BREE

Basin Resilience to Extreme Events
in the Lake Champlain Basin

REFERENCE MANUAL FOR UNDERGRADUATE INTERNS

2019-2020

Vermont EPSCoR
CWDD
Center for Workforce Development & Diversity
AT SAINT MICHAEL'S COLLEGE

VT EPSCoR Basin Resilience to Extreme Events (BREE) in the Lake Champlain Basin
Undergraduate Intern Program 2019-2020

Introduction:

Established in 2011, and funded by the National Science Foundation, the VT EPSCoR Center for Workforce Development and Diversity (CWDD) focuses on the goal of increasing both the Vermont Science-Technology-Engineering-Math (STEM) workforce and the diversity within it. The CWDD in its current form was created within the Basin Resilience to Extreme Events (BREE) award. BREE focuses on understanding the effects of extreme climate events, such as flooding and droughts, on the Lake Champlain Basin, and on developing adaptive management strategies for the Basin.

Scientists involved with BREE value the need for understanding these extreme events and their effects both within and outside the boundaries of the Lake Champlain Basin. With this in mind, BREE has been working with teams from outside of the Basin and out of state, including Puerto Rico. Since one extreme event can have a multitude of effects across the country, and because we expect the frequency of such events to increase, BREE scientists value the data that our High School teams gather within and outside of the Lake Champlain Basin.

BREE builds transdisciplinary teams of social and natural scientists to study the Lake Champlain Basin as a coupled human and natural system affected by climate change. We combine collections of data on physical processes, governance, and land use with complex systems modeling. The models developed under BREE will enable scenario testing to help Basin managers and policy makers investigate how adaptive management can be designed and implemented to respond to a changing climate. Below is the overarching question BREE aims to answer, and the main tasks each research team contributes towards that answer.

<u>Overarching Question</u>: What are the properties within the Lake Champlain Basin that drive hydrologic and nutrient responses to extreme events, and what are strategies for increasing resilience to protect water quality in the social ecological system?

<u>Ecological Systems Team</u>: Developing a new configuration of environmental sensors in an observation network that spans the important interface between the terrestrial and aquatic environment. Developing a coupled hydrological and biogeochemical model of this interface zone.

<u>Social Systems Team</u>: Considering a set of stakeholders within the basin and drawing on agent-based modeling and network analysis. Building calibrated, predictive models of the governance networks responsible for promoting existing and future hazard reduction practices for water quality resilience.

Integration Team: Developing the BREE Integrated Assessment Model (IAM) using complex systems approaches. This model allows for realistic simulations of the decision-making processes that potentially promote resilience for water quality.

CWDD increases the Vermont Science-Technology-Engineering-Math (STEM) workforce in size and diversity through multiple approaches:

- Inspire diverse high school students and undergraduates to enter STEM careers by involving them directly in BREE research. Support the professional development of high school and middle school teachers through involving them in BREE research.
- Match undergraduate interns with BREE research mentors.
- Target support for girls and underrepresented minorities, veterans, economically disadvantaged high school students, and students with disabilities.
- Involve students from Vermont, Puerto Rico, and other U.S. locations outside of Vermont to bring a diverse pool of participants into the STEM pipeline.
- Hold the VT EPSCoR Student Research Symposia through which CWDD participants share research results and network with other STEM professionals.
- Support Native American and First Generation Vermont college students through scholarships to study STEM majors in Vermont.
- Support Vermont Works for Women's scholarship program for middle school girls to attend the STEM summer Rosie's Girls program.

BREE Undergraduate Internship Events & Research Timeline

More information regarding these events will be emailed to you as the date approaches. If for any reason your preferred email changes during or after the internship, you must let us know your new email address. We will be using email as our main form of communication.

Date	Internship Event
May 28 – May 31	Orientation at Saint Michael's College/University of Vermont
Tuesday, June 4	EPSCoR BREE All Hands Meeting
Tuesday, June 25	Workshop: Poster Prep Session #1
Tuesday, July 9	Workshop: Personality Traits and Research Distilling
Thursday, July 18	Workshop: Poster Prep Session #2
Thursday, August 1	Research Symposium & Send-off Dinner

Timeline	Research Requirements
Weeks 2 - 3	Discuss research description and project ideas with mentor, determine research question, create sampling design (if appropriate), literature search
Weeks 3 - 7	Collect and begin analyzing data, begin work on poster/presentation, write introduction and methods sections
Monday, June 24 (Week 4)	Individual Research Description due to CWDD (submit paragraph explaining your research project to cwdd@smcvt.edu)
Weeks 7 - 9	Complete data analysis, make figures, write results and discussion
Monday, July 22 (Week 9)	Last day to submit draft of poster/presentation to mentor
Friday, July 26 (Week 9)	Last day to submit poster/presentation to the CWDD
Your mentor should be helping you with your Symposium product throughout the 10-week internship period. It is the goal of the CWDD to give you some undivided time to work on your poster/presentation during the two Poster Session Workshops.	

VT EPSCoR

Basin Resilience to Extreme Events (BREE) Internship Program - Summer 2019

Manual Contents

VT EPSCoR Center for Workforce Development and Diversity
Saint Michael's College
One Winooski Park, Box 137
Colchester, VT 05439

Email: *cwdd@smcvt.edu*
Phone: 802.654.3270
Website: *www.uvm.edu/~cwdd*
Fax: 802.654.2940

VT EPSCoR
BREE Intern Payroll Instructions and Schedule
May 28 – August 2, 2019

To report your hours, please send an email with your timesheet to cwdd@smcvt.edu before 4:00 pm on the Friday listed on the Payroll Schedule. Make sure to cc your mentor on each email. If you report your hours late, you will not get paid until the following pay period. An email reminder will be sent on Wednesday before the deadline.

Pay periods technically end on Saturday (one day after you are due to report your timesheet), so if you plan to work on Saturday, please provide an estimate of the number of hours you will be working. You must submit a correction to cwdd@smcvt.edu if your actual hours worked differ from that of your estimate. As a temporary grant-funded employee, you may not be paid for more than 40 hours in a given week. This is important: please do not submit a timesheet with more than 40 hours worked in any week.

NOTE: Your first paycheck will be a paper check, even if you chose to use direct deposit. This paycheck will be mailed to whichever address appears on your HR paperwork, so keep in mind that this might mean that your first check is mailed out-of-state to your permanent address. To avoid this, there is an option to have the CWDD hold your first check. Please let LeeAnn know if this is something you're interested in doing.

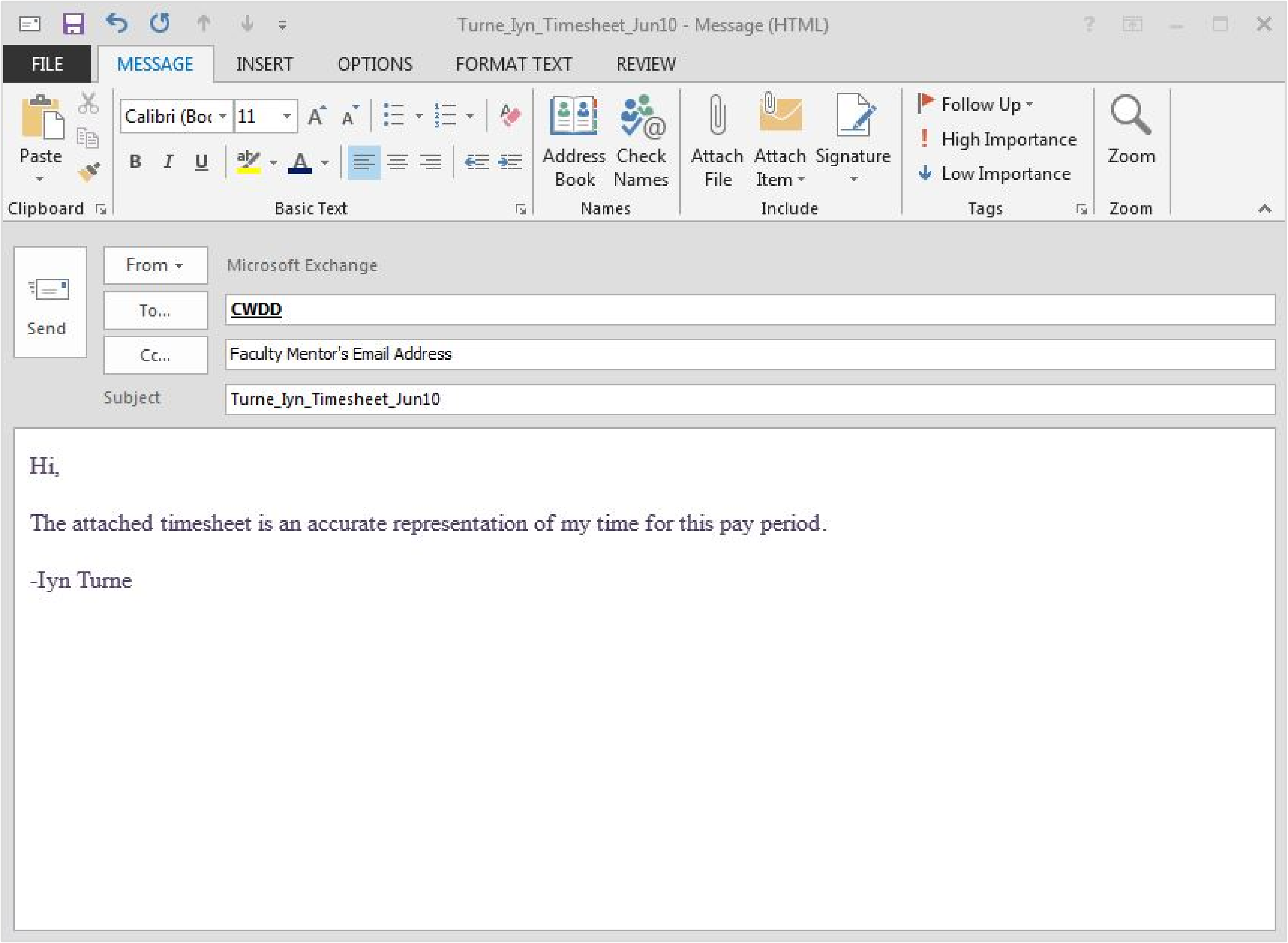
Instructions:

- You will be supplied with an Excel timesheet to be submitted according to the biweekly pay schedule.
- Save this Excel timesheet in your files and add your hours to it each week. The file name will read: "Last Name_First Name_Timesheet.xls".
- Fill out the timesheet daily according to the hours you work during each two-week pay period. As a temporary grant-funded employee, you may not work more than 40 hours in a given week. Please do not submit a timesheet with more than 40 hours worked in any week.
- On the Wednesday before the timesheets are due, you will receive an email reminding you to submit your timesheet on that Friday.
- Send the completed timesheet as an attachment to an email and copy your mentor:
  - Subject line: "Last Name_First Name_Timesheet_Date" (the Date is the pay period ending date: Jun 10, Jun 24, etc., as listed on the Payroll Schedule).
  - State in the body of the email that: "The attached timesheet is an accurate representation of my time for this pay period". This statement is required by HR.
  - Attach the timesheet to the email.
  - Send the email to LeeAnn at cwdd@smcvt.edu (make sure to **cc your mentor**).

2019 Payroll Schedule

Period Start	Period End	Timesheets Due	Check Date
Sun, May 26	Sat, Jun 08	**Fri, Jun 07**	Fri, Jun 14
Sun, Jun 09	Sat, Jun 22	**Fri, Jun 21**	Fri, Jun 28
Sun, Jun 23	Sat, Jul 06	**Fri, Jul 05**	Fri, Jul 12
Sun, Jul 07	Sat, Jul 20	**Fri, Jul 19**	Fri, Jul 26
Sun, Jul 21	Sat, Aug 03	**Fri, Aug 02**	Fri, Aug 09

Example Timesheet Email:



From: Microsoft Exchange

To...: **CWDD**

Cc...: Faculty Mentor's Email Address

Subject: Turne_Iyn_Timesheet_Jun10

Hi,

The attached timesheet is an accurate representation of my time for this pay period.

-Iyn Turne

Research Internship Guidelines

As with any academic work, we expect the work that you do for the Vermont EPSCoR program to be completed in a professional manner using your own words and concepts, or correct use of citations where appropriate. Below are definitions and resources to assist you in conducting high quality, professional research.

Plagiarism

Plagiarism is a **very serious** offense and will not be tolerated by Vermont EPSCoR and the Basin Resilience to Extreme Events program.

Plagiarism is often thought of as passing work completed by someone else off as your own. This represents an extreme case. Plagiarism takes a number of subtler forms as well, from improper paraphrasing or citation of a resource, to passing an existing idea or concept off as your own. As you conduct your research and draft your poster or oral presentation, please review the following web page to familiarize yourself with the different forms of plagiarism:

http://www.plagiarism.org/

Professionalism

The Vermont EPSCoR staff, faculty, postdocs, and graduate students are all excited to be working with you, though it's important to keep in mind that people have other time commitments. To best use your time and that of others, please consider the following:

- Come to meetings prepared with ideas and questions you'd like to discuss.
- If you need help or have questions related to your research don't wait until the last minute to set up a meeting with your mentor.
- Review your poster thoroughly yourself before asking your mentor to review it.
- Do not wait until the last minute to work on your poster – the later you start, the more work you will have to do on it during your next schoolyear.
- Be on time – this applies to meetings, work, and deadlines.
- Respect your research, respect yourself, respect your mentor, and respect your fellow interns.

Data Analysis

You should begin thinking about preparing your poster or oral presentation for the annual Vermont EPSCoR Student Research Symposium in March/April as soon as possible. Your poster or oral presentation will describe your research and your contribution to the overall BREE effort.

If your project includes data analysis, the CWDD **data analysis tutorial** may be useful. This tutorial guides you through the process of exploring and asking more in-depth analysis questions about your dataset. The tutorial can be found on the Vermont EPSCoR website here:

http://www.uvm.edu/~epscor/new02/?q=node/1027

The link on the page that says “Complete Tutorial Series - All Modules” will open a .pdf with all of the modules compiled into one document. The subsequent links are for accessing modules individually. The tutorial guides you through working with the online Streams Project dataset, which may or may not pertain to your work, however the guidance on working with datasets is applicable to many types of datasets. The following is a list of the individual modules and what they cover:

- Module 1: What is Science?
- Module 2: Understanding Streams Project Data
- Module 3: Refining and Retrieving Data
- Module 4: Data Exploration
- Module 5: Statistical Analysis
- Module 6: Summarizing Results and Drawing Conclusions

In this tutorial, statistical analysis is demonstrated using Microsoft Excel. Within each module, look for the “WATCH VIDEO” icon that looks like this:

These videos help you visualize a number of procedures outlined in the tutorial.

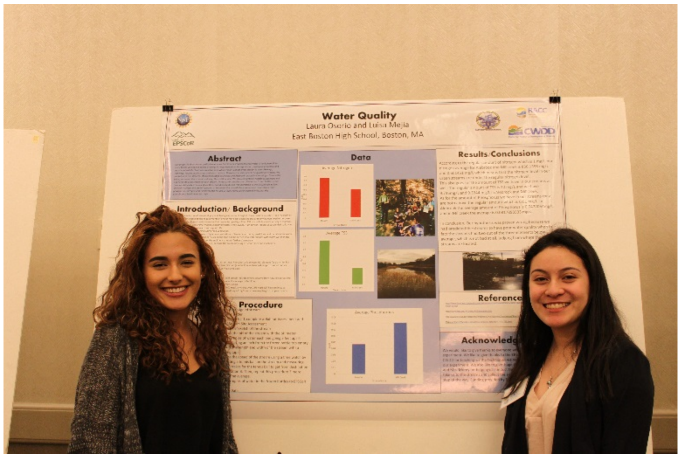
Presenting Your Data: Vermont EPSCoR Student Research Symposium

All participants of the BREE Undergraduate Internship program ***commit*** to presenting their research findings at the annual Vermont EPSCoR Student Research Symposium. A symposium is a great way for researchers to present and discuss their work and it provides an important channel for the exchange of information between researchers. At the Vermont EPSCoR Student Research Symposium, participants have the option to choose whether they present their research through a poster or an oral presentation. Both are great ways to share your work!

Posters versus Oral Presentations

Although it can be challenging to present a year's worth of work in 10 minutes, oral presentations can be a rewarding experience because you are the only one in front of an audience whose attention you know you have. Oral presentations are brief and consequently the presentation must be clearly and succinctly presented.

Posters are a visual presentation of information that is understandable to the viewer without verbal explanation. Poster presenters have the opportunity to share their work with one person at a time, over an extended period of time. This allows the presenter to describe and discuss their research in greater detail than would be possible in an oral presentation to significantly more people, and allows for dialogue with poster viewers.



Posters

A research or academic poster provides a means of communicating your research at a conference or research symposium. Posters printed by Vermont EPSCoR are 3' x 4' (or 36" x 48"), horizontally or vertically aligned. Submit your final poster file by July 26th. The CWDD will print and set up your poster at the symposium.

How to Create a Poster Using PowerPoint

For many, this is the first time creating a research poster. Here are some tips for making an informative and attractive research poster:

1. Open PowerPoint
2. Click the 'Design' menu/tab at the top of the screen and select 'Page Setup'
    i. Change the dimensions of the slide from the default setting to: Width=48, Height=36 (for a horizontal poster), or Width=36, Height=48 (for a vertical poster). This is an important **FIRST** step – if you change the dimensions after putting content on the slide, you will have to re-format all text boxes, graphs, tables, photos, etc.
3. Critical poster elements:
    i. Title, Author(s) and affiliation(s)
    ii. Abstract/Summary (*optional*)
    iii. Introduction/Background: a brief but important overview to secure the viewer's attention
    iv. Materials and Methods: a brief description of the processes and procedures used, photos (*optional*) should be >300dpi
    v. Results: outcomes, findings and data displayed through text, tables, graphs, photos, etc.
        - Bulleted lists (rather than paragraphs) may help the reader understand the most important findings
        - Tables, graphs and photos should have captions. Graphs should have a legend, avoid 3-D graphs as they are hard to interpret
    vi. Discussion/Conclusions: summary or discussion of the significance and relevance of the results, identify possible future research
    vii. References
    viii. Acknowledgements
    ix. The following text **MUST** be somewhere on the poster: Funding provided by NSF Grant OIA-1556770
4. Upload final poster via a link provided by the CWDD (Spring 2019)

Tips:

A. Use the "Designing Conference Posters" website to get ideas on poster layout and to download poster templates: http://colinpurrington.com/tips/academic/posterdesign
B. Choose a background and text color scheme. No need to go crazy: a white/light poster with black/dark text is often much easier to read than a multi-colored poster. Use cool/muted colors, solid colors, a color scheme, etc.
C. Lettering can make a difference in how easy-to-read your poster is. Here are some suggestions:
    - Title: at least 72 pt., bold preferred
    - Section Headings: at least 48 pt., bold preferred
    - Body Text: at least 24 pt.
    - Avoid using all capital letters
    - Use sans serif (Arial) for titles & headings
    - Use serif (Times New Roman) for body text
    - Use bulleted lists where possible instead of paragraphs

- Use *italics* instead of underlining
- White or light colored lettering is hard to read on a dark background when printed. Use black lettering instead on a light colored background

D. Logos: Do not forget to include the logos for the organization(s) that helped make the research possible

- Funding source: The National Science Foundation's (NSF) logo can be used by recipients of NSF support for the sole purpose of acknowledging that support: https://www.nsf.gov/policies/logos.jsp. The following text **MUST** be somewhere on the poster: Funding provided by NSF Grant OIA-1556770
- VT EPSCoR, BREE, CWDD and others if they were important contributors. Logos are available on the "Resources" website: http://www.uvm.edu/~epscor/new02/?q=node/900
- Your school logo – get the highest quality logo from your school's website

Example posters from the latest Student Research Symposium:

https://epscor.w3.uvm.edu/2/node/4591

Oral Presentations

A research talk provides a means of communicating your research at a conference or research symposium. Oral presentations at the VT EPSCoR Student Research Symposium are limited to 10 minutes: 8 minutes to present your research, 2 minutes for the audience to ask questions. Presenters often use the general rule of "2 slides per minute"; however the number of slides needed varies based on the complexity of the content of the slides. Submit your final PowerPoint file to the CWDD by July 26th and bring the file to the symposium on a USB drive. The CWDD will provide the computer, screen, podium, microphone and laser pointer for your use.

