhaps because the much cooler temperatures of the hypolimnion increase its capacity to hold oxygen, and because oxygen consumption by microbial decay of organic matter is minimal there due to the lack of major eutrophication problems in the main lake at present. The apparent linkages between local air and water temperatures suggest that climatic warming during this century is likely to increase surface



Salmon eggs and fry © USFWS

temperatures in Lake Champlain, with potentially significant consequences for its resident species.

Thermal effects on various plankton species could produce important ecological changes in the main body of the lake as they would in the littoral zone (see page 24), but changes in the physical structure of the water column could also be particularly important in offshore habitats. Modeling studies of northern Wisconsin lakes predict earlier and more stable summer stratification as climate warms (De Stasio et al., 1996), and similar changes are likely to occur in Lake Champlain as well. While the hypolimnion now provides fish with a large, well-oxygenated refuge from thermal stress in summer, avoidance of higher surface water temperatures in the future could disrupt community structure and trophic interactions in the lake. As the epilimnion warms and deepens during this century, the volume and suitability of deep-water refuges for cold-water fish such as salmon, lake trout and burbot may shrink significantly, especially in shallower areas such as the Inland Sea (J. E. Marsden, personal communication).

Fish may also become more vulnerable to reduced concentrations of dissolved oxygen if the eutrophication that already afflicts much of Lake Champlain's shallower regions begins to affect the main lake significantly, as well. The potential for hypoxia to occur in the water column offshore will likely increase as summer stratification becomes more persistent, especially if heavy phosphorus loads stimulate more phytoplankton blooms that eventually sink and decay, thereby consuming dissolved oxygen in the hypolimnion. Hypoxia can also mobilize additional nutrients from bottom sediments and potentially amplify phytoplankton blooms, further threatening fish and benthic organisms that require deep, well-oxygenated refuges. In this context, the prospect of future climate change makes the monitoring and control of nutrient pollution in the Champlain watershed more important than ever, because the hypolimnion of the main lake will be the principal seasonal refuge for cool- and cold-water species during warmer summers of the future.

FRESHWATER FISH ASSEMBLAGES

The Champlain Basin supports one of the most diverse fish communities in the Northeast, including approximately 69 species that are native to the lake and lower tributaries (R. Langdon, personal communication). Prehistoric connections to other water bodies have led to a mix of boreal fishes (whitefish, northern pike, lake trout), Atlantic coastal species (rainbow smelt, American eel, Atlantic salmon, sea lamprey, fallfish, cutlips minnow, chain pickerel, tessellated darter), and Mississippi watershed species (gar, sturgeon, bowfin). At last count, 15 kinds of nonnative fish are also present.

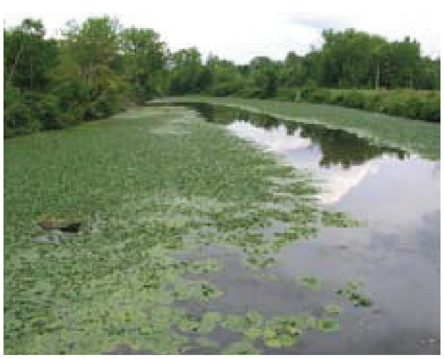
One reason why Lake Champlain supports such biodiversity is its great size and depth, which affords a wide range of habitats for both cold-water and warm-water fish. Lake-connected wetlands also provide spawning grounds for northern pike, yellow perch, brown bullhead, bowfin, largemouth bass, black crappie, carp, mudminnow and longnose gar. Regardless of the emissions scenario or model projection under consideration, large deep lakes such as Champlain should continue to support a diversity of aquatic environments during the rest of this century, including cold-water fish habitat, though the quality and extent of that habitat may be reduced (Stefan et al., 2001).

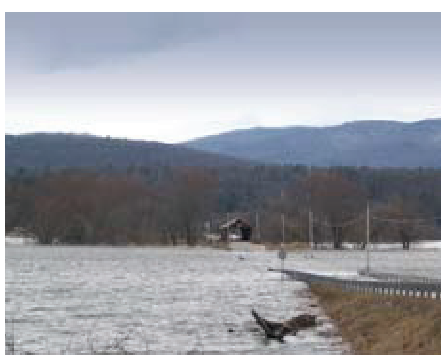
A fish's body temperature is about equal to the temperature of the water in which it lives. Still, future warming is less likely to threaten most fish directly than to alter their habitat, food sources and distribution. For example, climate-driven changes in the availability and composition of zooplankton could cause major changes in the lake's food web, particularly among post-larval fish that have absorbed their egg sac and whose survival depends on preferred prey being immediately available (R. Langdon, personal communication). In addition, the fraction of Lake Champlain that is classified as warm-water habitat is likely to expand, and higher water temperatures might make it easier for some heat-tolerant alien species to invade. Because the potential interactions between ecosystems and human behavior are too complex to let us predict with certainty how any given species will be affected by climatic changes or alien introductions, the most effective approach to addressing those risks will involve the careful, continuous monitoring and management of both game and nongame species.

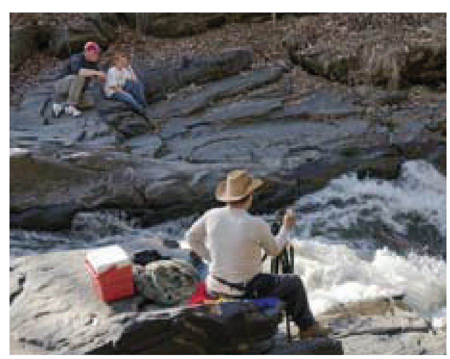
Different organisms will respond physiologically to future warming in the Champlain Basin in different ways. Rates of food consumption, metabolism and growth for some fish species are likely to increase if warming pushes thermal conditions closer to their preferred temperature ranges (Shuter et al., 2003); smallmouth bass and walleye in the Columbia River, for example, have been projected to increase their consumption of salmonids 4–6 % for every 1°C (1.8°F) increase in water temperature (Rahel and Olden, 2008). On the other hand, cold-water species such as burbot can become lethargic and fail to feed at higher temperatures (Jackson et al., 2008). As thermal habitats and biological communities within Lake Champlain are restructured, fish may also be forced to interact with new competitors, food sources and parasites within their home lake, a situation not unlike having to compete with introduced species (Ficke et al., 2007).