Oral Presentation Structure (*suggested*):

- Title, Author(s), Affiliation (1 slide)
- Outline, *optional* (1 slide): overview of the structure of your talk, some speakers prefer to put this at the bottom of their title slide, audiences like predictability
- Introduction/Background
    - Motivation and problem statement (1-2 slides): Why should anyone care? Most researchers overestimate how much the audience knows about the problem they are addressing.
    - Related Work (0-1 slides)
    - Methods (1 slide): Cover quickly in short talks
- Results (4-6 slides): Present key results and key insights. This is the main body of the talk. Its structure varies greatly as a function of the research conducted. Do not superficially cover all results; cover key result well. Do not just present numbers; interpret them to give insights. Do not put up large tables of numbers as your audience will not have time to take in that much information at once.
- Discussion/Conclusions (1 slide): summary or discussion of the significance and relevance of the results, identify possible future research.
- References
- Acknowledgements
- The following text **MUST** be somewhere on your slides: Funding provided by NSF Grant OIA-1556770

Logos: Do not forget to include the logos for the organization(s) that helped make the research possible!

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- Your school logo – get the highest quality logo from your school's website

Example presentations from the latest Student Research Symposium:

https://epscor.w3.uvm.edu/2/node/4589

Additional resources (http://epscor.w3.uvm.edu/2/node/2238) featuring links to:

» VT Department of Environmental Conservation Lake Champlain Long Term Monitoring

» VT Department of Environmental Conservation Volunteer Monitoring

» USGS Stream Gauge Data » Vermont Water Quality Data

» NOAA Quality Controlled Local Climatological Data

» VT EPSCoR Data Analysis Tutorials » Data Analysis in Excel

Present your research!

There are many venues in which you can participate and present the research you conduct this summer. You are ***required*** to present your project at the Vermont EPSCoR Student Research Symposium on August 1, 2019, and we encourage you to also present your research at other conferences to gain valuable experience. Scientific and policy associations and organizations exist for every discipline and most encourage undergraduate participation. Check with your department/college and faculty mentors to learn about these opportunities!

These are some annual symposia/conferences, but certainly check with faculty at your home institution:

Saint Michael's College Symposium (Late April, annually)
Sponsored by the SMC Undergraduate Research Committee, the Symposium is a day set aside by the College community for the presentation of student scholarship such as a thesis, research project, or performance. (https://www.smcvt.edu/on-campus/academic-symposium.aspx)

UVM Student Research Conference (Late April, annually)
As part of the University of Vermont's weeklong celebration of student achievement, the UVM Student Research Conference (SRC) showcases the research and scholarly activity of undergraduate, graduate and medical students across campus. All students working on a research or creative project with a UVM faculty member are eligible to present some aspect of their research at this forum. Research and creative projects at any stage of completion are welcome. The event also serves as a resource for students who are not yet involved with research but wish to learn about how to engage in research pursuits. (https://www.uvm.edu/four/student-research-conference)

SACNAS Conference (Society for Advancement of Hispanics/Chicanos and Native Americans) in Science; October 31- November 2, 2019
In 2019, this national conference will be held in Honolulu, Hawai'i. The SACNAS National Conference showcases cutting-edge science and features mentoring and training sessions for students and scientists at all levels. (https://www.sacnas.org/conference/)

ABRCMS Conference (Annual Biomedical Research Conference for Minority Students); November 13-16, 2019
In 2019, this national conference will be held in Anaheim, California. This is one of the largest communities of underrepresented minorities in science, technology, engineering and mathematics. Students attend this conference to present their research, explore graduate schools, and network. (http://www.abrcms.org/)

AGU Conference (American Geophysical Union); December 9-13, 2019
In 2019, this international conference will be held in San Francisco. AGU is a Union of scientists, working together on a broad spectrum of scientific topics that span all of the Earth and space sciences. (https://sites.agu.org/)

Should you present at any of these symposia or others, please let CWDD know! Email us at cwdd@smcvt.edu with any updates on your professional presentation portfolio. We would also love photos of you in action for our social media pages (and so we can brag about you, of course)!

Field Safety

First Aid Kit

When working in the field, it is important to be prepared for emergencies. Therefore, a well-stocked first aid kit is an important thing to have. Carry a first aid kit with you to your site or keep one in the vehicle. You may purchase a pre-made kit at the store, or you may make your own using the recommended list of items below as a reference. Whichever you chose, it is important to include any personal items such as medications and emergency phone numbers. Check the kit regularly and replace any used or out-of-date items.

Adhesive bandages (assorted sizes)
Antibiotic ointment
Antiseptic wipes
Instant cold compress
Hydrocortisone ointment
Scissors
Sterile gauze pads (assorted sizes)
Butterfly bandages
Tweezers
Prescription medications (asthma inhalers, Epi-pen)
Emergency phone numbers
Charged cell phone

Always notify your mentor when you are going out into the field, and tell them where you will be and for how long you intend to be gone. Never go to a field site alone – always go with *at least* one other person.

Poison Parsnip

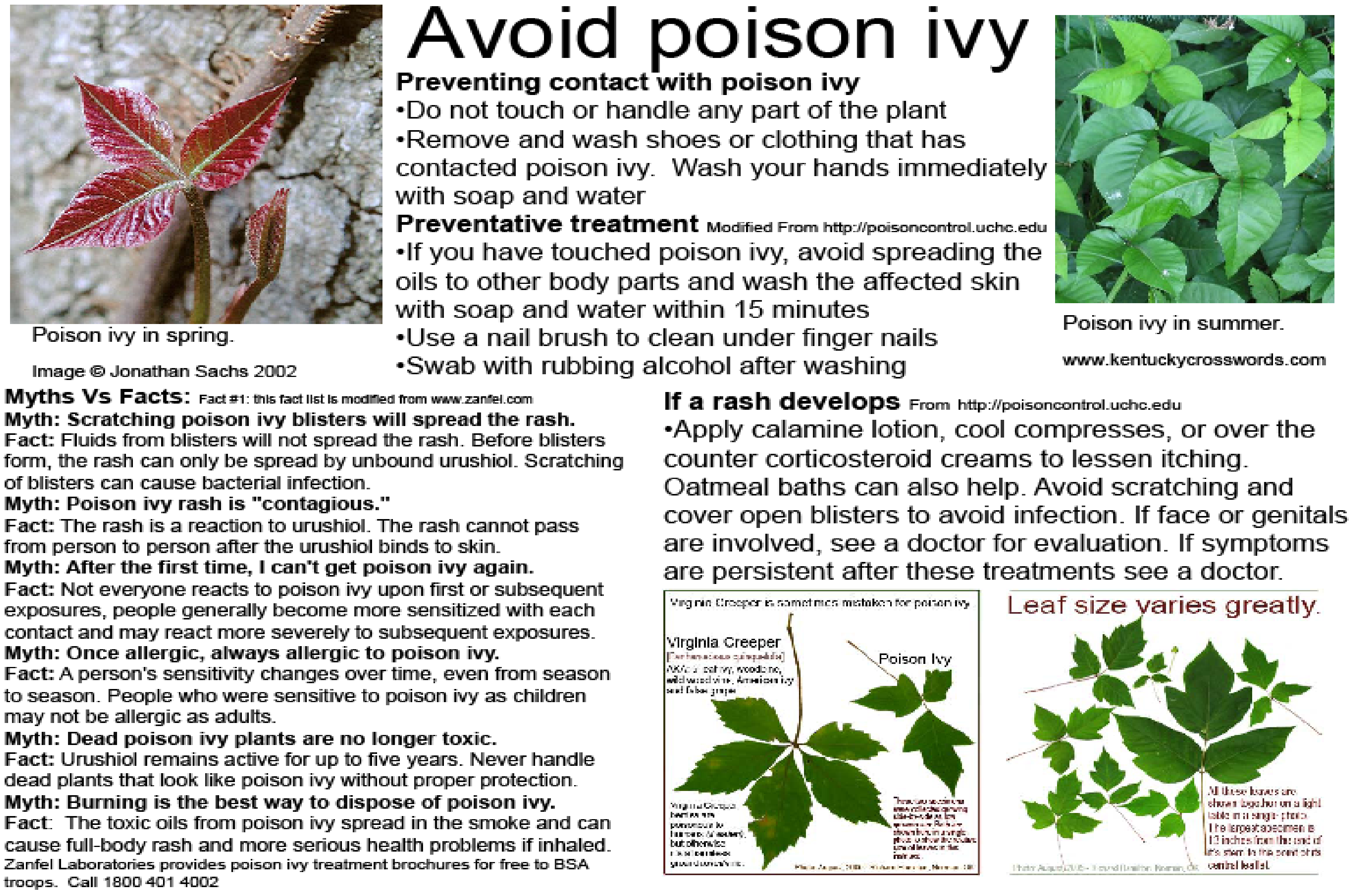
- **<u>Location</u>**: Predominately found on the sides of highways and fields throughout Vermont.
- **<u>Appearance</u>**: The plants typically grow 3-6 feet tall and resemble Queen Anne's Lace, but the flowers are yellow instead of white.
- **<u>Danger</u>**:
    - The plant contains a high concentration of furocoumarin chemicals
    - The plant's juices may be transferred to your skin if you brush against the flower tops or broken leaves or stems
    - When the juices on the skin are exposed to ultraviolet light on both sunny and cloudy days the furocoumarin chemicals bind with nuclear DNA and cell membranes.
    - **This process destroys cells and skin tissue, causing severe burns in which the skin to reddens and blisters**
- **<u>Protecting Yourself</u>:**
    - Avoid exposure to the plant by choosing stream sites or access areas free from poison parsnip
    - If unavoidable, wear long sleeve shirts, pants (or your waders!), and gloves to prevent direct contact with your skin
    - Rinse and wash all clothing items and skin surfaces immediately following possible exposure. Keep exposed skin out of sunlight.

Weather and Insects

Fieldwork may require you to be outdoors during inclement weather. Always check the weather before and even during fieldwork. Use common sense judgements to determine when it is unsafe to exit your vehicle or be in a stream. Be prepared by having several layers or otherwise appropriate clothing (i.e., rain jackets, boots, long pants, etc.). Weather in Vermont can change very quickly!

We are fortunate enough to not have many fatally poisonous organisms here in Vermont, but allergies to bees, hornets, and wasps are common. If you have a known allergy always have your medications/Epi-pen on you while doing fieldwork. If you don't know whether you're allergic or not, it's best to stay away! These critters generally only retaliate – they rarely start attacking unprovoked. If you hear a lot of buzzing near some shrubs, or see several of these insects in a group together, try to avoid walking in that area. For those who are not allergic, a sting from these insects will be a nuisance, but the pain will subside rather quickly. Some nests are found in the ground, so **<u>watch your step.</u>**

Poison Ivy



Avoid poison ivy

Poison ivy in spring.

Image © Jonathan Sachs 2002

Preventing contact with poison ivy

- Do not touch or handle any part of the plant
- Remove and wash shoes or clothing that has contacted poison ivy. Wash your hands immediately with soap and water

Preventative treatment Modified From http://poisoncontrol.uchc.edu

- If you have touched poison ivy, avoid spreading the oils to other body parts and wash the affected skin with soap and water within 15 minutes
- Use a nail brush to clean under finger nails
- Swab with rubbing alcohol after washing

Poison ivy in summer.

www.kentuckycrosswords.com

Myths Vs Facts: Fact #1: this fact list is modified from www.zanfel.com

Myth: Scratching poison ivy blisters will spread the rash.
Fact: Fluids from blisters will not spread the rash. Before blisters form, the rash can only be spread by unbound urushiol. Scratching of blisters can cause bacterial infection.

Myth: Poison ivy rash is "contagious."
Fact: The rash is a reaction to urushiol. The rash cannot pass from person to person after the urushiol binds to skin.

Myth: After the first time, I can't get poison ivy again.
Fact: Not everyone reacts to poison ivy upon first or subsequent exposures, people generally become more sensitized with each contact and may react more severely to subsequent exposures.

Myth: Once allergic, always allergic to poison ivy.
Fact: A person's sensitivity changes over time, even from season to season. People who were sensitive to poison ivy as children may not be allergic as adults.

Myth: Dead poison ivy plants are no longer toxic.
Fact: Urushiol remains active for up to five years. Never handle dead plants that look like poison ivy without proper protection.

Myth: Burning is the best way to dispose of poison ivy.
Fact: The toxic oils from poison ivy spread in the smoke and can cause full-body rash and more serious health problems if inhaled.

Zanfel Laboratories provides poison ivy treatment brochures for free to BSA troops. Call 1800 401 4002

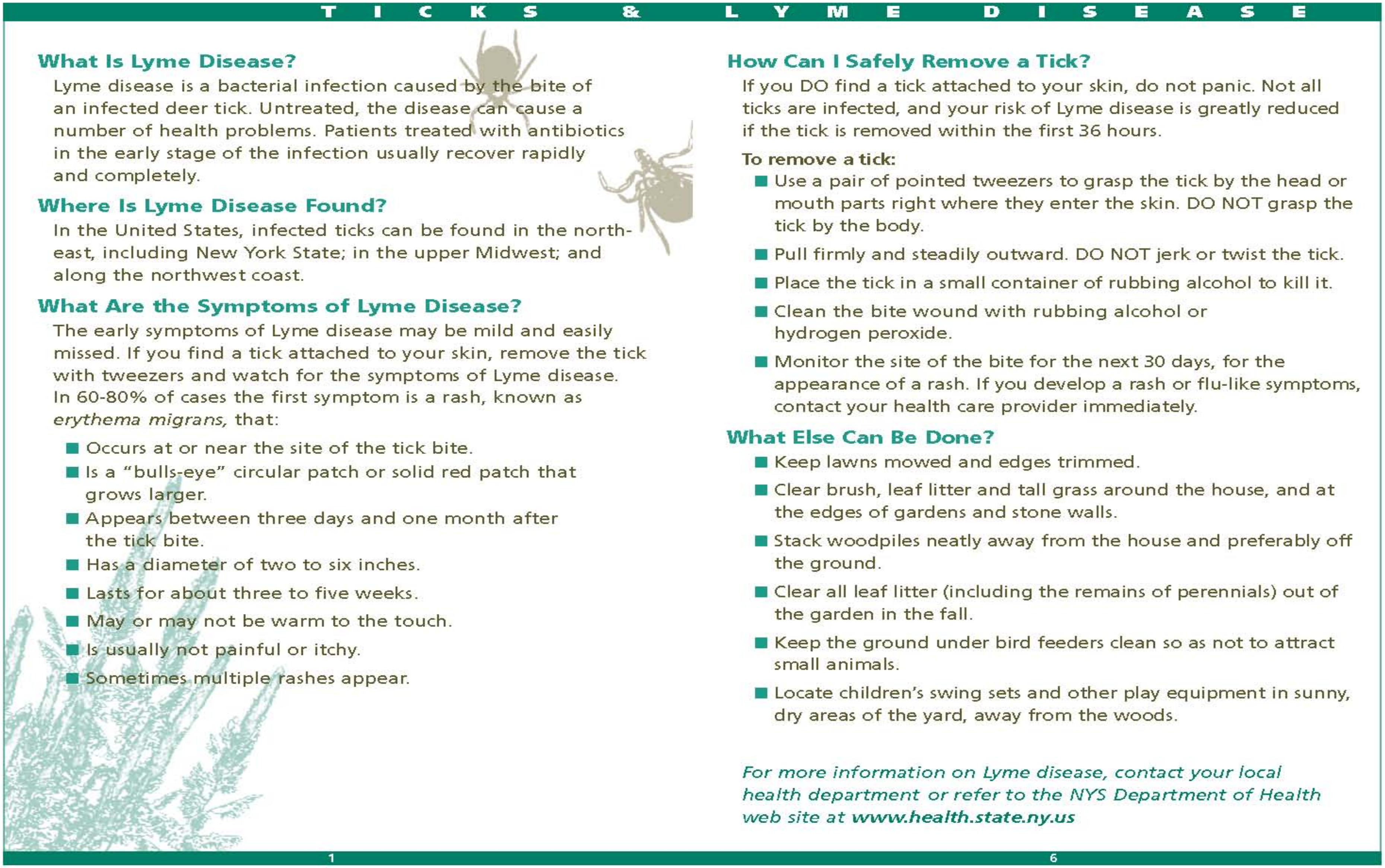
If a rash develops From http://poisoncontrol.uchc.edu

- Apply calamine lotion, cool compresses, or over the counter corticosteroid creams to lessen itching. Oatmeal baths can also help. Avoid scratching and cover open blisters to avoid infection. If face or genitals are involved, see a doctor for evaluation. If symptoms are persistent after these treatments see a doctor.

Virginia Creeper is sometimes mistaken for poison ivy

Leaf size varies greatly.

Ticks & Lyme Disease



What Is Lyme Disease?

Lyme disease is a bacterial infection caused by the bite of an infected deer tick. Untreated, the disease can cause a number of health problems. Patients treated with antibiotics in the early stage of the infection usually recover rapidly and completely.

Where Is Lyme Disease Found?

In the United States, infected ticks can be found in the northeast, including New York State; in the upper Midwest; and along the northwest coast.

What Are the Symptoms of Lyme Disease?

The early symptoms of Lyme disease may be mild and easily missed. If you find a tick attached to your skin, remove the tick with tweezers and watch for the symptoms of Lyme disease. In 60-80% of cases the first symptom is a rash, known as *erythema migrans,* that:

- Occurs at or near the site of the tick bite.
- Is a “bulls-eye” circular patch or solid red patch that grows larger.
- Appears between three days and one month after the tick bite.
- Has a diameter of two to six inches.
- Lasts for about three to five weeks.
- May or may not be warm to the touch.
- Is usually not painful or itchy.
- Sometimes multiple rashes appear.

How Can I Safely Remove a Tick?

If you DO find a tick attached to your skin, do not panic. Not all ticks are infected, and your risk of Lyme disease is greatly reduced if the tick is removed within the first 36 hours.

To remove a tick:

- Use a pair of pointed tweezers to grasp the tick by the head or mouth parts right where they enter the skin. DO NOT grasp the tick by the body.
- Pull firmly and steadily outward. DO NOT jerk or twist the tick.
- Place the tick in a small container of rubbing alcohol to kill it.
- Clean the bite wound with rubbing alcohol or hydrogen peroxide.
- Monitor the site of the bite for the next 30 days, for the appearance of a rash. If you develop a rash or flu-like symptoms, contact your health care provider immediately.

What Else Can Be Done?

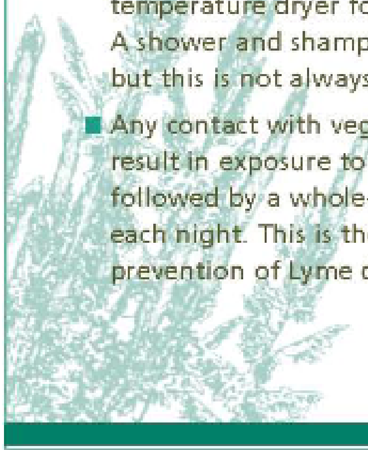
- Keep lawns mowed and edges trimmed.
- Clear brush, leaf litter and tall grass around the house, and at the edges of gardens and stone walls.
- Stack woodpiles neatly away from the house and preferably off the ground.
- Clear all leaf litter (including the remains of perennials) out of the garden in the fall.
- Keep the ground under bird feeders clean so as not to attract small animals.
- Locate children’s swing sets and other play equipment in sunny, dry areas of the yard, away from the woods.

*For more information on Lyme disease, contact your local health department or refer to the NYS Department of Health web site at **www.health.state.ny.us***

- Do NOT apply repellents directly to children. Apply to your own hands and then put it on the child.
- When applying repellents, avoid the child's face and hands.
- Do not apply repellents on skin damaged by sunburn, cuts, bruises or other conditions, such as psoriasis.
- Avoid prolonged and excessive use of DEET.
- Do NOT apply repellents in enclosed areas.
- Do NOT apply directly on your face.
- Do NOT apply near eyes, nose or mouth.
- Wash treated skin and clothing after returning indoors.
- If you believe you or a child is having an adverse reaction to a repellent containing DEET, wash the treated area immediately and contact your local health care provider or local poison control center.

Also consider these important facts:

- If you tuck pants into socks and shirts into pants, be aware that ticks will climb upward to hidden areas of the head and neck, so spot-check clothes frequently.
- Clothes can be sprayed with DEET or treated with permethrin. Follow label instructions carefully.
- Upon returning home, clothes can be put in a high temperature dryer for 20 minutes to kill any unseen ticks. A shower and shampoo may help to dislodge crawling ticks, but this is not always effective.
- Any contact with vegetation, even playing in the yard, can result in exposure to ticks. Frequent tick checks should be followed by a whole-body examination and tick removal each night. This is the single most effective method for prevention of Lyme disease.



Ticks will attach themselves anywhere including the thighs, groin, trunk, armpits and behind the ears. If you are infected, the rash may be found in one of these areas.

Around the time the rash appears, other symptoms, such as joint pain, chills, fever and fatigue can occur, but they may seem too mild to require medical attention. As Lyme disease progresses, severe fatigue, a stiff aching neck, and tingling or numbness in the arms and legs, or facial paralysis can occur.

The most severe symptoms of Lyme disease may not appear until weeks, months or years after the tick bite. These can include severe headaches, painful arthritis, swelling of the joints, and heart and central nervous system problems.