Shifts in the magnitudes and/or timing of peak snowmelt-driven stream flows in winter and spring might affect the reproductive cycles of stream-dependent species, because egg hatching is often timed in ways that allow young fish to find refuge from strong early-season flows. Most stream-spawners in the Champlain Basin spawn in spring, so earlier meltwater peaks could be potentially disruptive if fish fail to adjust their behavior accordingly. Projected increases in winter rain (as opposed to snowfall) could also generate more frequent cold-season floods and ice flows that can scour streambeds and kill eggs, larvae and adult fish (Frumhoff et al., 2007); this might be especially problematic for burbot, which may move into rivers to spawn in winter. Atlantic salmon spawn in autumn, so they might instead face problems from warmer and slower stream flows.

Swollen rivers tend to become more erosive and carry more sediment downstream, and the heavy silt loads associated with this can infiltrate the gills of fish, bury benthic habitats and invertebrates, and suffocate eggs as well as larval fish and invertebrates (Brennan and Culverwell, 2004). Under such conditions, species such as darters and sculpin that live or spawn on rocky or sandy substrates may be suppressed


South Bay, Lake Champlain © Bob Klein


Ice jam, Otter Creek, VT, courtesy of VT DEC


Willoughby Falls © Bob Klein

Ice fishing on Lake Champlain © Seth Lang Photography

in favor of competitors that are more amenable to silty or disturbed substrates. Some invasive species, such as alewives and white perch, are not dependent on clean substrate for spawning and are not greatly affected by siltation, so increased erosion due to increased precipitation and runoff might encourage the spread of such fish in the region.

Some of the most serious indirect effects of climate change on Lake Champlain fish will be related to water quality. For example, the methylation rate of mercury increases with temperature. Methylmercury impairs organ and nerve functions in vertebrates, and through bioaccumulation it can compromise the health of predatory fish as well as the people and animals that eat them. The largest inputs of mercury to Lake Champlain (ca. 56%) arrive via surface run-off and tributary flow (Gao et al., 2006), so higher temperatures and potentially increased flows could exacerbate methylmercury problems.

But an even more pervasive threat in the future may be nutrient enrichment and hypoxia. As warming drives more fish deeper into the water column for longer time periods, they will encounter less dissolved oxygen there than they do now if eutrophication becomes more widespread and intense in the future. Under such circumstances, the hypolimnion would become less and less hospitable as a thermal refuge during the warmer months of the year.

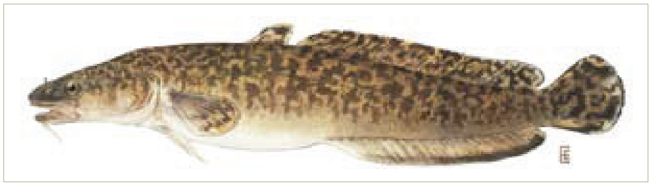
The issue of water quality raises one of the most important take-home messages from this study: there is more to climate change than temperature alone. Even though the thermal tolerances of most fish will not be exceeded by century's end, the eutrophication problems that are now largely restricted to the littoral regions of Lake Champlain could become far more serious threats throughout the lake in a warmer and possibly wetter future. And although there may be little that natural resource managers can do to prevent future climatic changes in the region, there is much that can be done to control nutrient enrichment. In this new environmental context, ongoing efforts to do so will become more important to the health of local aquatic ecosystems.

Potential Impacts on Selected Fish

Changes in water temperature, precipitation and hydrology will have different repercussions for different fish species in Lake Champlain. The key question—and one that will require careful monitoring—is which species can adapt to changes rapidly enough to deal successfully with those changes. Here is a look at potential impacts on eight fish species from the Champlain Basin:

Burbot (*Lota lota*)

The Fisheries Technical Committee of the Lake Champlain Fish and Wildlife Management Cooperative's 2009 "Strategic Plan for Lake Champlain Fisheries" (Fisheries Technical Committee, 2009) states that stable populations of native, nongame species such as burbot are important indicators of the overall viability of the fish



community. These freshwater codfish become lethargic and emaciated in waters warmer than 21°C (69.8°F), and their extirpation is anticipated in New York's Oneida Lake, a large but shallow water body with no stable hypolimnion (Jackson et al., 2008). Thermal changes may also help to explain a worldwide decline in burbot at the southern edges of their range (Stapanian, 2010).

Burbot inhabit Lake Champlain's cooler depths in summer. They spawn in winter, usually under ice, at temperatures between 33 and 35°F (0.5–1.6°C), some over sand and gravel shoals 1 to 4 feet deep, and some in deeper water or streams (Smith, 1985; McPhail and Paragamian, 2000). Although there has been no research published regarding burbot spawning in the Champlain Basin, ice cover may be important to their reproduction there as well. Prior to construction of the Libby Dam, on the Kootenai River in Idaho, portions of the lower river would freeze regularly in winter, and burbot would spawn in water temperatures between 34 and 37°F (1–3°C) [Paragamian et al., 1999]. River temperatures there are now 39–41°F (4–5°C) during winter, and many sections no longer freeze over; this and altered flows are thought to be factors behind a decline of burbot populations there (Paragamian et al., 1999). Projected ice cover reductions in the warming future may present a problem for this species in Lake Champlain. Enhanced stratification may also reduce the volume of cool, oxygen-rich refugia available to cold-water fish in summer.

Northern pike (*Esox lucius*)

Northern pike are native, nearshore predators in Lake Champlain and its larger, slower-flowing tributaries. They normally avoid surface temperatures above 77°F (25°C) [Reist et al., 2006].

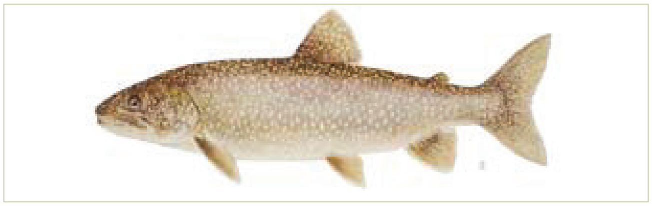
Increases in nutrient inputs, soft sediments and zebra mussels (which filter-feed on plankton and can increase water clarity) may spur growth of aquatic and emergent plants in Lake Champlain (Fisheries Technical Committee, 2009). Light-tolerant and adapted to weedy habitats, northern pike may thrive under such conditions, but potential gains could be offset by other variables. Pike spawn in early spring in lake-connected wetlands and shoreline meadows temporarily inundated by high waters. It is unclear whether these areas will expand or contract under future lake level scenarios, but spawning habitat could be altered.

Northern pike are widespread in North America, so warming is probably not a major threat to the species itself; the most likely effect will be to shift their geographic range northward (Reist et al., 2006). But within the Champlain Basin, resident pike are already near their southern limit. In a study of two Ontario impoundments, surface temperatures above 77°F restricted pike to the coolest available water for 2–3 months of the year (Headrick and Carline, 1993), which suggests that pike could also become

more frequently forced into deeper habitats in Lake Champlain as summer temperatures rise during this century. If the deeper waters of the main lake also become less oxygenated as a result of prolonged stratification and/or eutrophication, then potential offshore refuges for pike may shrink considerably.

Lake trout (*Salvelinus namaycush*)

This native cold-water piscivore was extirpated from Lake Champlain by the 1890s and is now maintained through annual stocking of 68,000 to 90,000 yearlings (Fisheries Technical Committee, 2009). Despite suitable breeding habitat and successful



reproduction by stocked fish, larval lake trout in Lake Champlain do not survive beyond their first winter. In addition, many adults are harmed by sea lamprey predation. Developing a self-sustaining population of lake trout despite these challenges is a goal of the 2009 "Strategic Plan for Lake Champlain Fisheries."

Climate change may pose more obstacles. A proliferation of fish such as alewives in response to warming (see below) could affect lake trout more than the direct effects of temperature alone; alewives favor slightly warmer waters that are likely to become more common in Lake Champlain during this century, and they are nutritionally inferior to the current preferred prey, rainbow smelt. Enhanced summer stratification may also reduce the volume of cool, oxygen-rich refugia available to cold-water species.

The effects of climate change on lake trout will depend on their ability to adapt. The more extreme the changes and the faster they occur, the less likely it will be that cold-water species can adjust successfully (R. Langdon, personal communication).

Atlantic salmon (*Salmo salar*)

This native cold-water piscivore was extirpated in the 1800s by dams and degradation of stream spawning habitat. Since 1972 it has been maintained in the Champlain Basin by stocking—currently 240,000 smolts and 450,000 fry per year (Fisheries Technical Committee, 2009). Restoring naturally reproducing Atlantic salmon is a goal of the 2009 "Strategic Plan for Lake Champlain Fisheries."

Climate change will add complications to an already challenging effort. Some Lake Champlain salmon swim upstream in autumn to spawn, but dams on every major tributary block access to preferred spawning areas, and if streams also become slower and warmer in autumn, spawning may be further compromised.

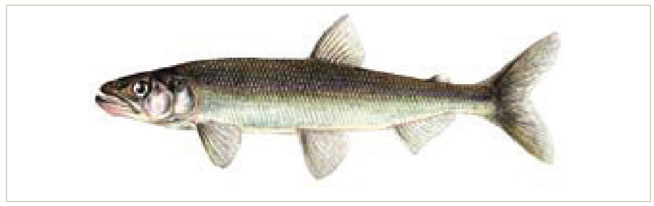
The downstream migration of juvenile salmon from river nurseries, usually in spring, is controlled by photoperiod, flow and temperature (McCormick et al., 1998). This behavior might be adversely affected by earlier or heavier cold-season runoff. Fish managers who stock fry and juvenile Atlantic salmon high in Lake Champlain tributaries do not yet know if any make it down to the lake, and the high mortality of young salmon observed in some Adirondack streams has yet to be explained (NYSDEC, personal communication). More research is needed to determine whether climate-related conditions are causing these problems.

Atlantic salmon prefer a temperature range of 35.6–48.2°F (ca. 2–9°C) and have died at 83.7°F (28.7°C) in laboratory studies (Beitinger et al., 2000). Maintaining ample well-oxygenated conditions in the deeper portions of Lake Champlain will be key to ensuring summer refuge for adult salmon.

Rainbow smelt (*Osmerus mordax*)

A goal of the 2009 "Strategic Plan for Lake Champlain Fisheries" is "populations of smelt that support a recreational fishery." Rainbow smelt have historically been primary salmonid prey in Lake Champlain (Fisheries Technical Committee, 2009). Trawl-monitoring catches of these small fish tend to oscillate widely from year to year, and the catch in deep waters is usually lower than in shallower areas. The 2009 plan calls for more monitoring and assessment, focusing on how rainbow smelt fare in competition with alewives, small invasive fish that also eat zooplankton but favor warmer waters and are therefore likely to become more abundant in a warmer future.