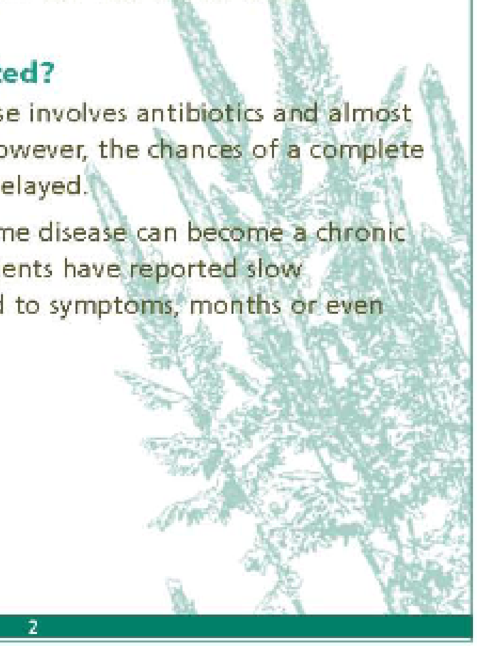
How Is Lyme Disease Diagnosed?

If you think you have Lyme disease, you should see your health care provider immediately. Early diagnosis of Lyme disease should be made on the basis of symptoms and history of possible exposure to ticks. Blood tests may give false negative results if performed in the first month after the tick bite.

How Is Lyme Disease Treated?

Early treatment of Lyme disease involves antibiotics and almost always results in a full cure. However, the chances of a complete cure decrease if treatment is delayed.

In a small number of cases, Lyme disease can become a chronic condition. However, some patients have reported slow improvement and even an end to symptoms, months or even years after treatment.



How Can I Protect Against Ticks and Prevent Lyme Disease?

Deer ticks live in shady, moist areas at ground level. They will cling to tall grass, brush and shrubs, usually no more than 18-24 inches off the ground. They also live in lawns and gardens, especially at the edges of woods and around old stone walls.

Deer ticks cannot jump or fly, and do not drop onto passing people or animals. They get on humans and animals only by direct contact. Once a tick gets on the skin, it generally climbs upward until it reaches a protected area.

In tick-infested areas, your best protection is to avoid contact with soil, leaf litter and vegetation. However, if you garden, hike, camp, hunt, work, or otherwise spend time in the outdoors, you can still protect yourself:

- **Wear light-colored clothing** with a tight weave to spot ticks easily.
- **Wear enclosed shoes, long pants and a long-sleeved shirt.** Tuck pant legs into socks or boots and shirt into pants.
- **Check clothes and any exposed skin frequently** for ticks while outdoors.
- **Consider using insect repellent.**
- **Stay on cleared, well-traveled trails. Avoid contacting vegetation.**
- **Avoid sitting directly on the ground or on stone walls.**
- **Keep long hair tied back,** especially when gardening.
- **Do a final, full-body tick check at the end of the day** (also check children and pets), and remove ticks promptly.

What Do Ticks Look Like?

Two common types of ticks are dog ticks and deer ticks. Deer ticks can carry Lyme disease. Dog ticks can carry Rocky Mountain spotted fever but have not been known to carry Lyme disease.


Deer Ticks Actual Size


Enlarged View Female Deer Tick

Female deer ticks have four pairs of legs and are red and black in color, while the male is all black. Young deer ticks - nymphs, are brown, the size of poppy seeds and very difficult to spot. An adult deer tick is only about the size of a sesame seed – still very small.


Adult Dog Tick Actual Size


Enlarged View, Male and Female Dog Ticks

Dog ticks are the most common type of tick, and, while feeding, can be as large as a small pea. They have four pairs of legs, are reddish-brown and are easier to spot. Dog ticks turn gray while feeding. Ticks can be found throughout the year, but they are most active during the spring, early summer and fall, when it is warm and moist.

What About Insect Repellent?

Two active ingredients found in repellents are DEET (the label may say N, N-diethyl-m-toluamide) and permethrin. Permethrin is only used on clothes. DEET repellents or products come in many different concentrations, with percentages as low as five percent or as high as 100 percent. In general, the higher the concentration the higher the protection, but the risk of negative health effects goes up too. Use the lowest concentration that you think will provide the protection you need. The New York State Health Department recommends taking these precautions when using repellents that contain these active ingredients:

- Store out of the reach of children and read all instructions on the label before applying.
- Do NOT allow children to apply repellents themselves.

Cyanobacteria

What is cyanobacteria?

Cyanobacteria, also known as blue-green algae, are naturally occurring bacteria that are present in Lake Champlain and other water bodies around the world. Like plants, they use photosynthesis to convert sunlight into energy. Usually cyanobacteria cannot be seen by the naked eye. However, under certain conditions, the algae grow prolifically and are visible as blooms. The blooms appear as a cloudy pea green accumulation in the water. Generally, these blooms of cyanobacteria occur when there is a balance of certain factors including: an abundance of available nutrients, warm surface water temperatures, and calm winds.

Why should be concerned?

Unfortunately, certain types of blue-green algae produce toxins or poisons. When the algae die and break down, these toxins are released into the water. Exposure to these toxins have health impacts on humans and animals. Human health effects from cyanobacteria blooms vary depending on the type and duration of exposure (including inhalation of water droplets). In the summers of 1999 and 2000, the deaths of several dogs were linked to the cyanobacteria in Lake Champlain.

Photo source: Lake Champlain Basin Program

Identification and Avoidance: *When in Doubt, Stay Out*

In general, blooms have the appearance of:

- Cloudy water as thick as pea soup or green paint on the water
- While generally green or blue-green in color, they can be brown or even purple
- A thick mat or foam may form as it accumulates onto shore

Blooms usually occur in August or September and can appear and disappear rapidly. There is no accurate way to identify the algae without a microscope. If you are suspicious, simply stay out of and away from the water.

References and Resources:

Check Current Conditions Online:

http://healthvermont.gov/enviro/bg_algae/weekly_status.aspx

Vermont Department of Health's Blue-Green Algae Guidance Document:

http://healthvermont.gov/enviro/bg_algae/documents/BGA_guide.pdf

Websites:

- http://healthvermont.gov/enviro/bg_algae/bgalgae.aspx
- http://www.lcbp.org/water-environment/human-health/cyanobacteria/
- http://www.lakechamplaincommittee.org/lcc-at-work/algae-in-lake/

Photo Galleries:

- http://www.lcbp.org/2012/12/photo-gallery-2008-cyanobacteria-blooms/
- http://healthvermont.gov/enviro/bg_algae/photos.aspx#bg

Report a Blue-green Algae Bloom:

If you have questions or want to report a suspected bloom:
Call 1-800-439-8550 or email AHS.VDHBlueGreenAlgae@state.vt.us

If you believe that someone has become ill because of exposure to blue-green algae, seek medical attention and contact the Health Department at 1-800-439-8550.

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Environmental Research Letters

LETTER

Coupled impacts of climate and land use change across a river–lake continuum: insights from an integrated assessment model of Lake Champlain's Missisquoi Basin, 2000–2040

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Abstract

Global climate change (GCC) is projected to bring higher-intensity precipitation and higher-variability temperature regimes to the Northeastern United States. The interactive effects of GCC with anthropogenic land use and land cover changes (LULCCs) are unknown for watershed level hydrological dynamics and nutrient fluxes to freshwater lakes. Increased nutrient fluxes can promote harmful algal blooms, also exacerbated by warmer water temperatures due to GCC. To address the complex interactions of climate, land and humans, we developed a cascading integrated assessment model to test the impacts of GCC and LULCC on the hydrological regime, water temperature, water quality, bloom duration and severity through 2040 in transnational Lake Champlain's Missisquoi Bay. Temperature and precipitation inputs were statistically downscaled from four global circulation models (GCMs) for three Representative Concentration Pathways. An agent-based model was used to generate four LULCC scenarios. Combined climate and LULCC scenarios drove a distributed hydrological model to estimate river discharge and nutrient input to the lake. Lake nutrient dynamics were simulated with a 3D hydrodynamic-biogeochemical model. We find accelerated GCC could drastically limit land management options to maintain water quality, but the nature and severity of this impact varies dramatically by GCM and GCC scenario.

1. Introduction

In the 'Age of the Anthropocene', changes in ecological systems are increasingly coupled with changes in social, economic and political systems [1, 2]. These coupled complex adaptive systems are broadly defined as 'Social Ecological Systems' (SESs) [3–7]. Social-ecological systems are complex adaptive systems characterized by threshold effects, path dependencies, nonlinear dynamics, multiple basins of attraction, and limited predictability [8]. Natural ecosystems often do not respond smoothly to gradual change [4], and may undergo sudden, threshold-based, nonlinear, long-lasting changes in structure and function [9, 10]. These nonlinear state transitions are amplified in SESs, where regime shifts in social-economic networks may result in rapid changes to resource utilization, resulting in dramatic variation in the stresses placed on ecological communities [4, 9]. Regime shifts in SESs can result in rapid state transitions in a variety of natural ecosystems, including coral reefs and fisheries [10–12], tropical forests and rangelands [13–17] among others. Of particular interest to the current study are well-documented state changes in freshwater lakes resulting from shifting land-use practices in lake catchments [18–28]. In the Lake Champlain Basin of Vermont, New York and Quebec, changes in agricultural activity resulting from evolving socio-economic pressures have resulted in increased nutrient loads to the lake, promoting a rapid shift to eutrophic conditions within significant portions of the lake [29]. The consequences of climate change contributing to the development of intractable eutrophic conditions may suggest that climate change impacts will outpace the land use management type of policy responses now in place in this region being enacted by EPA under the federal water quality act [53]. To understand this, a social-ecological systems approach to modeling these dynamics is needed.

To detect regime shifts in water systems, SES models have been developed using statistical approaches [10], system dynamic models [19, 30], equilibrium models [21] and to some extent process-based approaches; however, implementation of process-based SES models is frequently complicated by cross-scale incompatibilities in domain-specific models [4, 31]. This study aims to develop a computational SES modeling approach to simulate how the cross-scale dynamics of global climate change (GCC) (relatively slow) and regional land-use land cover change (LULCCs) (relatively fast) impact watershed scale hydrological systems (e.g. runoff) and downstream freshwater lakes and their bays (e.g. water quality indicators). Anthropogenic GCC will likely continue to induce higher intensity precipitation, and increase variability in both the precipitation and temperature of the North-Eastern United States [32, 33]. However, there is considerable variability in predictions from different global climate models (GCMs) under different greenhouse gas emission scenarios. It is therefore not clear how these climatic changes at global scales will couple with human induced LULCCs at regional scales to affect the dynamics of the hydrological system at watershed scales. Uncertainty in global scale GCMs, coupled with global green house gas mitigation scenario variability shown through differential representative concentration pathway (RCP) scenarios of IPCC [54], alters boundary conditions for regional scale watersheds and lakes. Usage of a single GCM or a single RCP in setting up policy and management goals at regional scales in the face of uncertainty at global scale dynamics poses fundamental challenges that require development of spatially sensitive and temporally nested computational SES models. This paper presents a proto-type for one of these cross-scale computational SES models, which we call a cascading integrated assessment model (IAM). This IAM is used to quantify the impact of the interaction of GCC induced temperature and precipitation variability with human-system induced LULCC on watershed nutrient loading and the frequency and severity of harmful algal blooms (HABs) in Missiquoi Bay of Lake Champlain for 2000–2040 timeframe under different GCM and RCP scenarios. The paper addresses the following overarching questions: *What will be the coupled impacts of climate change and land use change on riverine nutrient loading to the lake and, when combined with direct climate driven changes to lake water temperature, how will water quality evolve under different RCP and GCM scenarios*?

2. Methods

The cascading IAM (figure 1) is a spatio-temporal model that uses a complex adaptive systems computational approach to study the interactions of climate and LULCC in the Lake Champlain Basin. Statistical downscaling of four GCMs for three RCP scenarios was performed to generate a spatial grid of future temperature and precipitation (section 2.1). In parallel, an agent based model (ABM) simulated four extreme LULCC scenarios (section 2.2). Combinations of climate as well as four LULCC scenarios were used in a distributed hydrological model (RHESSys) to estimate river discharge and nutrient loading from the Missisquoi watershed into Lake Champlain (section 2.3). The nutrient dynamics in Lake Champlain is, in turn, simulated by high resolution hydrodynamic and biogeochemical lake models (A2EM) (section 2.4). The IAM output was calibrated with the USGS stream-flow gage data and water quality sensor data for a baseline scenario. We used the ‘extreme world method’ for alternate scenario generation to compare with the baseline scenario in the Missisquoi SES. The extreme world method captures the broadest possible range of relationships between critical uncertainties, predetermined trends and behaviors of individual and policy level actors in the system under study [59, 60]. The computational integration across models was undertaken in Pegasus (section 2.5).

2.1. Climate change downscaling

We developed an ensemble of topographically downscaled, high-resolution (30″, ~1 km), daily maximum and minimum temperature (at 2 m above the surface) and precipitation simulations by applying an additional level of downscaling to the 1/8° (~12 km) bias correction with constructed analogs dataset (BCCA) [34], hereafter referred to as intermediately

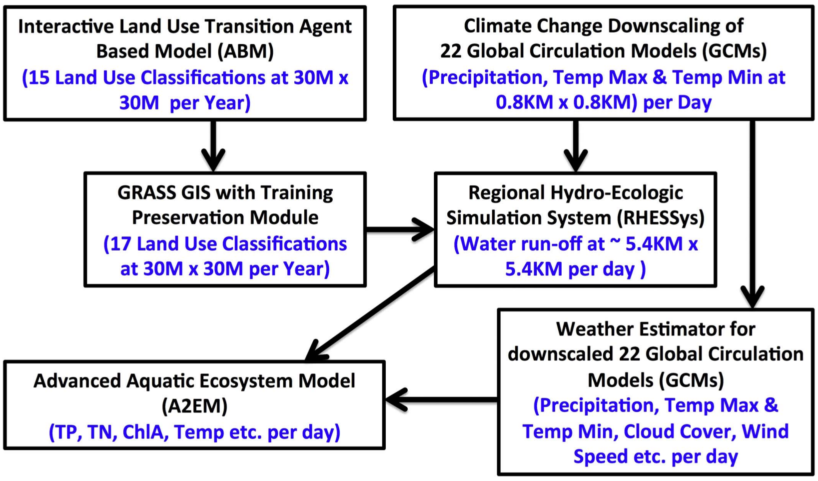

Figure 1. Schematic of the Missisquoi Basin IAM components (black boxes and text) illustrating example input variables and/or impact metric parameters (blue text) for each component, computationally connected (arrows) in a directed acyclic graph environment (Pegasus).

downscaled data. The process used high-resolution elevation and station observations, and consisted of four basic steps [35]: first, empirical relationships between surface temperature and elevation, and precipitation and elevation were derived. Second, the 1/8° intermediately downscaled GCM simulations were adjusted to a reference elevation (200 masl) using the derived relationships and a 1/8° digital elevation model (DEM). Third, the adjusted grids were interpolated to a grid with the resolution of 30″. Fourth, the 30″ interpolated data were topographically adjusted using the derived relationships and a 30″ DEM. The downscaled temperature and precipitation had a lower bias than the initial BCCA data when compared to station observations, especially for the higher elevation areas. The downscaling was particularly successful at decreasing the root mean standard deviation of temperature [35]. Additional methods details can be found in the supplementary materials [S1] and Winter *et al* [35]. The process was run for 63 climate ensemble members, comprising 21 intermediately downscaled GCMs and RCPs 4.5, 6.0 and 8.5. For the purposes of this paper, we chose four GCMs that bracket the range of expected changes in temperature and precipitation. To determine these four GCMs, we compared future trends among the available GCMs for RCP 8.5 and selected the GCMs with the highest and lowest changes in precipitation and average temperature. If one GCM ranked first in two categories, it was kept for one category and the next one ranked was chosen for the other category. We use bias-corrected GCM data, so temperature and precipitation across GCMs are approximately the same for the baseline period (1970–1999). The four GCMs therefore represent the greatest and least warming and largest increase and decrease in precipitation. The aim of this step was to select a subset of GCMs to maintain a manageable number of scenarios while creating a comprehensive set of potential extreme outcomes. We refer to these GCMs as: warm (MIROC-ESM-CHEM), cool (MRI-CGCM3), wet (NorESM1-M), and dry (IPSL-CM5A-MR) GCMs.

Relatively large uncertainty for projected changes in the temperature (figure 2(a)) and precipitation (figure 2(b)) for Missisquoi watershed exist. Using a 5 year average scale, the warm GCM predicted an average temperature increase of 3.6 ± 1 C by 2040 for RCP8.5, relative to the 1970–1999 baseline period. In contrast, the cold GCM only predicted a temperature increase of 1.2 ± 0.7 C. Similarly, the wet GCM predicted 0.35 ± 0.1 mm d^{-1} increase in precipitation for RCP8.5, while the dry GCM predicted 0.08 ± 0.31 mm d^{-1} increase in precipitation for RCP8.5. We note that changes in land use within the IAM do not impact the land use of climate projections. The land use for each individual climate projection is defined by the GCM itself.

2.2. LULCC ABM

The framework of the LULCC ABM, shown in figure S1 of supplementary materials and explained in detail by Tsai *et al* [36] and Zia *et al* [37, 38] consisted of four procedures. First, the ABM initialized agents and parameters based on 2001 National Land Cover Database, zoning and economic development data. Agents were categorized into two major types: human agents, who made land use decisions in each time period given their perceived expected utilities; and land grid cell agents, which produced ecosystem services (ESs) that affected the human agents' expected utilities. Three types of human agents were modeled: agricultural, urban residence and business landowners. Second, the ABM evaluated the landowners' expected utilities for the current year based on ESs produced from agricultural landholding. The agricultural landowners' expected utilities positively

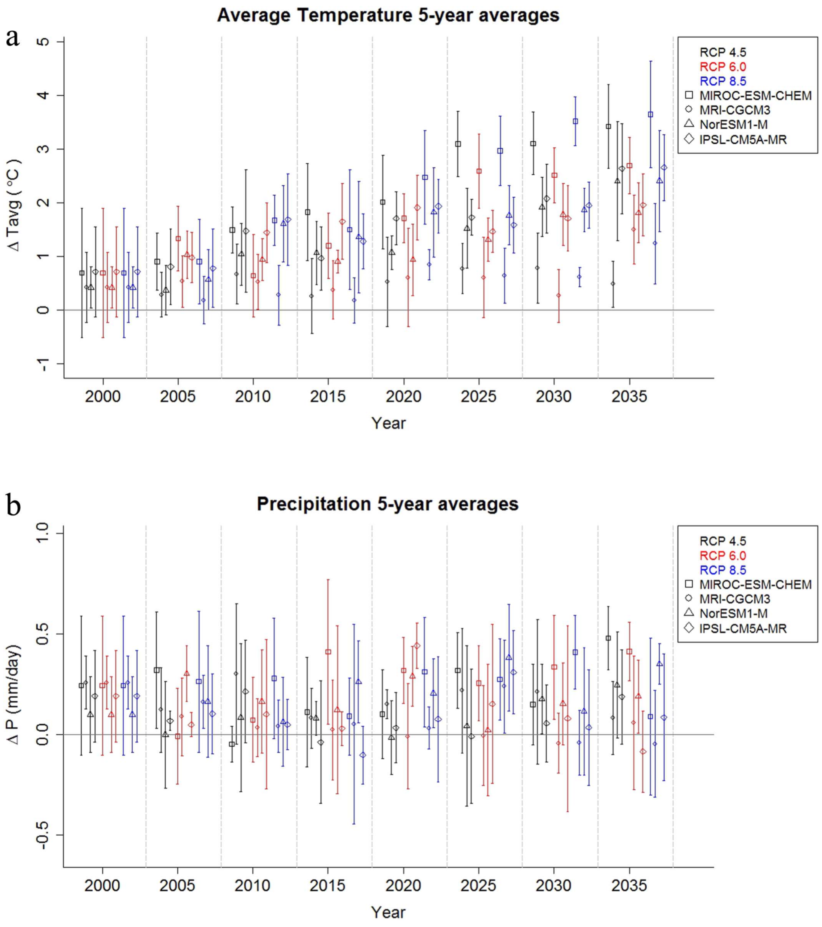

Figure 2. (a) Four GCM projections for three RCP scenarios of temperature change in the Misssisquoi watershed (baseline = 1970–1999). (b) Four GCM projections for three RCP scenarios of precipitation change in the Missisquoi watershed (baseline = 1970–1999).

correlated with ESs gained from managing their lands. The ESs provided by farmers' landholdings were expected to change corresponding to a land use transition. Given the level of the agricultural landowners' expected utilities, different land use decisions were made. When expected utility was small and landholdings were close to urban centers, farm lands were likely to be bought by developers and subsequently turned into urban lands, given that there was a demand for urban residences. Third, the ABM updated both the human and the land cell agents' properties and then re-categorized these agents based on their current properties. Last, the ABM generated simulated land use patterns for every year from 2001 to 2041.