Smelt are probably native to Lake Champlain, but more than 65 million were stocked during the early 1900s (Fisheries Techni-



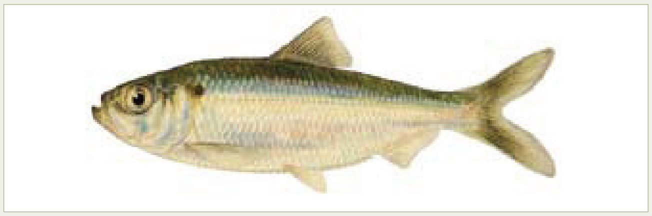
cal Committee, 2009). Unlike smelt in the Great Lakes, those in Lake Champlain generally do not ascend rivers to spawn but instead breed offshore in depths of 49 feet (15 m) [Fisheries Technical Committee, 2009].

Smelt essentially disappeared from the tidal Hudson River, at the southern extreme of the fish's reproductive range, after 1995 (Daniels et al., 2005), a time when Hudson water quality was improving and other native species were increasing in number. This implicates warming as one possible cause of the decline, and a trend of increasing water temperature has been documented in the river below Troy, NY (Daniels et al., 2005). It remains unclear whether warming in Lake Champlain will be detrimental to smelt, or whether their ability to spawn in deep waters will protect them.

Alewife (*Alosa pseudoharengus*)

Warming waters may favor invasive alewives over rainbow smelt. Native to the Atlantic coast, alewives are commonly used as bait and have become established in many lakes through planned and accidental introductions. They are planktivorous and compete with smelt and the fry of other pelagic species for food, in addition to consuming larval fish directly. Because of this, and also because they contain thiamine-destroying enzymes that can cause problems for lake trout, Atlantic salmon and other predatory fish, the expansion of alewife populations can trigger important changes in a lake ecosystem (Malchoff and Windhausen, 2006). Alewives first appeared in Lake Champlain's Missisquoi Bay in 2003 and were detected in the main body of the lake in 2005 (Malchoff and Windhausen, 2006).

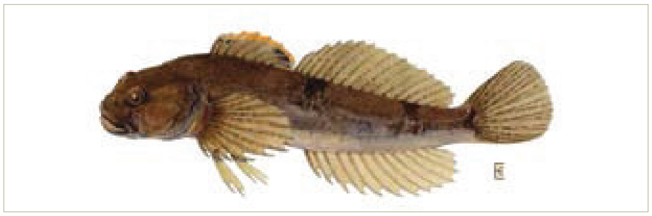
These fish apparently remain offshore for most of the year but enter shallow waters in late spring and early summer to spawn. If they do not have a long warm season in which to gain weight, alewives do not survive cold winters, which sometimes leads to massive seasonal die-offs in the Great Lakes (Lepak and Kraft,



2008). In winter they become stressed at temperatures colder than 37°F (2.8°C), and they generally try to avoid habitats at or below 34°F (1°C) [O'Gorman, 2006]. If cold is a major limiting factor for alewife populations, then warmer winters might lead to their expansion in Lake Champlain, to the detriment of other fish.

Slimy sculpin (*Cottus cognatus*)

A small, cold-water, bottom-dwelling fish in tributaries as well as in the lake itself, slimy sculpins are widely distributed throughout Canada and the northern United States. They spawn in spring at temperatures of 4.5–15.5°C (40–60°F) and frequently occur with brook trout in streams (Smith, 1985). They feed mostly on insect larvae and nymphs but also on crustaceans, small fish and plant materials.



Slimy sculpins and close relatives mottled sculpins (*C. bairdi*) face aggressive competition in the Great Lakes region as round gobies (*Neogobius melanostomus*) expand their range. Gobies have food, habitat and spawning requirements similar to those of sculpins and appear to be replacing them where the species overlap (Janssen and Jude, 2001; Chotkowski and Marsden, 1999). Round gobies have been moving eastward from Lake Erie via the Erie Canal, and they are better able to feed and spawn in very warm or murky water than slimy sculpins. As a result, warming and potentially increased runoff in the Champlain Basin could help gobies to outcompete native sculpins if they find their way into the watershed.

Channel darter (*Percina copelandi*)

Channel darters are rare in tributaries of the Champlain Basin and are listed as endangered in Vermont, the northeastern extreme of their range (Vermont Department of Fish and Wildlife[a], 2005; Smith, 1985).

Channel darters live and spawn in swift currents along the gravelly bottoms of the lower Winooski, LaPlatte and Poultney Rivers. There are also historical reports of channel darters in the Great Chazy River, but none have been found there re-

cently (Fisheries Technical Committee, 2009), perhaps because agricultural runoff has caused turbidity in the Chazy. These fish avoid silty or muddy substrates (Vermont Department of Fish and Wildlife[a], 2005). If erosion continues to degrade tributary habitats, especially if heavy rainfall and winter runoff pulses become more frequent, channel darters could be vulnerable. Sand darters (*Ammocrypta pellucida*), which live further downstream, might be more affected by mud and silt deposition because they inhabit slower currents.

On the other hand, if siltation is held in check, future warming might increase the viability of Champlain Basin channel darters, though it remains to be seen whether this isolated population could tolerate higher temperatures after having adapted to a relatively cool northern watershed (D. Facey, personal communication). It is as yet unknown how future warming will affect the darters' local food sources—mainly caddisfly, midge and mayfly larvae—and whether potentially reduced stream flows in summer might affect spawning (Smith, 1985).

Fish images in this section provided by the New York State Department of Environmental Conservation.

NATIVE MUSSEL ASSEMBLAGES

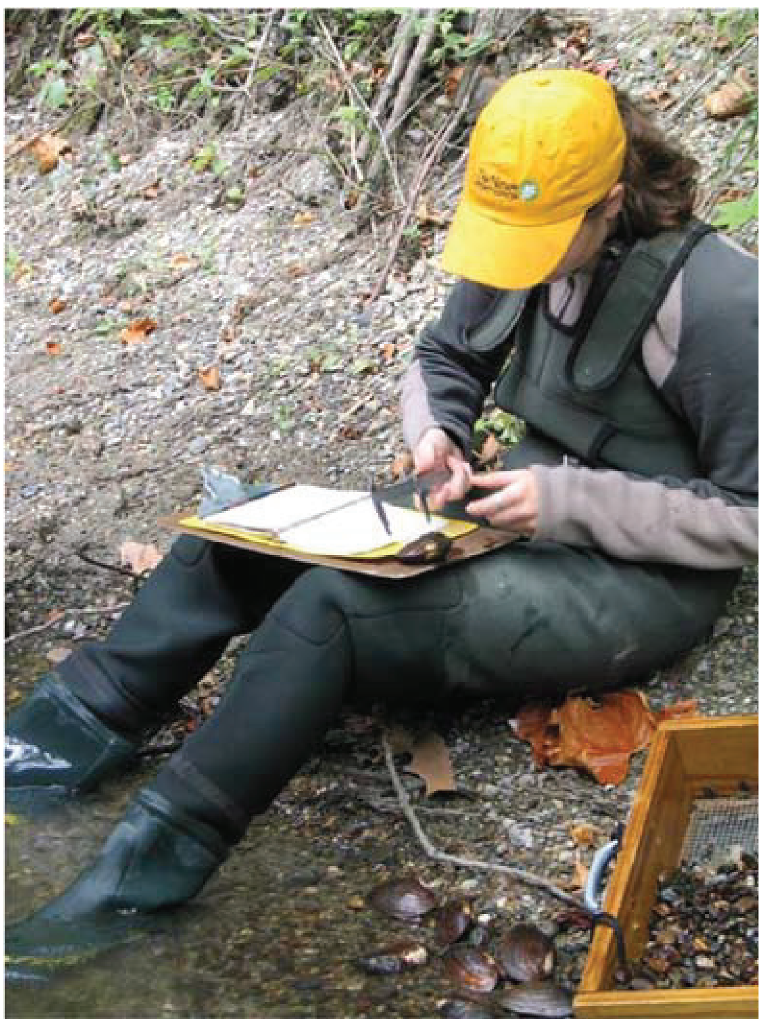
Freshwater mussels are among the most imperiled invertebrates in the world, and are highly sensitive to pollution, sedimentation and changing hydrological regimes. Lake Champlain and its tributaries are home to 14 species of mussels, eight of them listed as locally threatened or endangered.

Mussel physiology is strongly influenced by temperature, and species with greater temperature tolerances may be favored by future warming. But other factors will have increasingly important impacts on native mussels in the Champlain Basin, as well. Pesticides, heavy metals, agricultural nutrients, and other pollutants can accumulate in mussels and eventually kill them, and these mollusks can be smothered by the deposition of fine sediments (Vermont Department of Fish and Wildlife[b], 2005). Rising water temperatures could also increase the toxicity of metals that interfere with the calcium assimilation necessary for shell growth (UNIO list serve [2009]).

The Nature Conservancy's conservation plan for Lake Champlain identifies hydrological changes as a high threat to native mussels. Extremes in flow can alter mussel habitat in streams and deltas, where most of them are found, and the expected climate-driven changes in the timing and velocity of flows in late winter and early spring have the potential to scour streambed habitats more severely in some locations while increasing soft-sediment deposition elsewhere. Reduced late-summer flows and higher temperatures could also decrease the concentrations of dissolved oxygen in tributaries, especially if runoff pollutes them with nutrients that stimulate algae blooms.

Rising water temperatures could likewise alter the distribution of fish required to host mussel larvae. Freshwater pearl mussels (*Margaritifera margaritifera*), which are declining throughout their range and threatened in Lake Champlain, use only brown trout and juvenile Atlantic salmon as hosts (Skinner et al., 2003). Atlantic salmon are not naturally reproducing in Lake Champlain streams and may already be negatively affected by warming streams (see "Potential Impacts on Selected Fish," page 28).

Invasive species could represent the greatest threat to Lake Champlain's native mussels, particularly if warmer, possibly wetter and/or more eutrophic conditions happen to favor some of those invaders. The explosion of nonnative zebra mussel populations in the lake since 1993 has already greatly reduced native mussel numbers, though they still manage to persist in tributaries and deltas where moving waters impede colonization by zebra mussels. Preventing the introduction of more alien species remains the most effective conservation strategy.



Mussel research, Poultney River drainage
© Mary Droege/TNC

Invasive Species and Climate Change: A Pervasive Synergy

At last count, there were 18 nonnative invertebrate species in Lake Champlain, 15 nonnative fish, 13 plants and 2 pathogens. Still, the Champlain Basin contains far fewer exotic aquatic species than the Great Lakes, in part due to its relative isolation from commercial shipping traffic (Marsden and Hauser, 2009).

Exotic species have been introduced in many ways, including authorized and unauthorized stocking, and bait bucket and aquarium dumping. But the most important sources may be the Champlain and Chambly Canals that link Lake Champlain to the Hudson River, Mohawk River, Erie Canal, St. Lawrence River and the Great Lakes, where European and Asian species have been introduced by ship ballast water. An estimated 20 species have entered Lake Champlain via canals, including water chestnut, zebra mussels and white perch. More are approaching, including quagga mussels, spiny water fleas, whirling disease, Asian clams and round gobies.


White perch (*Morone americana*) © USFWS

Climate change may affect ecological interactions among species already present in the Champlain Basin. Some may be at a disadvantage in a warming future because they will no longer inhabit the temperature range to which they are currently adapted. Some organisms may increase in prevalence (Hellman, 2008), potentially causing trophic changes that could be beneficial or detrimental to other species (Rahel and Olden, 2008).