Figure 3 shows four alternate LULCC scenarios derived for the focus watershed that might emerge in response to differential policy and human behaviors during the study period (see supplementary materials S2 for more information on calibration and validation procedures). The calibrated scenario for LULCC projects forward to 2041 allowing the evolution of land use without any major significant policy, economic or governance changes. Henceforth, we call the calibrated scenario increased economic disparity scenario. In contrast, the agriculture expansion scenario assumes significant investments in agriculture (both dairy and crop production), relaxation of current land-use conservation laws/policies, and increases in the main dairy and crop market prices, which lead to farmers' financial gains and, in turn, increase the fraction of farm land in the watershed. This is defined as large wealthy farmers' population (LWFP) scenario. On the other extreme, a forest conservation scenario, 2041 end-state shown in figure 3, assumes the opposite of agricultural expansion scenario: current land-use conservation laws/policies remain intact, main dairy and crop prices remain stagnant, and a sizeable fraction of farmers continue to suffer losses over time, which reduces farm land in the watershed over time compared with the calibrated scenario. The forest conservation scenario is characterized as large poor farmers' population (LPFP) scenario. Finally, the urbanization scenario assumes moderate expansion of urban areas with higher (than calibrated scenario) influx of population and an increase in the size of existing firms and addition of new firms operating in the urban regions that generate new jobs for urban residents (figure 3). The urbanization scenario is called increased development scenario. Given large

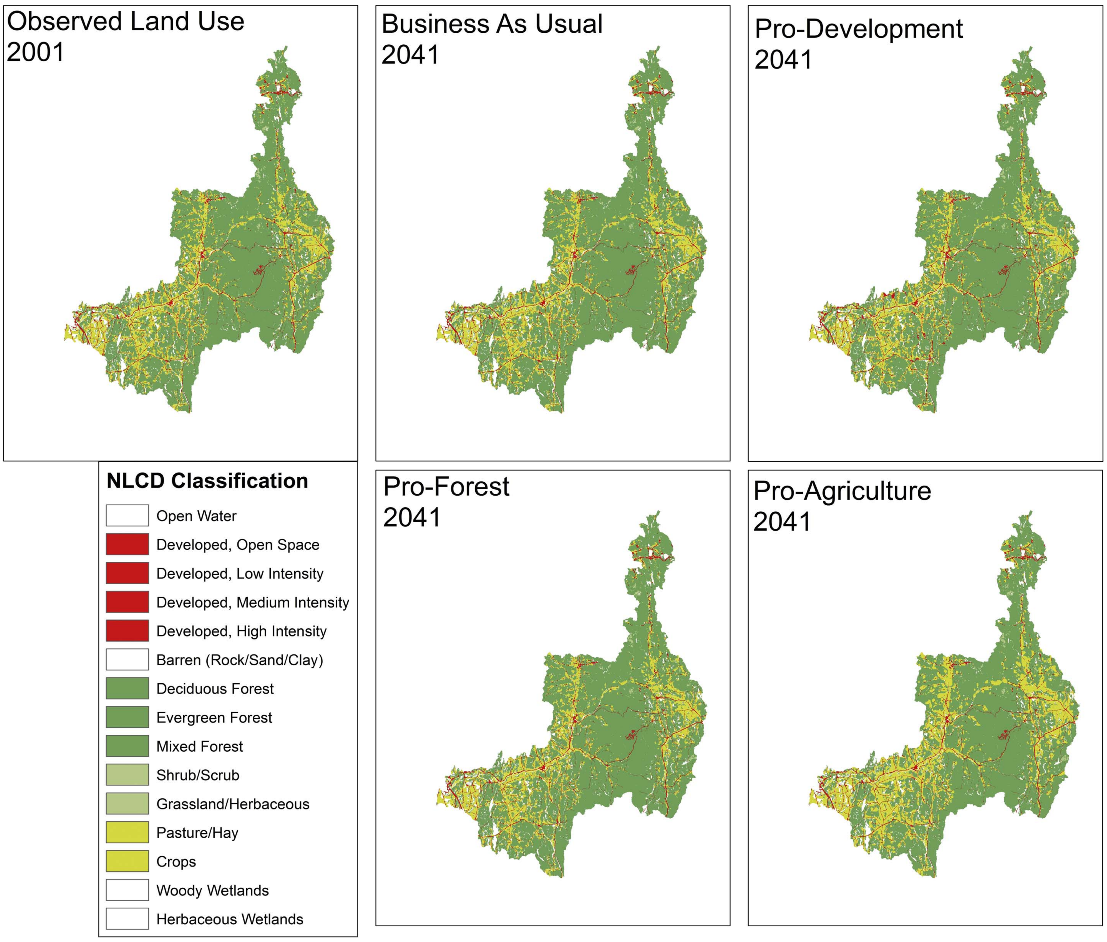

Figure 3. Land-use classifications produced by the LULCC model for four economic and policy scenarios for the final simulation year (2041), also showing initial land-cover at start of simulation.

path dependencies in LULCC, as well as shorter (40 years) simulation horizon, the net changes between agriculture, forest and urban cells within the watershed were relatively small (see table S1). Direct effects of climate change on LULCC are not modeled in this ABM.

2.3. Physically based hydrological model (RHESSys)

The regional hydro-ecologic simulation system (RHESSys) model is a distributed hydrology model designed to simulate interactions between carbon and water fluxes, and climate patterns within a mountainous environment [39, 40]. We employed the RHESSys model here to examine the impacts of climate and LULCC on nutrient loadings within the Missisquoi River watershed. RHESSys combines both a set of physically based process models and a methodology for partitioning and parameterizing the landscape over spatially variable terrain (~10 m to hundreds of kilometers). The RHESSys hydrologic process models have been adapted from several preexisting models and include snow accumulation and melt, interception, infiltration, transpiration, soil and litter interception, evaporation and shallow and deep groundwater subsurface lateral flow. For example, RHESSys uses the Penman Monteith method for evaporation and sublimation of intercepted water, transpiration and soil and litter evaporation processes [41]. RHESSys also uses the Jarvis model for stomatal conductance calculations based on air temperature, vapor pressure deficit, wind speed and other environmental factors such as light and CO_2 [42]. The version of RHESSys used for this work includes both surface and subsurface storage routing and a deep groundwater store. Water is explicitly routed between spatial patches, representing spatial heterogeneity in soil moisture and lateral water flux to the stream (see supplementary materials S3 for calibration details). Figure 4 depicts the RHESSys performance during the calibration year. Simulated runoff results were able to explain about 62% of the variance observed in daily runoff during the calibration year (i.e. Nash Sutcliffe Efficiency = 0.62). The model overestimates the daily runoff by about 6% during the calibration years (i.e. 1998 water year). The annual precipitation amount over the study watershed during the calibrated water year is 1270 mm, and the total observed runoff at the watershed outlet is 755 mm.

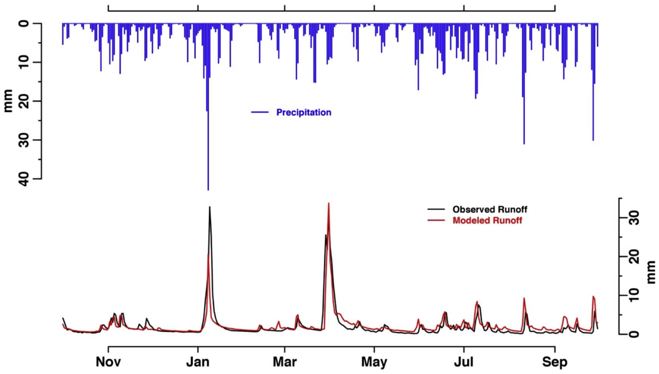

Figure 4. Daily simulated (red line) and observed (black line) runoff during the 1998 water year (October–September) for the Missisquoi River watershed at the USGS streamflow gauge # 04294000. Blue lines on the top give daily precipitation values aggregated over the Missisquoi watershed during the 1998 water year.

2.4. Advanced aquatic ecosystem model

The modeling framework chosen for Missisquoi Bay consisted of a 3D hydrodynamic model known as environmental fluid dynamics code (EFDC) [43, 44]; and a water quality model, row column AESOP (RCA) [55], containing an integrated sediment diagenesis submodel capable of tracking changes in sediment nutrient stores over time [56]. EFDC [43] is widely used and maintained by the US Environmental Protection Agency. EFDC uses a finite volume solution scheme for hydrostatic primitive equations on a staggered grid, and predicts water temperature, flow, and salinity based on meteorological forcing variables and hydrologic inputs. RCA is a water quality model that has been applied in a number of lake, river, and estuary studies to support management decision making [44–49]. This version of RCA has been modified to simulate up to 5 phytoplankton groups, in addition to carbon, oxygen, nitrogen, phosphorus, and silica dynamics, and other ecological processes that are not utilized here. Four phytoplankton groups were represented, approximating spring diatoms, summer eukayotes, non-N-fixing cyanobacteria, and N-fixing cyanobacteria. RCA also has an integrated sediment diagenesis subroutine based on the three G-class model [56], and has the ability to track sediment nutrient deposition, transformation, release, and burial over time. The sediment model consists of a 2-layer representation of the sediment, with a variable-depth oxygenated surface layer, the depth of which is driven by modeled sediment oxygen demand. The sediment model simulates partitioning of $PO_4{}^{3-}$ between dissolved and particulate fractions as a function of sediment oxygen concentrations. Both EFDC and RCA have been modified by LimnoTech (Ann Arbor, MI) to allow cross-model compatibility and simulation of additional processes. The coupled EFDC-RCA model components are collectively referred to as the advanced aquatic ecosystem model (A2EM). A2EM was calibrated using 23 years of long-term monitoring data for temperature, total nitrogen, total phosphorus (TP), and chlorophyll-a (ChlA) at two sites within the bay, in addition to two years of comprehensive high-frequency biological, chemical, and hydrodynamic data collected as part of this study. Detailed description of model calibration is found in the supplemental material (S4.2 and figures S9–S15).

2.5. Model integration

The model interactions in figure 1 are transformed into an abstract computational workflow using the Pegasus workflow management system (figure S16), [50]. Pegasus enables the seamless coupling of different component models within the IAM, allowing necessary input/output data flows between the component models without interruption of execution of the overall IAM. It does so by combining information from a site catalog (describing the execution environment), a replica catalog (providing location of the input data), and a transformation catalog (describing available software) to transform the abstract workflow into a concrete, or executable, workflow. The workflow is then executed with HTCondor [57] on a local 32 core (with hyperthreading) compute resource and NCAR's Yellowstone cluster.

While the total number of tasks that would have to be manually executed in a 40 year, 48-scenario workflow is in the tens of thousands, many of these tasks consist of relatively routine data preparation and analysis scripts. Considering only the main modeling tasks as shown in figure 1, table 1 below shows the breakdown of the number of tasks for each model where **c** is the number of climate scenarios, **s** is the total number of scenarios, and **d** is the number of decades in the simulation. The Climate Downscaling Model is absent from the table because each GCM, for each RCP, was downscaled prior to the workflow and is simply copied from a downscaled climate library for each scenario. Currently, only the LULCC ABM model is able to take advantage of multiple cores, but significant parallelism is achieved by queueing multiple scenarios and independent years simultaneously. A more detailed description of the parallel structure used

Table 1. Number of main model tasks for 40 yr, 48-scenario workflow that generated nearly 600 GB of data consisting of LULCC ABM land-use maps every 5 years, daily Missisquoi River flows and saturation maps from RHESSys, and daily lake temperature and water quality maps from A2EM.

Model	Number of tasks in a workflow	Number of tasks for $d = 4, c = 12, s = 48$	Approx. single task execution time
Weather estimator	c	12	15 min
LULCC ABM	sd	192	45 min
GRASS GIS	sd	192	10 min
RHESSys	sd	192	400 min
A2EM—EFDC	$10sd$	1920	240 min
A2EM—RCA	$10sd$	1920	75 min
Total	$c + 23sd$	4428	

for the workflow is available in the supplemental materials (S5).

One of the biggest integration challenges is compensating for the different spatial and temporal scales used in each model. Spatial scale mismatches are addressed by using the center points of each cell to query for the desired data. For instance, to look up a precipitation value for grid cell in RHESSys, the center point of that grid cell is used to determine the same location in the downscaled data and the precipitation value for the downscaled grid cell in which that point is contained is used in RHESSys. Some models use an interpolation algorithm to include information from surrounding cells, but others simply use the value from a single cell. For this manuscript, the model's default spatial mismatch resolution strategy, as determined by each model's own community of use, was used instead of arbitrarily forcing each model to use the same strategy to resolve spatial scale mismatches.

Temporal scale mismatches are normally resolved by using the last known value for the variable of interest. However, some models interpolate between known values and others use a temporal mean to represent all values within a certain temporal range. As with the spatial scale mismatch resolution strategies, the model's default temporal scale mismatch resolution strategy was used. For instance, EFDC and RCA use a subdaily internal time step and interpolate between available values (daily, weekly, monthly, etc) for many of their weather-related input parameters. However, for more discrete input parameters such as land use, RHESSys simply uses the last known land use classification as determined by the LULCC ABM.

3. Results and discussion

3.1. Impacts of climate change and LULCC on the hydrological system

Climate had more impact than land cover on the runoff magnitude and seasonality projections (figure 5). This is evident given the similarity in magnitude and shape of seasonal runoff fluctuations in all LULCC scenarios. It is likely that the land cover changes produced by the LULCC model were below the threshold needed to create significant runoff changes and hence affect the runoff pattern. Our results suggest that seasonal runoff magnitude fluctuations are going to witness a change in the future. Projected runoff magnitudes during spring season are expected to decrease, while winter season runoffs are going to increase. We attribute this seasonal change in runoff pattern to less snow and more rain during winter months in the GCM climate data. Projected changes in winter-spring runoff timing results (2030s decade) presented in this work extend twentieth century findings for the region [51, 58]. Our results suggest that among the climate models studied, climate scenario (RPCs) contributes to more runoff magnitude fluctuations than climate model choice (GCMs).

3.2. Cascading impacts of changing climate , LULC and riverine inputs on the lake system

Water temperatures rose substantially during the study period, but these changes were not uniform across seasons. In all scenarios, the greatest increases were in spring (April and May), and late fall (November) (figure 6). Increases during summer were more modest. The GCM scenarios differed dramatically with respect to spring water temperatures, which were highest in the MIROC-ESM-CHEM (warm GCM), and lowest in MRI-CGCM3 (cool GCM). The temperature increase between the first decade (2001–2010) and the last decade (2031–2040) was 5 °C in April in the MIROC-ESM-CHEM simulation, but less than 1 °C in MRI-CGCM3. The variability in spring temperatures between GCMs is likely driven primarily by the timing of snowmelt, which suppresses spring water temperatures in Missisquoi Bay; scenarios with earlier snowmelt have substantially warmer water temperatures in spring. There were also substantial differences between GCMs with respect to late season water temperature, particularly in low-emissions scenarios. Again, MRI-CGCM3 had the lowest temperature increases, while MIROC-ESM-CHEM and IPSL-CM5A-MR (dry GCM) had the highest temperature increases. There was a noticeable effect of increasing emissions scenarios on temperature, with warmer water temperatures observed in RCP 8.5 than RCP 4.5 scenarios, but these effects were generally smaller than the variation among GCMs. There was no effect of land use scenarios on lake temperature.

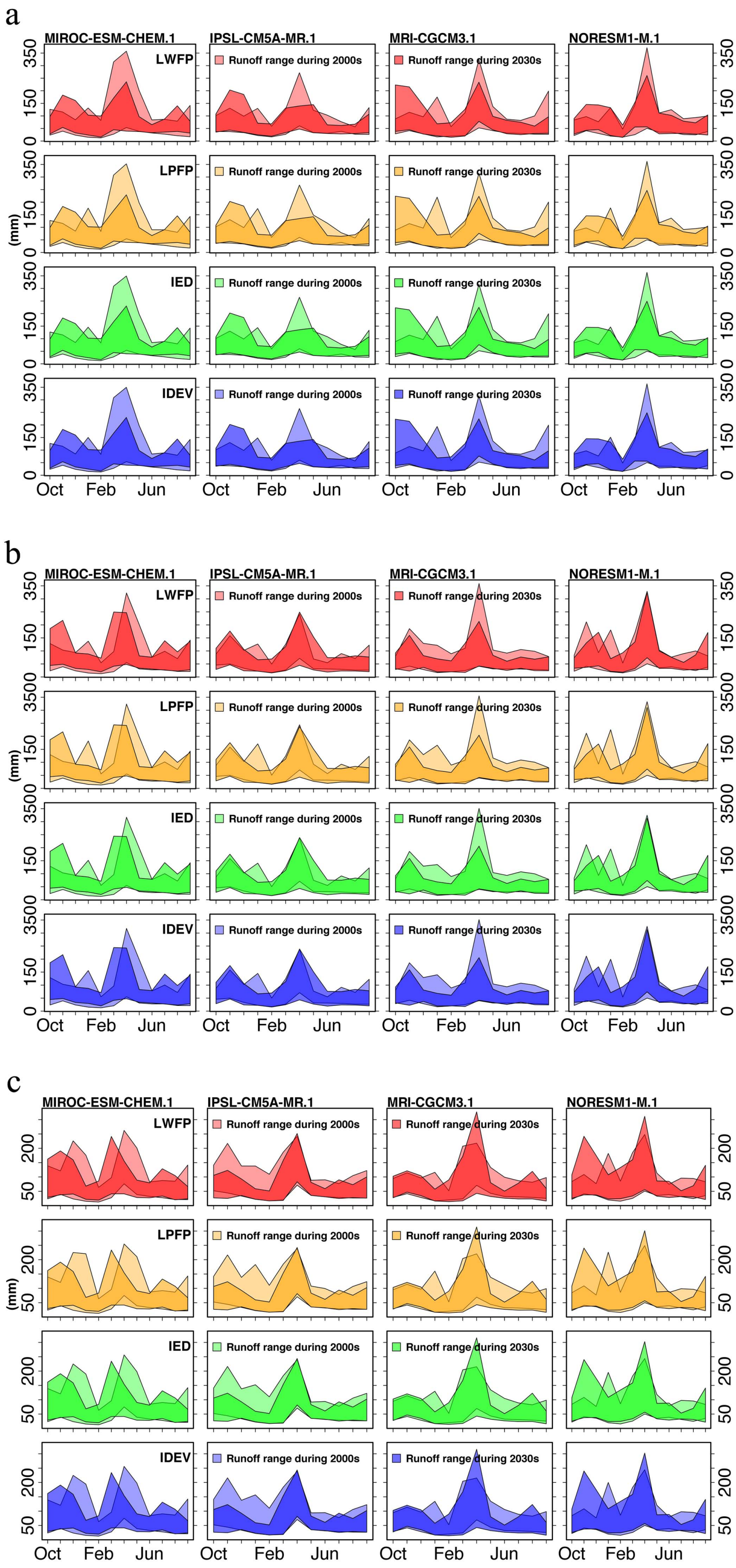

Figure 5. Monthly runoff magnitude fluctuations presented as range of maximum and minimum runoffs in the Missisquoi watershed during the 2000s decade (October 1999–September 2010 with lighter shading) and the 2030s decade (October 2029–September 2040 with darker shading) under four GCMs (MIROC-ESM-CHEM, IPSL-CM5A-MR, MRI-CGCM3, and NorESM1-M) and four LULCC forecast scenarios (LWFP, LPFP, IED, and IDEV). The 2030s decade runoff projections shown are from the climate scenario RCP 4.5 (6a), RCP 6.0(6b) and RCP 8.5 (6c).