Responses will vary. Warming may have no direct effect on already-established invasive plants such as water chestnut, Eurasian water milfoil and purple loosestrife, or on invasive animals such as zebra mussels, none of which is near the limits of its temperature range in this region. On the other hand, warming is expected to benefit cold-sensitive alewives while possibly harming native salmonids and forage fish such as rainbow smelt. Precipitation changes that threaten to carry more silt and nutrients to the lake could favor species such as white perch, which was introduced in the 1980s and is becoming dominant in the more eutrophic portions of Lake Champlain (Fisheries Technical Committee, 2009).

Myxobolus cerebralis, which causes whirling disease in salmon and trout, is a European fish parasite recently found in a tributary of Lake Champlain (Vermont Fish and Wildlife Department, 2009). Its virulence increases with temperature, so warmer water is likely to magnify the pathogen's impact (Rahel and Olden, 2008). On the other hand, Viral Hemorrhagic Septicemia (VHS), which has killed a wide variety of fish in the Great Lakes and St. Lawrence River since it was discovered there in 2005, tends to last longer in cold, clear water (Gunderson, 2010) and might become less of a threat as local temperatures rise.

While research is important to understanding how native and invasive species may respond to future climatic changes, the time for pursuing research and using it to inform management techniques is short. Ecologists and managers in the Champlain Basin have already established platforms for action with an interagency invasive species council for the lake: the Lake Champlain Basin Program's Technical Advisory Committee subcommittee on Aquatic Nuisance Species. Its Lake Champlain Basin Rapid Response Action Protocol will be an important framework for tracking and responding to climate-driven species changes.

The Advisory Committee and key partners have agreed to pursue proactive action through a biological barrier on the Champlain Canal. A barrier should also be considered for the Chambly Canal. A renewed emphasis on public education will also be important in preventing or slowing future introductions of nonnative species into the watershed.

Social Impacts

Climate change affects more than plants and wildlife. The people who live and work in the Champlain Basin will also be influenced by higher temperatures and, possibly, increasing precipitation. For most of us, gradual climatic shifts will not pose great threats to our health, livelihoods or property, but some of the associated environmental changes will be quite noticeable and may also be undesirable.

- We can expect an increase in the number of uncomfortably hot days in summer, particularly in the more humid lowlands of the Champlain Basin. Unfortunately, the region's rivers and lakeshore beaches will not provide as much relief as they do today if water quality problems become more common and severe in the future. This makes it all the more important to eliminate sources of phosphorus and other pollutants that are washed into the lake and its tributaries.

- Anglers and fishing outfitters may be among the first to notice environmental changes related to climate. Reductions of ice cover will probably reduce the duration and extent of ice-fishing, and cold-water game fish populations in the basin could decline as certain invasive and warm-water species gain competitive advantages.

- Winter recreation in the form of snowmobiling, skating and skiing is likely to decline along with ice-fishing as winter thaws and cold-season rains progressively reduce snow and ice cover.

- Fish-consumption warnings could become more common as warmer water increases the toxicity of pollutants such as methylmercury, which causes developmental disabilities in children.

- More than 4,000 households and 99 public water systems (approximately 200,000 people) draw drinking water directly from Lake Champlain. Potentially heavier runoff and erosion may reduce water quality and cause microbial contamination and outbreaks of waterborne disease by washing animal waste into the water.

- Blooms of toxic cyanobacteria may become more common, threatening the quality of water supplies used for drinking, washing and swimming.

- Potentially heavier rains and higher water levels, particularly in winter, may increase property damage by erosion, flooding and storms in settled and agricultural areas.

- In warmer and possibly drier summers and early autumns, water tables and lake levels might fall farther than they do today, potentially reducing seasonal water availability for homes, industry and agriculture.

Lake Champlain at flood stage
© Nicholas Perez

The repercussions of future climate change, however, are not necessarily all negative. For example, heating costs may be reduced, and winter roads may not need as much plowing or salting, which would lessen corrosion of cars and salt inputs to waterways. And, unlike some parts of the world, the Champlain Basin is projected to maintain air temperatures and precipitation patterns that are generally hospitable to agriculture throughout the rest of this century.

Residents of the Champlain Basin are well advised to consider impending climate changes as they manage their own properties and make decisions in their communities. While this report was written with conservation managers in mind, it can also be a resource for citizens in general. By encouraging the establishment and conservation of shoreline vegetation, keeping fertilizers out of waterways and staying informed about long-term trends and their effects, we can all play a role in strengthening the region's resilience in a changing climatic future.

VI. Conclusions and next steps

Increasingly warm, ice-free and potentially wetter conditions during the rest of this century will affect ecosystems and species in the Champlain Basin significantly, but how conservation managers and land-use planners prepare for and respond to those changes will help to determine the extent of environmental impact.

Fortunately, dealing with these new climatic settings will not require an entirely new suite of conservation tools. Many of the best adaptation strategies are already known and in use in the Champlain Basin: these include river corridor protection, vegetated stream and lake shoreline buffers, best-management practices for runoff, wetland and forestland conservation, proactive measures against invasive species, and biologically based shoreline stabilization guidelines. Impending climate change lends new urgency to these actions. Now, more than ever, they need to be strengthened and applied consistently throughout the watershed. Although financial support is often lacking, dealing proactively with climate change will ultimately be less costly and more effective than trying to respond after the fact.

Long-term monitoring of ecosystems and a wide diversity of organisms (not just popular games species) is an important funding priority, fundamental to developing scientifically sound management strategies. Rigorous monitoring of the physical conditions in local hydrologic systems, in particular, will be needed to provide early warnings of change as well as baseline information with which to support future management decisions, especially in light of the limitations of local-scale and seasonal climate model projections.