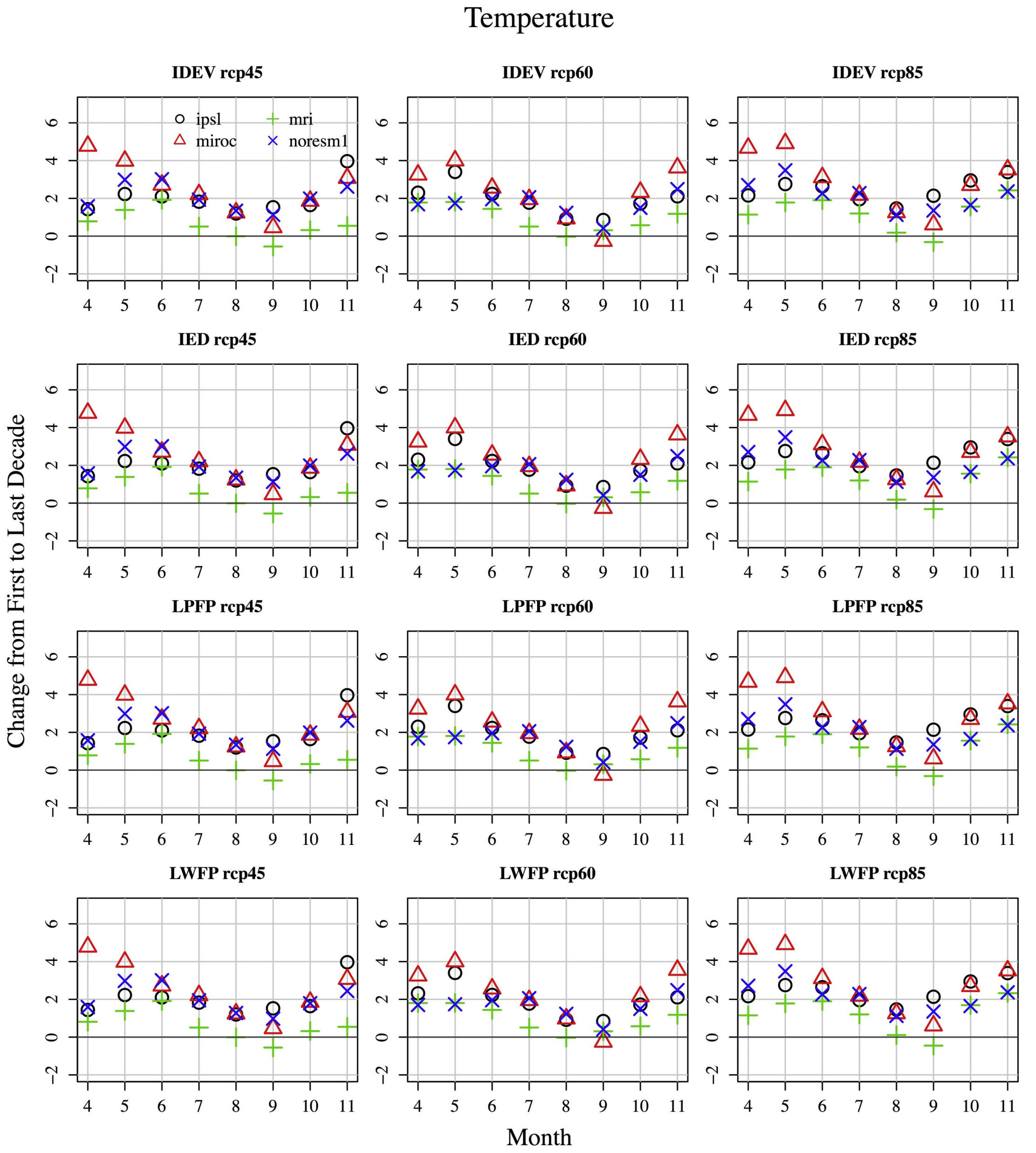

Figure 6. Projected changes in mean monthly lake temperature (°C) from the first (2001–2010) to the last (2031–2040) decade of the simulation period. ΔTemperature is shown by month for each LULCC scenario (rows), RCP (columns), and GCM (symbols). Results are omitted for December–March because EFDC does not simulate ice-cover dynamics.

Increases in ChlA are indicative of increased cyanobacteria blooms. ChlA increased during the summer months (July and August) for all scenarios, but the extent of these increases were variable with GCMs and RCPs (figure 7). ChlA increased in all GCMs, and by as much as 15 $\mu \mathrm{g\,l}^{-1}$ in RCP8.5. The largest summer ChlA increases occurred in the wet NorESM1-M GCM, suggesting that increased TP loads resulting from higher river discharge under wet scenarios may contribute to increases in-bloom severity. The lack of a strong difference between warm and cool scenarios is unsurprising, because there is minimal difference in the water temperature predictions for the summer months between most GCMs (figure 6).

In September and October, ChlA increased more in RCP8.5 than in RCP4.5 or RCP6.0, suggesting a lengthening of the HAB season was most pronounced under the highest concentration pathway due to the warmer fall water temperatures. Indeed, the fall ChlA increases were greatest in the dry IPSL-CM5A-MR scenario, which also had the largest temperature increases in those months under RCP8.5 (figure 6). Overall, most of the variability in ChlA results from the selected GCM, but the RCP scenarios had an important secondary effect that impacted both the severity and duration of bloom conditions. There effect of LULCC scenarios on ChlA was very minimal (which can be observed in the difference between forest conservation (LPFP) and pro-agriculture (LWFP) scenarios at RCP8.5; figure 7), reflecting the relatively small impact of the modeled LULCC scenarios on nutrient loading to the lake. While GCM signal is the

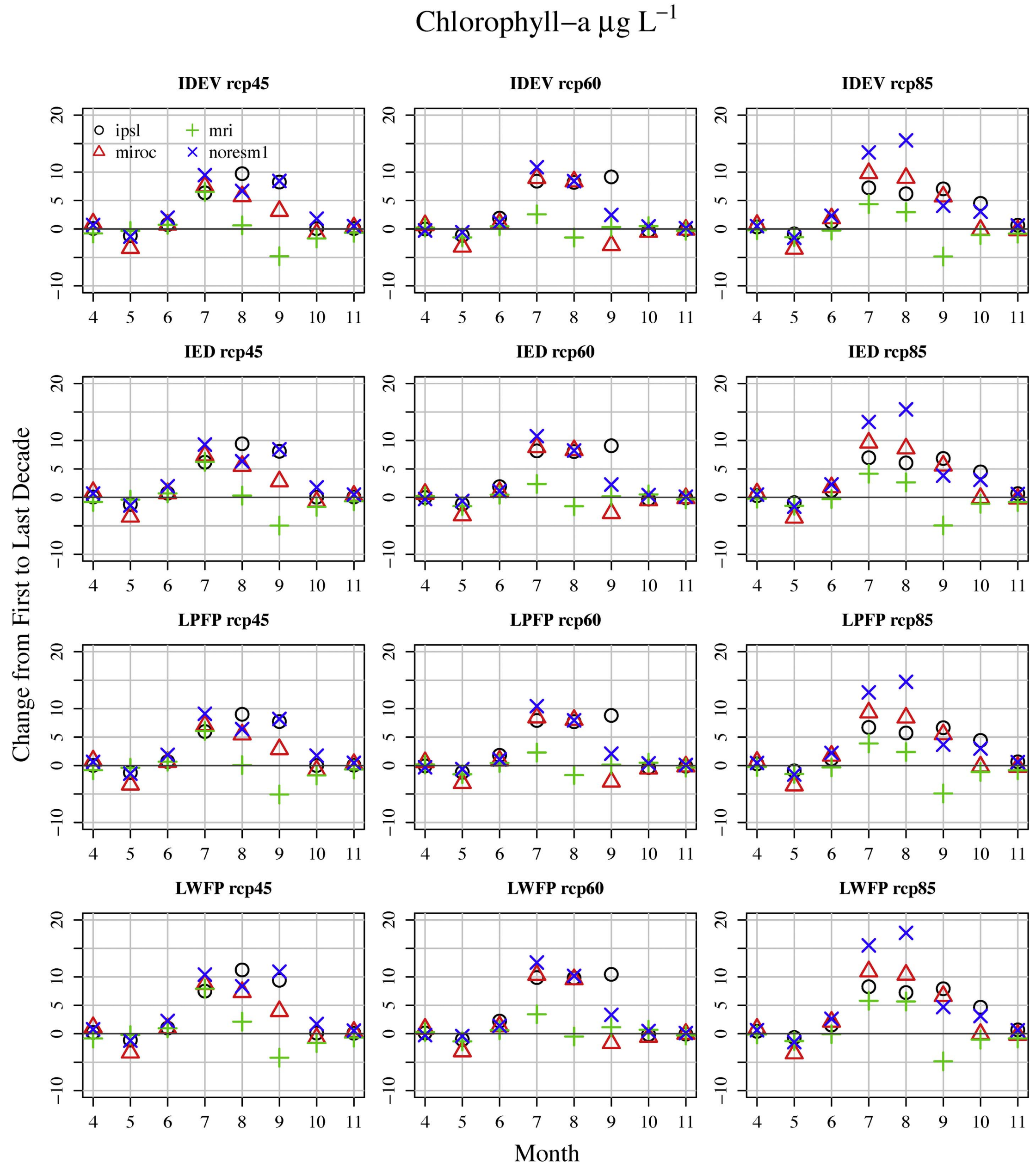

Figure 7 Projected changes in ChlA (μg l^{-1}) during the growing season between the first (2001–2010) and last (2031–2040) decades of simulation at long term monitoring station 51. ΔChlA is shown in the identical configuration of scenarios as figure 7, i.e. by month for each LULCC scenario (rows), RCP (columns), and GCM (symbols).

strongest, followed by RCP and LULCC signals, the choice of the GCMs is needed to bracket the uncertainties in climate models. The greater impacts due to different RCPs are expected later in the century, yet it is difficult to reliably project LULCC that far.

Spatially, the model predicted higher ChlA concentrations in the Canadian portion of the bay in the north and east (figure 8). The southern and western arm of the bay consistently had the lowest ChlA concentrations, particularly in the wet NorESM1-M GCM. The spatial variability is likely due to prevailing winds out of the southwest during summer bloom months. Cyanobacteria groups in the model are positively buoyant, resulting in higher concentrations of ChlA in surface layers. With winds out of the southwest, surface layer water is transported towards the northeast, resulting in net transport of cyanobacteria biomass to the Canadian portion of the bay.

4. Conclusions

The IAM output suggests that the Missisquoi Bay system is more sensitive to changing climate relative to the simulated land use changes due to the direct effects of warming water temperature as well as indirect effects through changes in riverine inputs. However, we also find large uncertainty across RCP scenarios (RCP 4.5 versus RCP 8.5) as well as across different GCMs within each RCP scenario, suggesting a wide

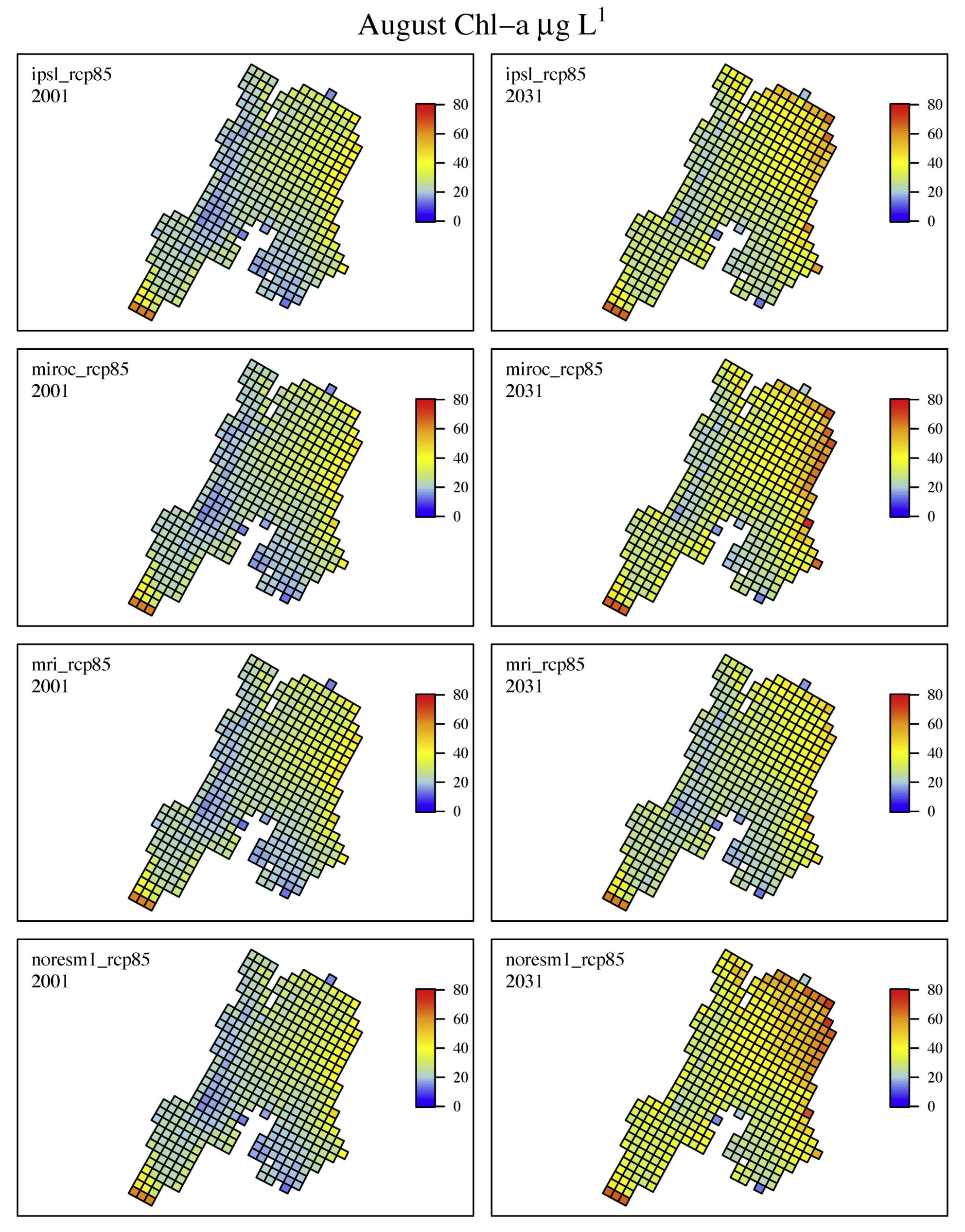

Figure 8. Maps of Missisquoi Bay showing ChlA concentration ($\mu g\ l^{-1}$) averaged for the month of August; comparing first decade (2001–2010) with last decade (2031–2040) projections for four GCMs under IED land-use scenario.

array of potential water quality outcomes depending on the emission scenario and GCM chosen. In contrast to many previous studies, our study demonstrates the importance of characterizing the range of potential climatic variability when assessing potential changes in water quality resulting from cascading climate-land use changes. Using a large swath of GCMs, set at the watershed scale and integrating multiple scale changes in a computational modeling framework, we clearly demonstrate that using one GCM or a limited number of land-use change scenarios may misrepresent the embedded uncertainty that drives regime shifts in SESs. The findings and insights from this study, taking into account both direct and indirect effects of climate change, suggest that the current total maximum daily load (TMDL) processes mandated by United States EPA under the Clean Water Quality Act may be inadequate in the context of changing climate. In the most recent TMDL for Missisquoi Bay, for example, EPA [53: pp 26] used only one GCM and one RCP scenario (scenario A2 from IPCC's fourth assessment report) to conclude, 'any increases in the phosphorus loads to the lake due to the climate change are likely to be modest (i.e. 15%).' Yet our variable projections regarding significant climate-driven increases in run-off and water temperature, drivers of external and internal P loading respectively [52], over the remarkably short (~25 year) simulated climate projection, indicate that this may not be the case; and caution in making such statements based on limited projections is warranted. We demonstrate that an ensemble of GCM and RCP scenarios is needed for policy design and implementation processes. Furthermore, the high degree of climate-induced uncertainty highlights the necessity of using an adaptive risk management approach to avoid worst-case scenarios with respect to water quality. While land management practices at watershed scales might be able to reduce nutrient loading (e.g. through conservation of forests and wetlands, modification of agricultural technologies and practices, and storm water management in urban areas), the nonlinear effects of increasing temperature and changing precipitation would appear to over-ride the land management effects across large ensembles of GCMs.

In this study, we have demonstrated our ability to predict the biogeochemical conditions of the lake in response to changing climatic, land-use and hydrological conditions, in a dynamic and spatially explicit framework, and advanced the current state of the SES computational modeling. Such computational approaches enable propagation of uncertainty across climate and land use change scenarios as well as models that will prove critical as management communities develop plans to promote or preserve water quality as global climate continues to warm. More importantly, such computational models enable disaggregation of multi-scale drivers of change occurring at different speeds and accelerations. Future SES research needs to investigate this complex problem in a wider sample of watersheds and lakes, and should work to integrate feedback loops and learning effects between ecosystem state and human decision making.

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Lake Champlain 2010: A summary of recent research and monitoring initiatives

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ABSTRACT

Lake Champlain shares a geological history with the Great Lakes and, as part of the St. Lawrence drainage, also shares biological and ecological similarities. The complex bathymetry and extensive shoreline provide a variety of lacustrine habitats, from deep oligotrophic areas to shallow bays that are highly eutrophic. The large basin:lake ratio (19:1) makes Lake Champlain vulnerable to impacts associated with land use, and in some parts of the lake these impacts are further exacerbated by limited water exchange among lake segments due to both natural and anthropogenic barriers. Research in Lake Champlain and the surrounding basin has expanded considerably since the 1970s, with a particularly dramatic increase since the early 1990s. This special issue of the Journal of Great Lakes Research brings together 16 reports from recent research and monitoring efforts in Lake Champlain. The papers cover a variety of topics but primarily focus on lake hydrodynamics; historical and recent chemical changes in the lake; phosphorus loading; recent changes in populations of phytoplankton, zooplankton, and fishes; impacts of invasive species; recreational use; and the challenges of management decision-making in a lake that falls within the legal jurisdictions of two U.S. states, one Canadian province, two national governments, and the International Joint Commission. The papers provide not only evaluations of progress on some critical management issues but also valuable reference points for future research.

Introduction

After the last ice age drew to a close and the Laurentide ice sheet retreated northward, for a period of about 1500 years water from the Great Lakes region drained through what is now the Lake Champlain valley on its way to the Atlantic Ocean. As a result, the Great Lakes and Lake Champlain share a geological history and biological and ecological similarities. Lake Champlain is much smaller and shallower and has a short retention time relative to the Great Lakes. In contrast, the Lake Champlain drainage basin is quite large compared to the lake area (a 19:1 ratio); 11 major rivers (32–102 km) and many smaller streams drain the Green Mountains to the east and the Adirondack Mountains to the west. Consequently, the lake is highly vulnerable to severe precipitation events, snowmelt conditions, and human alterations of the landscape. As evidence of this, the water level normally fluctuates 1–2 m in a year; in the historic spring flood of 2011, the lake level rose to 103.3′ above sea level (31.5 m), 1 m above the flood stage of 30.5 m, and over 2 m above the mean lake level (29.1 m).

Lake Champlain has a complex bathymetry, with over 70 islands, a shoreline of over 800 km (Myer and Gruendling, 1979), and many semi-isolated bays and inlets. The lake is divided into five major lake basins created by natural and anthropogenic barriers: the South Lake, the Main Lake, the Northeast Arm, Malletts Bay, and Missisquoi Bay (Fig. 1). The South Lake is shallow (<7 m), narrow (average width 1 km), warm, eutrophic, and essentially riverine. Water flows northward through a narrow constriction at Crown Point into the Main Lake, which extends northward to the Canadian border and drains, via the Richelieu River, into the St. Lawrence River near Montreal. The Main Lake, which is oligotrophic to mesotrophic, extends from the Crown Point bridge north to Rouses Point, New York, at the Canadian border and contains over 80% of the total lake volume, including almost 60% of the surface area and the deepest portion of the lake (122 m) (Myer and Gruendling, 1979). The Alburg peninsula, two large islands, and a series of causeways separate the northern Main Lake to the west from three smaller basins to the east. The southernmost of these basins is Malletts Bay, which is moderately deep (maximum depth 30 m) and mesotrophic. Water from Malletts Bay flows west into the Main Lake through two narrow gaps in an old railroad causeway, and north through a gap in a second causeway into the Northeast Arm, also known locally as the Inland Sea. Historically, the Northeast Arm was partially isolated from Malletts Bay by a shallow sandbar resulting from sediments deposited by the Lamoille River; a highway causeway with a single narrow opening now crosses that sandbar. The Northeast Arm is moderately deep

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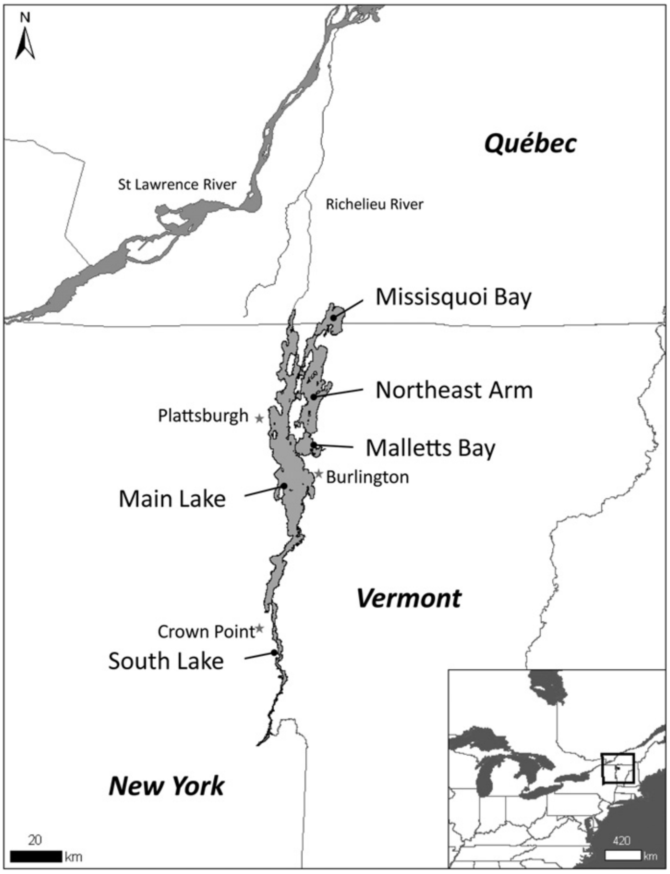

Fig. 1. Map of Lake Champlain showing the five basins.

(maximum 50 m) and oligotrophic to mesotrophic. To the north of the Northeast Arm is Missisquoi Bay, a shallow (4.3 m), warm, now eutrophic bay that spans the Vermont–Quebec border. The natural narrow opening between the Northeast Arm and Missisquoi Bay was further constricted by a highway causeway, which was replaced by a bridge in 2003. As a result of its bathymetric profile – long, narrow, with a deep ravine – the lake has a complex hydrological dynamic involving long-term and short-term seiches and substantial currents (Manley, 2004; Manley et al., 1999b, 2012b).

Management and research background

Similar to the Great Lakes, management and policy decisions regarding Lake Champlain are made all the more challenging by the fact that multiple legal entities have jurisdiction over different parts of the lake and the basin. In Lake Champlain, as many as six jurisdictional entities may weigh in on some issues — the states of New York and Vermont, the province of Quebec, the U.S. and Canadian federal governments, and the International Joint Commission. Québec, New York, and Vermont have a formal memorandum of understanding on cooperation of environmental management of Lake Champlain. The Lake Champlain Special Designation Act created the Lake Champlain Basin Program (LCBP) in 1990 with the goal of coordinating and funding efforts which benefit the Lake Champlain basin's water quality, fisheries, wetlands, wildlife, recreation, and cultural resources. Among the challenges faced by the LCBP has been negotiating positions among the six legal jurisdictions. In this special issue, Wroth (2012) reviews the historical legacies of the six managing jurisdictions and offers insight into potential ways to further facilitate solutions to the issues confronting those agencies with the responsibility of addressing the multiple environmental challenges of the Lake Champlain basin.

Many agencies have conducted monitoring and research programs in the watershed. The first major biological survey of Lake Champlain was conducted in the early 1900s by the New York State Conservation Department (Moore, 1930). Extensive work on lake habitat, hydrodynamics, chemistry, and the lower food web was conducted in the 1960s and 1970s by Henson and Potash (1970) and Myer and Gruendling (1979). Subsequent fisheries surveys were conducted by both states (reviewed by Marsden and Langdon, 2012).

In 1991 the newly formed Lake Champlain Research Consortium (LCRC) brought together seven academic institutions in the Lake Champlain basin to coordinate and facilitate research on Lake Champlain. The LCBP and LCRC have cooperatively and independently organized and facilitated several small research conferences, and larger conferences in 1998, 2002, and 2008; papers from the first two conferences were published in special volumes (Manley and Manley, 1999; Manley et al., 2004; http://academics.smcvt.edu/lcrc/). In 2010, the LCRC and LCBP co-hosted a research conference that brought together a range of research presentations focusing on Lake Champlain and its watershed (http://academics.smcvt.edu/lcrc/); many of the papers published in this special issue of the *Journal of Great Lakes Research* are based on research presented at that conference.

Hydrodynamics

The complex physical structure of Lake Champlain presents challenges for understanding the lake's hydrodynamic patterns. New York's Adirondack Mountains to the west and Vermont's Green Mountains to the east channel winds through the Champlain Valley, such that prevailing winds are from the south or north. Winds produce internal seiche activity in the Main Lake that extends as far as the South Lake and create circular currents along the western and eastern sides of the lake (Manley, 2004). A closer study of these circular patterns from 2002 to 2004 by Manley et al. (2012b) in this issue revealed three main circulation systems: (1) offshore, both the epilimnion and hypolimnion showed circular to elliptical motions; (2) nearshore currents created linear to curvilinear motions; and (3) southerly winds generated a strong westerly subsurface flow (10–16 m) and a strong southerly flow near the western shore. The western subsurface flow seems to be driven by upwelling of hypolimnetic water along some parts of the shoreline. Northerly winds may create an opposite circulation pattern, with easterly subsurface flows and a northerly current along the east shore (Manley et al., 2012b).

The benthic currents created by the seiche activity are capable of displacing sediments, thereby creating areas of erosion and deposition based on benthic topography. Benthic sedimentary furrows oriented along the long axis of Lake Champlain are a result of the redistribution of sediments by seiche-driven bottom currents (Manley et al., 1999a). In more recent work presented in this issue, high-resolution seismic profiles in a deep section of the Main Lake show two lacustrine sediment drifts, and subsequent dating of sediment core reveal that these began developing about 8700–8800 years ago (Manley et al., 2012a).

Chemical and biological characteristics

The large size of Lake Champlain's watershed, relative to lake volume, makes the lake vulnerable to land-use changes such as deforestation, increasing use of manure and fertilizer in agriculture, wastewater inputs, and industrial effluent. Monitoring of several fundamental physical and chemical parameters of Lake Champlain was conducted in the 1960s, but a more intensive and regular long-term monitoring program began in 1992, conducted jointly by the Vermont and New York Departments of Environmental Conservation in collaboration with the LCBP. In this issue, Smeltzer et al. (2012) evaluate data from this long-term monitoring effort to assess changes in physical and chemical attributes of the lake. For example, summer water clarity in the Main Lake increased by over a meter between 1964 and 2009. Most of this increase occurred after 1993, the year that zebra mussels (*Dreissena polymorpha*) became established in the lake. August surface temperatures increased by 1.6–3.8 °C from 1964 to 2009, a possible effect of climate change. The lake now freezes over later in the year and in fewer years, than historically (Stager and Thill, 2010).

The collaborative long-term monitoring effort by the Vermont and New York Departments of Environmental Conservation also includes collections of phytoplankton and zooplankton from 24 reference sites throughout the lake; information critical to understanding long-term changes in the biological community of Lake Champlain. In this issue, Smeltzer et al. (2012) report that phytoplankton communities are still dominated by diatoms and other chrysophytes, as was the case in the 1970s (Myer and Gruendling, 1979) and early 1990s (Shambaugh et al., 1999), but cyanobacteria are now much more abundant in Missisquoi Bay, the Northeast Arm, and Malletts Bay. This increase in cyanobacteria abundance may be associated with high nutrient inputs from land-use changes and increasing water temperatures (Smeltzer et al., 2012).

Efforts to reduce nutrient inputs to the lake have been partially successful. Smeltzer et al. (2012) note that total phosphorus and nitrogen concentrations in some sections of the lake have decreased since 1979; these concentrations have remained fairly stable in other parts of the lake despite increases in land conversion and development in the basin that have accompanied increasing human population (Mihuc et al., 2006; Smeltzer et al., 2012). In Missisquoi Bay, however, total phosphorus levels have increased dramatically. Increased phosphorus may be associated with an approximate doubling of chlorophyll-*a* levels and recent increases in the dominance of cyanobacteria in this part of the lake, resulting in noxious cyanobacteria blooms in several recent summers. Cyanobacteria blooms are not only unsightly, thereby impacting recreational use of lakes, but they can result in production of toxins that are dangerous to human health (Boyer et al., 2004). Monitoring for the emergence of these blooms and tracking their movements, which are often associated with wind patterns, is important to human use of affected waterways. In this special issue, Wheeler et al. (2012) report on a comparison of high-resolution (2.4 m) *QuickBird* and lower resolution (300 m) *MERIS* satellite imagery to field observations of a cyanobacteria bloom in Missisquoi Bay in 2004. They found that both technologies were effective; *QuickBird* permitted mapping of algal spatial distribution, and *MERIS* allowed reasonably accurate estimates of chlorophyll *a* and phycocyanin concentrations.

Not surprisingly, nutrient inputs that stimulate cyanobacteria blooms are tightly tied to river and stream discharges (Medalie et al., 2012). The high year-to-year variability due to fluctuations in precipitation and the timing of runoff from snowmelt can make it difficult to assess trends, especially over relatively short time frames of only a few years. This has led to frustration of resource managers, policy makers, and the public as a whole in determining whether the many, and often expensive, efforts to reduce nutrient loads in the lake have been effective. In this issue Medalie et al. (2012) report on efforts to minimize the effects of yearly fluctuations in assessing the effectiveness of management by applying a statistical approach based on weighted regressions to evaluate trends in phosphorus and nitrogen inputs from Lake Champlain tributaries from 1990 to 2008. Both nutrients increased in most tributaries from 1990 to 1999 but decreased from 1999 to 2008, suggesting that nutrient management efforts are paying off, albeit slowly.

This special issue also includes an evaluation of lake productivity over a longer, historical, time frame. Levine et al. (2012) evaluated sediment cores from Missisquoi Bay and the Northeast Arm (including St. Alban's Bay) to assess evidence of changes in the trophic status of these areas since European settlement of the Champlain Valley. Chemical and microfossil analyses suggest that these areas were oligotrophic at the time of European exploration in the 17th century. European settlement and expansion eventually led to large-scale deforestation over much of the Lake Champlain basin by the mid 1800s, with expected increases in sediment input from tributaries. Levine et al. (2012) suggest, however, that the forest removal and associated sediment inputs did not have a high impact on algal productivity in this region of the lake. Eutrophication of St. Alban's Bay seems to have occurred initially after the installation and expansion of sewer systems in the early 1900s, and again with conversion of former forest and agricultural land into urban development in the 1960s and 1970s. Missisquoi Bay was always shallower and warmer that other parts of Lake Champlain, but remained largely mesotrophic until about the 1970s (Levine et al., 2012). Since that time, much of the gravel substrate that supported spawning by lake whitefish (*Coregonus clupeaformis*, Marsden and Langdon, 2012) has become silted, littoral macrophyte growth has increased, and the bay has become highly eutrophic. The bay frequently experiences cyanobacteria blooms in the warmer summer months, which has a dramatic negative impact on the local tourist-dependent economies in both Vermont and Quebec.

The long-term monitoring information provided by the collaboration between the Vermont and New York Departments of Environmental Conservation and the LCBP, has also allowed the evaluation of changes in the Lake Champlain zooplankton community since 1992. In this issue, Mihuc et al. (2012) report that zooplankton communities in different areas of Lake Champlain have changed significantly. Mihuc et al. evaluated changes in the Lake Champlain summer zooplankton community at five study sites and report that rotifer abundance and diversity declined in the mid 1990s, concomitant with the appearance of zebra mussels in 1993. The more recent invasion by alewife (*Alosa pseudoharengus*) seems to be driving another restructuring of the zooplankton community. Since alewife have become abundant, the average body length of some of the larger zooplankters, such as the copepod *Leptodiaptomus* and cladoceran *Daphnia retrocurva*, has decreased to below the size preference for alewife. With less competitive pressure from the larger zooplankton, some smaller copepods, such as *Diacyclops thomasi*, have increased in abundance, although abundance of some other smaller zooplankton has not changed.

Fish and fisheries

In this issue, Marsden and Langdon (2012) review the history and comment on the future of the Lake Champlain fish community, which currently includes 72 native fish species. The historical connection with the upper mid-west fish fauna as the last glaciers receded, combined with the more recent connections with the Atlantic coastal systems, provided a diverse freshwater fish assemblage for the Lake Champlain drainage, compared to other lakes in New England. However, several species have been extirpated or severely reduced, largely as a result of land-use changes that impacted the lake (sediment and nutrient inputs), and habitat fragmentation as a result of the construction of man-made barriers that blocked access to tributaries and subdivided the basins of the lake (Marsden and Langdon, 2012). Commercial fisheries for lake trout (*Salvelinus namaycush*), lake whitefish, and walleye (*Sander vitreus*) were small-scale compared to those in the Great Lakes, being conducted largely from shore, and were closed in US waters by 1912. Commercial fishing for lake sturgeon (*Acipenser fulvescens*), walleye, and American eel (*Anguilla rostrata*) continued until the late 1900s; each of these species has declined severely. Since the 1970s, New York, Vermont, and federal fish and wildlife agencies have collaborated on efforts to restore populations of lake trout and salmon to the lake, but natural reproduction by stocked fish is limited.

Currently, there are 15 non-native fish species established in Lake Champlain; of these, alewife and white perch (*Morone americana*) may have the most severe effects on the food web. In this issue, Simonin et al. (2012) evaluate potential competition between invasive alewife and rainbow smelt (*Osmerus mordax*), which are a critical link in the deep-water trophic web of the lake. They found that adult and juvenile rainbow smelt tended to be in deeper, colder water than alewife of the same age, thereby limiting habitat overlap of these fishes within the lake. There was, however, some overlap between the upper/warmer limit of the rainbow smelt range and the deeper/cooler limits of the alewife range.

Managing nuisance species

There are currently 48 non-native species in Lake Champlain, including fishes. Several of these species have reached nuisance status (Marsden and Hauser, 2009) and are the focus of management efforts to control their populations. The nuisance species that presents the greatest management challenge is the sea lamprey (*Petromyzon marinus*) which, in contrast to its status in the upper Great Lakes, is likely native to Lake Champlain. Anthropogenic changes in the watershed and to fish communities appear to have altered the balance of sea lamprey and their prey in the Lake Champlain ecosystem (Marsden and Langdon, 2012). In consequence, sea lamprey control has emerged as one of the top fishery-related management issues in Lake Champlain. An experimental sea lamprey control program from 1990 to 1998 reduced the incidence of lamprey wounding on salmonids, and a long-term control program began in 2002. The primary means of control have been chemicals that target the filter-feeding larvae, but there is ongoing concern about the impacts of these chemical treatments on nontarget species, some of which are endangered or threatened. Alternative control methods, including permanent barriers and seasonal traps to block adults from spawning habitat, have been used in several streams, and additional alternatives such as pheromones to attract pre-spawning adults have been explored. In this issue, Howe et al. (2012) present a model of sea lamprey population dynamics created to help guide more effective control of sea lamprey populations. The model is based on life history parameters, and the results suggest that targeting the larval stage is critical to effective control, but that supplemental efforts to reduce survivorship at early life stages and to block spawning may also be effective aspects of an overall control strategy.

Double-crested cormorant (*Phalacrocorax auritus*) are also considered by many people to be a nuisance species in the Lake Champlain basin, due in part to the impact of their nesting colonies on terrestrial habitats and other colonial nesting bird species, and because of their consumption of fish. In this special issue, Kuentzel et al. (2012) report on a study of attitudes of different recreation groups toward cormorants and found that most respondents had an overall negative view of the species, supported their designation as a “nuisance” species, and therefore support control measures designed to prevent the spread of nesting areas, such as hazing, shooting, and oiling of eggs. The authors found that the most negative attitudes toward cormorants were expressed by anglers and lakeshore homeowners, and also noted that negative attitudes may be linked to socioeconomic status of the respondents.

This special issue contains two additional research studies of Lake Champlain's cormorants, both focused in part on the diet of this population. DeBruyne et al. (2012) compared diets of double-crested cormorants during the breeding seasons of 2001–02 and 2008–09 and noted a shift to consumption of alewife in recent years as this species has become abundant. Cormorant diets are, however, also somewhat site-specific, with those nesting on Young Island eating large numbers of yellow perch. This diet is probably a consequence of the proximity of Young Island to areas with large yellow perch populations. Management efforts to limit the expansion of cormorant nesting ground have included oiling of eggs at Young Island; this action has resulted in cormorants moving to the Four Brothers Islands further south and in the Main Lake. The movement of nesting colonies has resulted in a shift in cormorant diets from yellow perch to rainbow smelt and may result in an overall increase in the number and mass of fish eaten, as the cormorants meet the bioenergetics demands of having to travel further between nesting and feeding areas (Duerr et al., 2012).

Recreation

Lake Champlain has been an attractive area for the development of “low-impact” recreational use such as canoeing and kayaking, and the Lake Champlain Paddler's Trail, comprised of simple camping areas along the lake, is an appealing option. This issue includes two studies of attitudes and impressions of recreational paddlers in their use of Lake Champlain. Goonan et al. (2012) report on an evaluation of the primitive campsites along Lake Champlain and elsewhere in the northeastern US and found that those along Lake Champlain are high in quality with respect to size and condition of vegetation. The authors suggest that this may be in part due to the use of a camping “at large” policy rather than confining camping to designated spots. Finding acceptable ways to balance the quality and impacts of different types of recreational uses has always been a challenge, and recreational use of Lake Champlain is no exception. Anderson et al. (2012) assessed the quality of the paddling experience on parts of Lake Champlain and found that shoreline development and the presence of sailboats and motorboats are approaching a “minimum acceptable level condition”, suggesting that other lake users may already be impacting the paddling experience.

Conclusion

Lake Champlain is a magnificent resource — a beautiful lake between two mountain ranges with fine winds for sailing, space for boating, water suitable for swimming, and excellent fishing opportunities. Water quality has improved dramatically in many parts of the lake due to decades of tightened regulations. However, some problems persist, and new issues continue to arise. Beach closings, although rare, still occur occasionally after heavy rains overwhelm municipal wastewater facilities, leading to increased bacterial counts in nearshore areas. Efforts to limit nutrient inputs appear to have had some positive effects (Medalie et al., 2012) but ongoing land development and dramatic increases in precipitation and runoff in recent years seem to be preventing overall progress. Cyanobacteria blooms have become common in some areas, in part due to the combined effects of nutrients and higher water temperatures, and can limit recreational access due to health concerns about cyanotoxins that may accompany blooms. Fishing is excellent, and sea lamprey wounding has declined, but consumption advisories remain in effect due to concerns about levels of mercury or PCBs in older fishes of some species.

Lake Champlain has experienced substantial physical, chemical, and biological changes over the past two centuries due to the rapid increase in the human population and its influence on the watershed. Many of these changes are either irreversible, such as the addition of self-sustaining non-native species, or will be very slow to reverse, such as phosphorus loading, eutrophication, and reconnecting aquatic habitats through removal of dams and alteration of causeways. Natural resource managers in New York, Vermont, and Québec, working at the federal, state, provincial, and local level, are committed to finding ways to build on past successes, address new issues as they arise, and protect and preserve the valuable regional resource that is Lake Champlain. The research summarized in this issue will be valuable as reference points for measuring our progress in the future.

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Environmental change in Lake Champlain revealed by long-term monitoring

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ABSTRACT

Long-term monitoring data on Lake Champlain spanning the past two to five decades were analyzed to document water quality and biological changes in the lake. August mean surface water temperatures increased during 1964–2009 in most Lake Champlain regions at rates (0.035–0.085 °C/year) similar to what has been observed in the Laurentian Great Lakes and elsewhere. Secchi disk transparency increased by over a meter during 1964–2009 in regions along the main stem of the lake, with much of the increase occurring after the 1993 zebra mussel invasion. Transparency declined in northeastern regions where zebra mussel densities were lower. No trends in hypolimnetic dissolved oxygen concentrations or depletion rates were found in any of the deep lake regions during 1990–2009. Sodium concentrations tripled in the Main Lake region since the 1960s. Chloride increased in the Main Lake by 30% since 1992, but declined in northeastern regions of the lake during recent years, coincident with reductions in road salt use in Vermont. Total phosphorus concentrations decreased during 1979–2009 in southern and northwestern lake regions, but increased by 72% in Missisquoi Bay where chlorophyll-a concentrations doubled over the period. There was a general lakewide trend of decreasing total nitrogen levels during 1992–2009 that may have been due in part to reductions in atmospheric nitrogen loading to the watershed. Cyanobacteria increased their dominance within the phytoplankton community in northeastern regions of the lake since the 1970s.

Introduction

Awareness of environmental change, and an understanding of the response of ecosystems to air and water pollution and land-use changes, are essential to designing appropriate management interventions (Lovett et al., 2007; Watzin, 2007). Because the rate of most ecological changes is very slow, usually occurring over decades to centuries, long-term environmental monitoring is essential for detecting trends in ecological variables.

Lakes are often the subject of long-term monitoring because representative samples can be readily obtained that integrate the influence of watershed and atmospheric disturbances (Schindler, 2009). Important knowledge has been gained from long-term monitoring of large lakes, including insights about lake ecosystem response to nutrient loadings, invasions by nonnative species, and climate change (Eimers et al., 2005; Rockwell et al., 2005; Jankowski et al., 2006; Dobiesz and Lester, 2009; Fahnenstiel et al., 2010; Mida et al., 2010). In some cases, long-term lake monitoring data were used for purposes that were unforeseeable at the time the monitoring program was initiated (Hampton et al., 2008).