Following are more specific recommendations for research and data needs and for management, planning and policy strategies, organized by:

1. **Recommendations for scientists and researchers**
2. **Recommendations for conservation managers and land-use planners**
3. **Recommendations for local, state and federal policymakers**

Research expedition, Lake Champlain © Gus Goodwin/TNC

1. For scientists and researchers: research and monitoring needs

Finding reliable, practical information about climate change projections in the context of local environmental issues can be a challenge for natural resource managers and municipal and land-use planners, who are already busy with other pressing concerns. More interaction among researchers and environmental decision-makers is needed to inform preparations for coming changes, and scientists should be encouraged to compile, synthesize and disseminate relevant information to managers and decision-makers as widely and expeditiously as possible.

Specific research needs that have been identified by scientists and managers working in the Champlain Basin include:

- Lake and tributary water temperatures and dissolved oxygen concentrations should be monitored more consistently and comprehensively at existing study sites in order to help predict and manage the viability of aquatic species in the Champlain Basin. Furthermore, additional instrumentation is needed in tributaries and lakewide to increase spatial coverage. Ideally, measurements of the entire water column should be taken weekly throughout the ice-free periods of the year.
- Fish species with narrow temperature tolerances should be identified, and their population sizes, health and distribution closely monitored to provide a basis for biologically sound management in the context of long-term climate change.
- The timing of game- and prey-fish spawning should be closely monitored as a basis for updating appropriate fishing-season parameters.
- Understanding of hydrological processes in the watershed should be improved to allow more precise near-term forecasting of weather-related changes in lake level, stream flow and other environmentally important factors. More stream-level data are needed. An accurate watershed precipitation- and evaporation-response model could be helpful for both short- and long-term prediction of stream flow and lake level changes.
- Some long-term stream discharge data do exist, but analyses have mainly focused on standard flow-frequency metrics averaged across the entire record. This database should be analyzed more thoroughly for trends and other patterns of change.
- Wind patterns should be analyzed for trends and indications of change, because winds influence shoreline erosion as well as lake hydrodynamics.
- More detailed shoreline elevation maps are needed to illustrate the range of possible effects from future changes in lake level. These should be used to generate shoreline and wetland inundation and exposure maps that would lead to better understanding of how seasonal and inter-annual fluctuations in lake level might affect lakeshore environments and structures.
- The current extent of lakeshore hardening and its impacts on conservation targets should be assessed to provide a basis for future retaining-wall guidelines.
- The distributions, population sizes and health of freshwater mussel assemblages should be more closely monitored along with the hydrological conditions associated with them.
- A major research and monitoring program is needed to track the community structure, distribution, phenology and viability of phytoplankton and zooplankton assemblages in Lake Champlain, as well as their influences on other species that depend on them.
- We also encourage the development of a follow-up study that more thoroughly investigates the expected impacts of climate change on terrestrial components of the Champlain watershed as a complement to this report, which focuses mostly on aquatic systems.

2. For conservation professionals and land-use planners: adaptation strategies and management

TRIBUTARY AND RUNOFF MANAGEMENT

- Accelerate implementation of best management practices on landscapes to reduce non-point sources of phosphorus transport in the watershed.
- Design and update stormwater control structures that can help to reduce erosion and nutrient transport during both high and low flow events, adapting regulations using the current precipitation period of record.
- Accelerate efforts to re-establish and maintain geomorphic conditions that accommodate fluvial and floodplain processes that in turn protect ecosystems and infrastructure.
- Encourage landowners and zoning bodies to maintain buffered river corridors, including vegetated zones along streams and associated wetlands. Deforested riparian areas should be revegetated with native trees and plants as much as possible in order to minimize erosion and runoff, and to provide shade that would help to mitigate increases in water temperatures.
- Encourage natural connectivity between aquatic habitats through barrier removal or other appropriate measures to restore the migration of native species.
- Evaluate stream-flow data for possible changes in median August flows, which are critical to the viability of many aquatic organisms.
- Work with municipalities to protect river corridors and floodplains in order to better accommodate their natural processes as well as to improve resilience to flooding and to improve water quality.
- Increase public education and provide resources for local residents regarding impacts of fertilizer use on water quality and the benefits of vegetated buffers.

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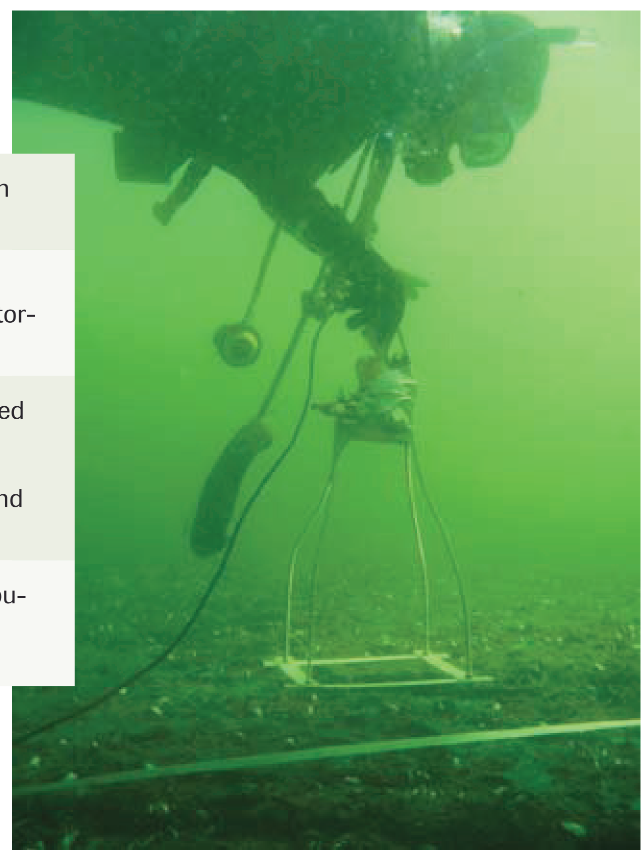
LAKE LEVEL ADAPTATION