Lake Champlain is one of the largest lakes in North America, with a 1127 km^2 surface area, a mean depth of 22 m, and a 21,326 km^2 drainage basin that are shared by the States of Vermont and New York and the Province of Quebec (Cohn et al., 2007). The lake has a complex morphology with numerous shallow bays and arms that are partially isolated from the deep main stem of the lake by natural land forms or causeways. As a result, a wide variety of limnological conditions exists in Lake Champlain with respect to phosphorus loadings and trophic state (Medalie and Smeltzer, 2004), ionic composition (Potash et al., 1969), thermal and hydrodynamic features (Manley et al., 1999), optical properties (Effler et al., 1991), and plankton communities (Shambaugh et al., 1999).

Like many large lakes worldwide, Lake Champlain faces a number of environmental stressors. Global climate change, land use changes, agricultural and industrial contaminants in water runoff, and increased opportunities for transport of exotic species all have the potential to substantially alter lake ecosystems. A substantial proportion of the Lake Champlain drainage was deforested in the 1800s and converted to farmland, leading to increased erosion and anthropogenic inputs of fertilizers. In comparison with the Great Lakes, the Lake Champlain Basin has a relatively low human population density and few major industrial discharges. Similarly, the lake does not receive substantial shipping traffic, which is a major vector of exotic species introductions in the Great Lakes and elsewhere. However, there are several stressors affecting the Lake Champlain Basin that would be expected to produce environmental changes within the lake.

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Water temperature increases in large lakes have provided evidence of a warming global climate (Dobiesz and Lester, 2009; Austin and Colman, 2007; Hampton et al., 2008). Summer air temperatures have increased in the Lake Champlain region over the past several decades (Stager and Thill, 2010, Fig. 1a), and we would expect summer lake water temperatures to have increased in Lake Champlain as a result.

Increasing chloride concentrations have been found in lakes (Chapra et al., 2009; Novotny and Stefan, 2009), rivers (Robinson et al., 2003; Kauschal et al., 2005), and groundwater (Mullaney et al., 2009; Eyles and Meriano, 2010) across the northern hemisphere, particularly as a result of the application of deicing salts for winter road maintenance (Chapra et al., 2009; Daley et al., 2009; Trowbridge et al., 2010). Road salt application rates in Vermont state highway districts within the Lake Champlain Basin increased during the 1990s but then declined in more recent years (Fig. 1b), either as part of a conscious management effort or as a result of less severe winter driving weather. With urban land uses representing 8% of the watershed and increasing over time (Troy et al., 2007), we would expect to find changes in sodium and chloride concentrations in Lake Champlain linked to road salt usage.

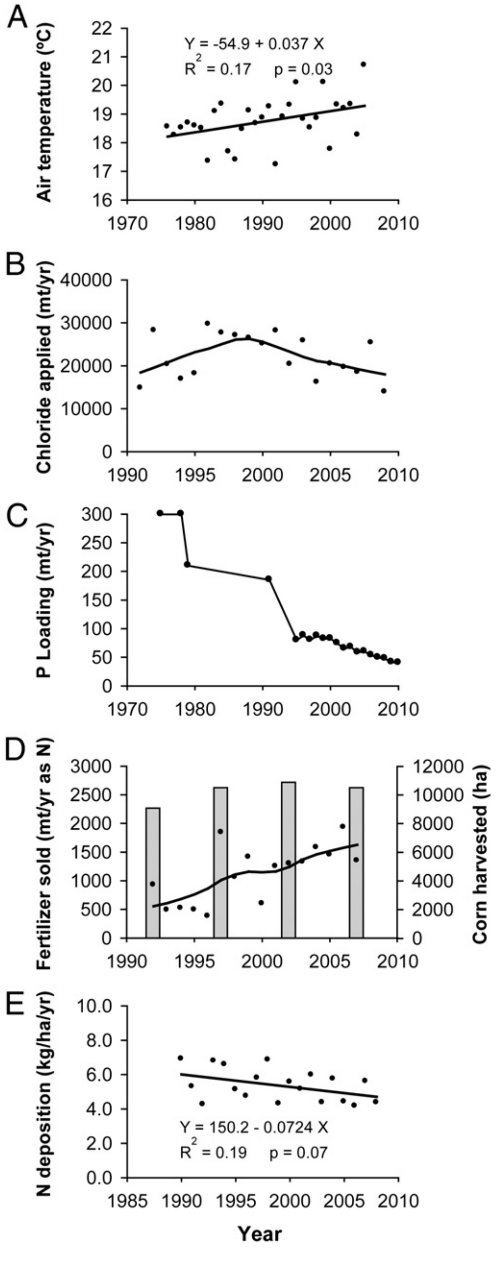


Fig. 1. Trends in Lake Champlain environmental stressors. A. Summer mean air temperature in the Lake Champlain Basin, 1976–2005 (modified from Stager and Thill, 2010). B. Winter road salt application rates (metric tons per year as chloride) for Vermont state highway maintenance districts within the Lake Champlain Basin, 1990–2009 (Vermont Agency of Transportation data). C. Total phosphorus loading to Lake Champlain from Vermont and New York wastewater treatment facilities, 1975–2010 (Smeltzer et al., 2009; Bogdan, 1978). D. Nitrogen fertilizer sold (dots and LOWESS trend line) and area of corn harvested (vertical bars) in Franklin County, VT, 1992–2007. Fertilizer sales data are from the Vermont Agency of Agriculture, Food, and Markets and do not include manure. Corn data are from the U.S. Department of Agriculture Census of Agriculture. E. Annual mean atmospheric wet deposition rates of inorganic nitrogen at Underhill, VT, 1990–2008 (National Atmospheric Deposition Program data).

Lake Champlain receives phosphorus loadings from multiple point and nonpoint sources in excess of its assimilative capacity (Smeltzer and Quinn, 1996). Control of eutrophication in Lake Champlain through phosphorus reduction has been a priority for resource management agencies since the 1970s. Phosphorus detergent laws were in place basinwide by 1978. These laws, and requirements for phosphorus removal from wastewater effluent at large treatment facilities, have reduced wastewater phosphorus loads to Lake Champlain by 86% since the 1970s (Fig. 1c). Efforts to reduce nonpoint source phosphorus loading to the lake accelerated in recent years with over $120 million being committed since 2004 to support enhanced stormwater management, implementation of agricultural best management practices through regulatory and incentive-based programs, and river corridor protection measures (Vermont Agency of Natural Resources and Vermont Agency of Agriculture, Food, and Markets, 2010). Consequently, reductions in lake variables associated with eutrophication, such as phosphorus, chlorophyll-a, and cyanobacteria concentrations, and increases in water clarity and hypolimnetic dissolved oxygen, would be expected over this time period.

Nitrogen loading to lakes can be influenced by factors including crop production on agricultural land and atmospheric deposition (Elser et al., 2009). Nitrogen fertilizer sales and the amount of corn land harvested within the most heavily agricultural sub-watersheds within the Lake Champlain Basin increased since 1990 (Fig. 1d). However, there has been a 19% decrease in atmospheric deposition of total (wet + dry) nitrogen in the eastern U.S. during 1990–2008 (MACTEC, 2010), and a marginally significant decline of similar magnitude in the wet deposition rate of inorganic nitrogen at a monitoring station located within the Lake Champlain Basin (Fig. 1e). The net effect of these and other factors on nitrogen concentrations in Lake Champlain is difficult to predict.

Hydrologic connections between Lake Champlain, the Hudson River, and the Great Lakes via the Champlain Canal and the Richelieu River, and other vectors, have created pathways for invasion of Lake Champlain by 48 exotic species (Marsden and Hauser, 2009). Of these species, zebra mussels, in particular, can have profound effects on temperate lake ecosystems as a consequence of filtration activity, resulting in significant water-column decreases in suspended solids, phosphorus, and chlorophyll, with corresponding increases in water clarity and alterations in the phytoplankton and benthic communities (Barbiero and Tuchman, 2004; Raikow et al., 2004; Higgins and Vander Zanden, 2010). Based on experiences in other lakes, increases in Secchi disk transparency and proliferation of cyanobacteria species such as *Microcystis aeruginosa* could be expected in Lake Champlain since the arrival of the mussels in 1993.

Environmental changes that result from anthropogenic activities tend to initially be small, and masked by naturally high inter-annual variability. In order to detect and monitor lake-wide changes, and be able to evaluate efficacy of management efforts to remediate environmental damage, collection and examination of long-term data are critically needed. Lake Champlain water quality managers and researchers had the foresight, decades ago, to establish long-term monitoring programs to detect changes in water quality that may result from human activities, and that could affect ecological processes and human uses of the lake. Long-term records are available for lake variables including temperature, water transparency, hypolimnetic dissolved oxygen, inorganic ions, nutrients, chlorophyll-a, larval zebra mussel densities, and phytoplankton community composition. Our objective in this paper is to integrate data from three such monitoring programs in order to assess the extent to which the expected water quality and biological changes in Lake Champlain have occurred over the past several decades.

Table 1
Sampling methods for long-term monitoring programs on Lake Champlain, including the Henson and Potash surveys (H–P), the Vermont Lay Monitoring Program (LMP), and the Long-Term Water Quality and Biological Monitoring Program on Lake Champlain (LTMP). Analytical methods are documented in Vermont DEC and New York State DEC (2010).

	Monitoring program		
	H–P	LMP	LTMP
Period of record	1964–1974	1979–2009	1992–2009
Sampling season	April–Nov[a]	May–Sept	April–Nov
Sampling frequency	Variable	Weekly	Bi-weekly
Total number of monitoring sites	69	39	15
Monitored variables used in this analysis	SDT, Na^{+}[b], Ca^{++}[b], temperature	SDT, TP[c], Chl-a[c]	SDT, TP[d], Chl-a[c], TN[d], Cl[d], Na^{++}[d], Ca^{++}[d], DO[e], temperature[e], net phytoplankton[f], zebra mussel veligers[f]
Additional variables available in the dataset	pH, alkalinity, conductivity, manganese, potassium, DO		Dissolved phosphorus [g], soluble reactive phosphorus, dissolved reactive silica[g], total Kjeldahl nitrogen, total nitrate–nitrite nitrogen, total ammonia nitrogen, alkalinity[g], conductivity[g], manganese[g], potassium[g], total iron, total lead, total organic carbon, dissolved organic carbon, total inorganic carbon, total suspended solids, net zooplankton[g]

[a] Winter (December–March) data were removed from the data set prior to analysis.
[b] Surface grab samples.
[c] Vertically-integrated hose samples to twice the Secchi depth.
[d] Upper mixed layer discrete-depth composites.
[e] Vertical water column discrete-depth profiles.
[f] Vertical 63 μm net tows.
[g] Sampling of these additional variables is on-going.

Methods

Data sources

Data for this analysis were obtained from three monitoring programs including early limnological surveys on Lake Champlain by University of Vermont limnologists E.B. Henson and M. Potash (H–P), citizen monitoring supported by the Vermont Lay Monitoring Program (LMP), and a Long-Term Water Quality and Biological Monitoring Program on Lake Champlain (LTMP) supported by the Lake Champlain Basin Program. The H–P surveys were conducted during 1964–1974 (Henson and Potash, 1966; Potash and Henson, 1975) and the data from these surveys were later compiled electronically and documented by Henson and Potash (1987). The LMP began in 1979 and is supported by the Vermont Department of Environmental Conservation (DEC). The citizen volunteers are trained by professional staff and adhere to approved procedures that ensure data quality (Picotte and Pomeroy, 2000; Canfield et al., 2002). The LTMP was initiated in 1992 and is operated by state agency staff (Vermont DEC and New York State DEC, 2010).

The monitoring variables selected for this analysis included those sampled by at least two of these programs consistently over a multiple year period, as well as additional measures of interest available only from the LTMP dataset (Table 1). The H–P surveys included data on Secchi disk transparency (SDT), sodium ion (Na^{+}), calcium ion (Ca^{++}), and water temperature. The LMP and the LTMP datasets included SDT, total phosphorus (TP), and chlorophyll-a (Chl-a) results. Additional measurements included only in the LTMP dataset were total nitrogen (TN), chloride ion (Cl^{-}), hypolimnetic dissolved oxygen (DO), net phytoplankton cell densities and biovolume, and zebra mussel (*Dreissena polymorpha*) larval densities. Other variables measured by these monitoring programs but not included in this analysis are also listed in Table 1. All of the LTMP data, including those summarized in this paper, are available online at www.anr.state.vt.us/dec/waterq/lakes/htm/lp_longterm.htm.

Sampling methods and locations

The three monitoring programs differed with respect to sampling season, frequency of sampling, and sample depths (Table 1), although there was broad overlap in the sampling seasons and all programs obtained samples from the upper mixed layer of the water column in offshore locations. Data obtained during the winter months (December–March) by the H–P surveys were excluded from the analysis for better comparability with the results from the LTMP and LMP programs which operated during the growing season only.

Sampling locations were selected for this analysis to include ten sites distributed throughout the lake that were common to all three programs and where the sampling effort was sustained across the years (Fig. 2). Sampling stations for the LTMP were precisely located in the field using LORAN or GPS receivers. Each LMP station listed in Fig. 2 was co-located with a corresponding LTMP station, but the volunteer monitors generally used visual landmarks to find their stations. Sampling locations for the H–P survey were not precisely recorded, as would be possible with modern electronic navigation aids. Instead, Henson and Potash (1987) divided the lake into 69 lake areas and identified each of their sampling location as being within one of those lake areas. H–P data from the lake areas corresponding to the station locations shown in Fig. 2 were used in this analysis.

Chemical and physical analytical methods

All chemical analyses for the LMP and LTMP programs were conducted by state environmental laboratories in Vermont or New York using standard methods under Quality Assurance Project Plans approved by the U.S. Environmental Protection Agency (Vermont DEC and New York State DEC, 2010). Methods used for the H–P surveys were comparable, though not identical, to these methods. Lake surface temperature was measured during the H–P surveys using a calibrated bucket thermometer (Henson and Potash, 1987), while the LTMP employed calibrated thermistor probes. Ca^{++} and Na^{+} were analyzed during the H–P surveys by atomic absorption spectrophotometry (Potash and Henson, 1975), whereas the LTMP used varying methods for these elements during the monitoring period including inductively coupled plasma (ICP) atomic emission spectrometry (1992–2001), atomic absorption (2002), and ICP mass spectroscopy (2003–2005).

Temperature

Water temperatures were measured in situ throughout the water column at each LTMP lake station using thermistors on cables or multiprobe devices. However, comparable depth profile data were not obtained during the H–P surveys, and temperature data were consistently available only for the summer months. The analysis of temperature trends was therefore limited to surface measurements recorded during the month of August, which was the month typically

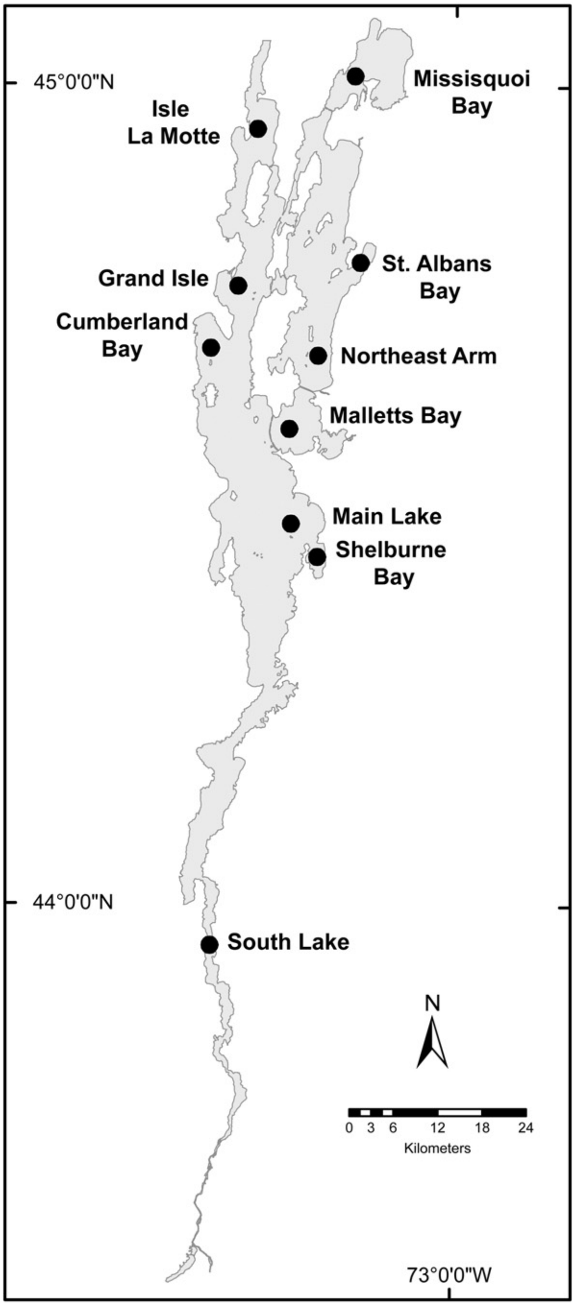


Fig. 2. Location of sampling stations in Lake Champlain. Stations sampled by the H–P surveys were not precisely located, but corresponded to the general lake region indicated.

having the largest number of measurements. All temperatures recorded at 1 m depth during August (N = 1–5/year) were averaged by year to calculate an August mean surface temperature in each lake region for years where data were available.

Hypolimnetic dissolved oxygen

Hypolimnetic DO was measured by the LTMP using both Winkler titration and in situ electrode methods (Vermont DEC and New York State DEC, 2010). However, several different instruments were employed across the years for the electrode measurements and the Winkler method provided more consistently calibrated data over the entire monitoring period. Therefore, only the Winkler titration results were used for long-term trends analysis.

Conventional measures of hypolimnetic hypoxia such as the areal or volumetric hypolimnetic oxygen depletion rate (Burns et al., 2005; Matthews and Effler, 2006) were difficult to apply to Lake Champlain because the complex morphometry and sometimes indistinct thermocline created uncertainty about the spatial extent of the hypolimnion at some sampling stations. Trends in hypolimnetic hypoxia were assessed instead using measurements of late-summer DO concentrations recorded by the LTMP in the near-bottom waters of three deep lake regions, including the Main Lake (90 m), Malletts Bay (25 m), and the Northeast Arm (45 m). In order to standardize the comparison of late-summer DO conditions across years, DO concentrations were interpolated between sampling dates to provide an estimate of the DO concentration at these depths on September 1 of each year. Additionally, summer-long hypolimnetic DO depletion rates were calculated from the differences in bottom-water DO concentrations between June 1 and September 1 each year. The depth locations of the hypolimnetic DO samples used for this analysis were the same across all years within each lake region. DO data obtained during 1990–1991 by a preceding study using comparable methods (Vermont DEC and New York State DEC, 1997) were used to supplement the LTMP dataset for this analysis.

Zebra mussel veligers

Zebra mussel adults were first discovered in the South Lake region of Lake Champlain in 1993, and their planktonic larvae (veligers) were monitored by the LTMP starting in 1994 to provide an indirect measure of population densities as the mussels spread to other regions of the lake. Zebra mussel veligers were sampled by vertical net tows concurrently with the water quality monitoring efforts (Stangel and Shambaugh, 2005). Tow depths varied between 3 and 10 m depending on the depth of the sampling station. Enumeration procedures followed Marsden (1992). The seasonal timing of veliger production varied from site to site and year to year. In order to provide a standardized basis for comparison, veliger densities at each station were reported as a time-weighted season mean calculated by numerically integrating the measured densities over 150-day periods within each May–October sampling season, starting and ending with zero density observations (Stangel and Shambaugh, 2005).

Phytoplankton

Large phytoplankton were sampled by the LTMP beginning in 2006 using a 63 μm mesh Wisconsin net. Samples were collected by vertical net tows from twice the Secchi depth and preserved with acid Lugol's solution for later analysis. Individuals with at least one linear dimension >50 μm were identified to the lowest taxonomic level practical and enumerated. Ten randomly selected individuals from each taxon were measured and the median values of these dimensions were used with standard geometric formulae to determine a representative biovolume per cell (Wetzel and Likens, 2000).

Statistical analysis

All sampling results were averaged for each date to reduce field replicates to a single value per sampling date. Locally weighted scatterplot smoothing (LOWESS) was used to visualize temporal trends in the data including any non-linearity, while illustrating the variability in the data. LOWESS identifies the centerline of the time series plots, illustrating the underlying trends amidst the considerable variability present in the data (Helsel and Hirsch, 2005). Regression window widths for weighting were controlled using moderate smoothness values of 0.4–0.6 for most variables in this analysis.