- The Lake Champlain Basin Program has developed guidelines for shoreline stabilization but they have been adopted by only a few communities. Those standards should be updated with a stronger consideration of the conservation targets identified in this report and promoted among local and state regulatory bodies, engineers, builders and property owners.
- If credible forecasts can be made of future lake levels and shoreline inundation or exposure (see research needs), wetland conservation strategies should be adjusted accordingly by federal, state and nongovernmental organizations to help prepare them to act in a timely manner to reduce or prevent anticipated wetland loss.
- The measures currently used in regulatory processes (such as the 100-year flood hazard zone and mean high water level) should be recalculated regularly, using the current period of record and more accurate topographic information. This includes revision of the FEMA flood hazard maps and the definition of "mean high water" as applied in federal, state and local regulations. More accurate high-resolution maps of land surface elevations (such as those that could be produced through partnership with the USGS's National LIDAR Initiative) are needed in order to determine the precise locations, extent and vulnerabilities of flood-prone areas.
- Shoreline erosion mitigation strategies should be planned in ways that are sustainable and that minimize undesirable ecological impacts. Governing agencies on all sides of the lake should work toward consistent, biologically sound shoreline stabilization regulations.
- Increase shoreowner education on the water-quality impacts of fertilizer use and the benefits of vegetated buffer zones to shoreline stabilization efforts.

FISH AND MUSSEL ASSEMBLAGE MANAGEMENT

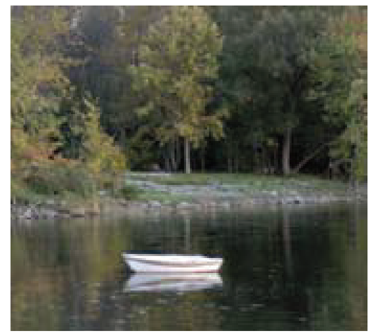
- Incorporate climate considerations such as those outlined in this report into fisheries management plans.
- Design fishing seasons to take account of climate-driven changes in the timing of spawning (see research and monitoring needs).
- Management decisions should be more consistently informed by accurate and up-to-date information concerning water temperature, plankton ecology, species viability, and other considerations identified in the preceding list of research and monitoring needs.
- Stream and runoff management recommendations (see "tributary and runoff management") are key to maintaining viable fish and mussel habitats.



Aquatic invasive species research, Lake Champlain, courtesy of Ann Bove, VT DEC

Courtesy of APIPP

Eurasian water milfoil, courtesy of APIPP



Lake Champlain © C. Black

3. For federal, state and local policymakers: legislative and funding recommendations

- Environmental monitoring in the context of ongoing and predicted climatic change should become a funding priority for state and federal governments as well as private foundations.
- More funding is needed for river corridor protection, including vegetated buffer zones as well as wetland and forest conservation throughout the watershed.
- The invasion of new nonnative species will continue to pose a serious and chronic threat to ecosystems in the Champlain Basin for the foreseeable future. The best protective strategy, with or without climate change in the picture, will be to keep them out in the first place. In particular, more state and federal funding is needed for the design and construction of dispersal barriers that can discourage invasive species from entering the lake via the Champlain and Chambly Canals.
- Vermont, New York and Quebec should adopt consistent invasive species policies and enforcement that include stronger bait bucket laws, live-well cleaning programs, engine-flushing prohibitions, and prohibitions on introduction of nonnative species.
- Fund and strengthen efforts to educate the public about the causes and consequences of invasive species introductions, especially by expanding monitoring and educational activities of lake steward programs at boat launches.
- More effective federal regulation is needed to reduce airborne mercury deposition in the Northeast.
- More efforts are needed at all levels to reduce CO_2 emissions.

Glossary

AOGCMs: Atmospheric and Oceanic General Circulation Models

LCBP: Lake Champlain Basin Program

IPCC: Intergovernmental Panel on Climate Change

NOAA: National Oceanic and Atmospheric Administration

USGS: United States Geological Survey

USHCN: United States Historical Climatology Network

Trophic: related to feeding interactions among members of a food web.

Oligotrophic: clear water with an abundance of dissolved oxygen and a deficiency of plant nutrients.

Eutrophication: the process by which a body of water becomes rich in dissolved nutrients that stimulate plant and phytoplankton growth, often with a deficiency in dissolved oxygen.

Cultural eutrophication: when eutrophication is caused by human-generated pollution.

Benthic: pertaining to lake or stream bottoms.

Pelagic: pertaining to deep, offshore waters.

Littoral: the shallow nearshore zone in lakes and freshwater ecosystems where light penetration to the bottom allows the growth of rooted plants.

Hypolimnion: lower, cooler, noncirculating water in a thermally stratified temperate lake in summer.

Epilimnion: upper warm relatively thin (usually) mixed layer in a thermally stratified lake in summer—lying over the deeper usually considerably thicker, cold hypolimnion.

Riparian: pertaining to the banks of rivers and streams.

Phytoplankton: autotrophic (cyanobacteria, protists, plants) plankton.

Zooplankton: heterotrophic (protists and animals) plankton.

Hypoxia: low in dissolved oxygen content, pertaining here to water.

Key ecological attributes: aspects of natural-system or species-assemblage biology or ecology that, if missing or altered, would lead to the loss of viability or integrity over time.

Adaptation: adaptation to climate change refers to adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities.

Sources: "Glossary of Pelagic Biogeography," (1990) by R.K. Johnson, B.J. Zahuranec, D. Boltovskoy and A.C. Pierrot-Bults; The Nature Conservancy; and the Intergovernmental Panel on Climate Change

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