One of the concerns about using data from monitoring programs with different sampling methods operating over different time periods (Table 1) is the potential for an apparent temporal trend to be an artifact of methodological differences. To check for such differences and minimize the influence of method artifacts, annual mean values for STD, TP, and Chl-a were calculated from data that were log-transformed for normality for all lake stations and years that were sampled concurrently by the LMP and LTMP programs. A paired *t*-test ($p<0.05$) was used to test the statistical significance of any differences between these two sampling programs in the distributions of the annual means for each lake station and water quality variable. Where significant differences were found, separate LOWESS curves were fit to data from the LMP and LTMP programs and shown in parallel. Since the H–P surveys did not overlap in time with the other two monitoring programs, it was not possible to test for bias in the H–P results relative to the LMP or LTMP data.

The statistical significance of temporal trends suggested by the LOWESS plots was tested by linear regression of concentration vs. time in decimal years over the entire monitoring period. Means of the annual mean values were compared between the LMP and LTMP for each variable and lake station. For any variable and lake station found to be significantly different between the two programs during concurrent time periods, indicating possible programmatic bias, data from the LMP only were retained for the regressions because of the longer period of record from this program, and LTMP results were excluded. Unless noted otherwise, trends reported in the results as "increasing" or "decreasing" had slopes that were significantly different from zero ($p<0.05$), based on the linear regression analysis.

Intervals between sampling events within a particular lake region were typically a week or more, but the potential for temporal autocorrelation and overstated statistical significance of the regression results exists. While not tested, the influence of possible temporal autocorrelation on the general findings of these analyses is likely to be small because most regressions noted as statistically significant had p values well below the 0.05 criterion.

Results and discussion

Temperature

August mean surface water temperatures increased during the period of 1964–2009 in all lake regions, with statistically significant increases occurring at eight of ten stations (Fig. 3, Table 2). Linear regression lines were shown for temperature in Fig. 3 instead of LOWESS plots because of the discontinuity in the time series. August mean surface temperatures increased by 1.6–3.8 °C (0.035–0.085 °C/year) in these eight lake regions over this 46-year period.

The increasing trends in August surface water temperatures in Lake Champlain during 1964–2009 illustrate an effect of a warming regional climate over this period. The observed rates of summer water temperature increase in Lake Champlain were in a similar range as rates observed in Lake Ontario (0.048 °C/year), Lake Huron (0.084 °C/year), Lake Superior (0.11 °C/year), and Lake Baikal (0.038 °C/year) (Dobiesz and Lester, 2009; Austin and Colman, 2007; Hampton et al., 2008).

Summer air temperatures increased at an average rate of 0.037 °C/year in the Lake Champlain Basin during 1976–2005 (Stager and Thill, 2010, Fig. 1a). The observation that summer water surface temperatures in Lake Champlain increased faster than summer regional air temperatures is consistent with findings from the Great Lakes (Austin and Colman, 2007; Dobiesz and Lester, 2009). Winter ice cover has been declining in Lake Champlain (Stager and Thill, 2010), and the increase in summer water temperatures may be enhanced by greater heat absorption in the absence of ice and the resulting earlier onset of thermal stratification in the spring, as suggested by Austin and Colman (2007) and Stager and Thill (2010).

Secchi disk transparency

SDT is the water quality variable with the longest and most nearly continuous monitoring record in Lake Champlain, with data beginning in 1964 (Fig. 3). There has been a general trend of increasing SDT in lake regions along the main axis of the lake over the past four decades (Table 2). SDT increases ranged between 26 and 48% in the Main Lake, Shelburne Bay, Cumberland Bay, Grand Isle, and Isle LaMotte regions over the monitoring period. Water transparency in the South Lake more than doubled, with most of this increase occurring since the early 1990s. These trends were in contrast to observations in the northeastern regions of the lake where no significant trends were seen in the Northeast Arm, Malletts Bay, or St. Albans Bay over the period of 1964–2009. SDT decreased in Missisquoi Bay by about 25%, primarily since 1980.

Hypolimnetic dissolved oxygen

Three lake regions were chosen for evaluation of trends in hypolimnetic anoxia, including two regions (Northeast Arm and Malletts Bay) with historically known hypolimnetic DO deficits (Myer and Gruendling, 1979) and the Main Lake region where orthograde DO profiles with a metalimnetic minimum exist during the summer. There were no significant trends in late-summer hypolimnetic DO concentrations or June–September depletion rates in any of these lake regions during the monitoring period of 1990–2009 (Table 2). Examination of late summer depth profiles in the Main Lake did not indicate any change in the extent of the metalimnetic DO minimum during this period.

Sodium and chloride

The trend of increasing Na^+ in the Main Lake first noted by Potash and Henson (1975) continued lakewide through 2005 (Fig. 4, Table 2). Na^+ levels in the Main Lake region tripled since the 1960s. Linear regression lines were shown for Na^+ in Fig. 4 instead of LOWESS plots because of the discontinuity in the time series.

The Cl^- record (Fig. 4, Table 2) showed that the trend of increasing salt concentrations continued in the Main Lake and northern regions through 2009. Cl^- increased in the Main Lake by about 30% since 1992, although concentrations leveled off in recent years. In contrast, Cl^- concentrations declined in the northeastern regions of the lake since 1992 (Missisquoi Bay, St. Albans Bay, Northeast Arm, Malletts Bay), especially during recent years. Cl^- levels in the South Lake, which are affected by a paper mill discharge (Vermont DEC and New York State DEC, 1997), were elevated above concentrations measured elsewhere in the lake but remained stable over the 1992–2009 monitoring period.

Winter road salt application rates on Vermont state highways in the basin ranged between 14,000–30,000 mt/year as Cl^- during 1991–2009 (Fig. 1b). These quantities, when combined with the additional Cl^- used for deicing or summer dust suppression on local town roads in Vermont and on roads in the New York and Quebec portions of the watershed, represent a significant portion of the 125,000 mt/year total Cl^- load to Lake Champlain from all sources

Fig. 3. Long-term trends in August mean surface water temperature (1964–2009), SDT (1964–2009), and season mean zebra mussel veliger densities (1994–2009). Linear regression lines are shown for lake regions where the slope of the August mean temperature vs. year relationship was significantly different from zero ($p<0.05$). Separate LOWESS curves for SDT were fit to the H–P/LMP data and the LTMP data in lake regions where statistically significant differences were found between monitoring programs during concurrently sampled years. Note that the SDT scales vary, some data points were outside of the plot range, and initial zero values for zebra mussel densities were not plotted.

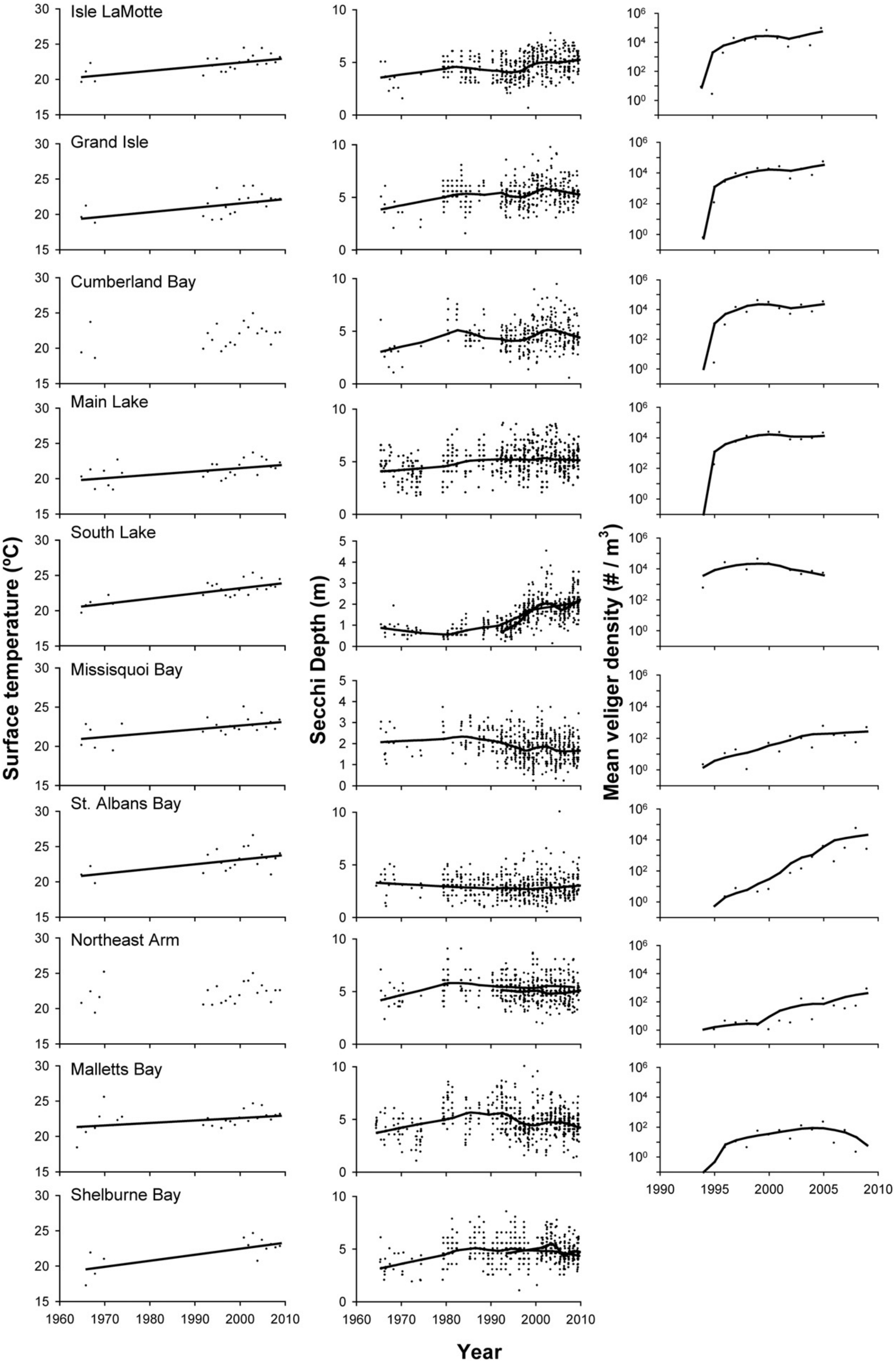

Isle LaMotte
Grand Isle
Cumberland Bay
Main Lake
South Lake
Missisquoi Bay
St. Albans Bay
Northeast Arm
Malletts Bay
Shelburne Bay
Surface temperature (ºC)
15
20
25
30
Secchi Depth (m)
0
5
10
1
2
3
4
Mean veliger density (# / m^3)
10^0
10^2
10^4
10^6
1960
1970
1980
1990
2000
2010
1995
2005
Year

Table 2
Linear regression results for water quality dependent variables vs. time in decimal years. Bold p values indicate slopes that were significantly different from zero ($p<0.05$). Data were from programs including the Henson and Potash surveys (H–P), the Vermont Lay Monitoring Program (LMP), and the Long-Term Water Quality and Biological Monitoring Program on Lake Champlain (LTMP). Footnotes indicate the specific time periods and program data used in the regressions.

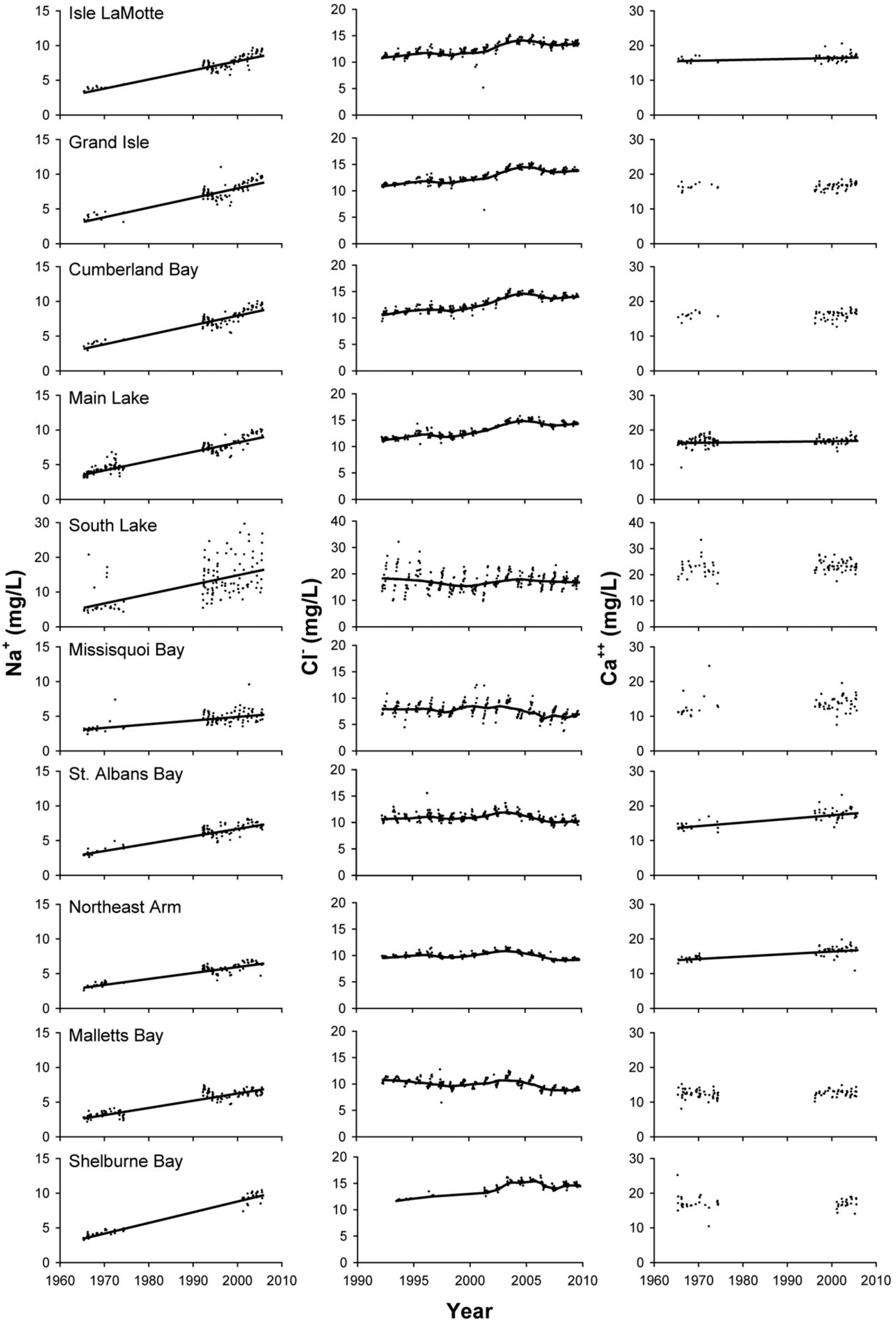
Variable/station	Intercept	Slope	p	Variable/station	Intercept	Slope	p
Temp °C				SDT (m)			
Isle LaMotte[a,b]	−80.6	0.0515	**0.010**	Isle LaMotte[a,c]	−66.1	0.0354	<**0.001**
Grand Isle[a,b]	−101.6	0.0615	**0.017**	Grand Isle[a,c]	−35.6	0.0205	**0.001**
Cumberland Bay[a,b]	−71.4	0.0466	0.101	Cumberland Bay[a,c]	−41.2	0.0229	**0.005**
Main Lake[a,b]	−74	0.0477	**0.006**	Main Lake[a,c]	−46.2	0.0257	<**0.001**
South Lake[a,b]	−124.7	0.0739	<**0.001**	South Lake[a,d]	−81	0.0413	<**0.001**
Missisquoi Bay[a,b]	−73.6	0.0481	**0.005**	Missisquoi Bay[a,c]	39.9	−0.0191	<**0.001**
St. Albans Bay[a,b]	−107	0.0651	**0.017**	St. Albans Bay[a,c]	8.6	−0.0029	0.504
Northeast Arm[a,b]	−18.7	0.0205	0.358	Northeast Arm[a,d]	−14.6	0.0101	0.134
Malletts Bay[a,b]	−47.2	0.0349	**0.038**	Malletts Bay[a,c]	16.6	−0.0059	0.212
Shelburne Bay[a,b]	−147.7	0.0851	**0.004**	Shelburne Bay[a,d]	−19.9	0.0124	**0.046**
DO Sept 1 (mg/L)				DO rate (mg/L/d)			
Main Lake 90 m[e,f]	−18.2	0.0145	0.386	Main Lake 90 m[e,f]	0.4	−0.0002	0.251
Northeast Arm 45 m[e,f]	5.2	−0.0005	0.989	Northeast Arm 45 m[e,f]	0.3	−0.0001	0.783
Malletts Bay 25 m[e,f]	−40.9	0.0222	0.765	Malletts Bay 25 m[e,f]	1.2	−0.0006	0.560
Na^+ (mg/L)				Cl^- (mg/L)			
Isle LaMotte[b,g]	−255.7	0.1317	<**0.001**	Isle LaMotte[f,h]	−350.1	0.1811	<**0.001**
Grand Isle[b,g]	−270.5	0.1393	<**0.001**	Grand Isle[f,h]	−401.6	0.207	<**0.001**
Cumberland Bay[b,g]	−267.27	0.1376	<**0.001**	Cumberland Bay[f,h]	−464	0.2382	<**0.001**
Main Lake[b,g]	−259.4	0.1338	<**0.001**	Main Lake[f,h]	−411.5	0.2121	<**0.001**
South Lake[b,g]	−535.3	0.2751	<**0.001**	South Lake[f,h]	19	−0.001	0.978
Missisquoi Bay[b,g]	−101.4	0.0531	<**0.001**	Missisquoi Bay[f,h]	187.8	−0.0901	<**0.001**
St. Albans Bay[b,g]	−205.4	0.1061	<**0.001**	St. Albans Bay[f,h]	66.5	−0.0278	**0.005**
Northeast Arm[b,g]	−167.2	0.0866	<**0.001**	Northeast Arm[f,h]	45.7	−0.0179	**0.013**
Malletts Bay[b,g]	−200.4	0.1033	<**0.001**	Malletts Bay[f,h]	178.77	−0.0844	<**0.001**
Shelburne Bay[b,g]	−298.7	0.1537	<**0.001**	Shelburne Bay[f,h]	−286.3	0.1499	<**0.001**
TP (μg/L)				Chl-a (μg/L)			
Isle LaMotte[i,j]	−54.5	0.0374	0.460	Isle LaMotte[i,k]	34.2	−0.0154	0.238
Grand Isle[i,k]	249	−0.1181	<**0.001**	Grand Isle[i,k]	34.5	−0.0154	0.233
Cumberland Bay[i,k]	562.2	−0.2743	<**0.001**	Cumberland Bay[i,k]	91.4	−0.0439	**0.002**
Main Lake[i,j]	−3.7	0.0102	0.863	Main Lake[i,k]	22	−0.0091	0.449
South Lake[i,j]	418.7	−0.1944	**0.002**	South Lake[i,k]	−2.2	0.0047	0.857
Missisquoi Bay[i,k]	−1201.2	0.6237	<**0.001**	Missisquoi Bay[i,j]	−1635.3	0.8275	<**0.001**
St. Albans Bay[i,j]	106.1	−0.035	0.752	St. Albans Bay[i,k]	−11.8	0.0113	0.847
Northeast Arm[i,j]	−501	0.2609	**0.001**	Northeast Arm[i,j]	−18.7	0.0116	0.761
Malletts Bay[i,j]	−290.9	0.1523	<**0.001**	Malletts Bay[i,k]	7.5	−0.0021	0.828
Shelburne Bay[i,j]	−156.8	0.0875	**0.023**	Shelburne Bay[i,j]	16.3	−0.006	0.712
TN (mg/L)				Ca^{++} (mg/L)			
Isle LaMotte[f,h]	4.4	−0.002	0.058	Isle LaMotte[b,g]	−32.7	0.0245	**0.014**
Grand Isle[f,h]	6.3	−0.003	**0.001**	Grand Isle[b,g]	−11.3	0.0138	0.155
Cumberland Bay[f,h]	9	−0.0043	<**0.001**	Cumberland Bay[b,g]	−7	0.0115	0.303
Main Lake[f,h]	7.4	−0.0035	<**0.001**	Main Lake[b,g]	−14.9	0.0158	**0.026**
South Lake[f,h]	9.44	−0.0045	<**0.001**	South Lake[b,g]	−37.1	0.0301	0.115
Missisquoi Bay[f,h]	11.54	−0.0054	**0.045**	Missisquoi Bay[b,g]	−64.1	0.0388	0.058
St. Albans Bay[f,h]	9.14	−0.0043	**0.001**	St. Albans Bay[b,g]	−191.4	0.1043	<**0.001**
Northeast Arm[f,h]	6.1	−0.0029	<**0.001**	Northeast Arm[b,g]	−126.3	0.0713	<**0.001**
Malletts Bay[f,h]	4.4	−0.002	**0.026**	Malletts Bay[b,g]	−11.3	0.0118	0.099
Shelburne Bay[f,h]	6.9	−0.0032	**0.030**	Shelburne Bay[b,g]	23.5	−0.0033	0.829

[a] 1964–2009.
[b] H–P,LTMP.
[c] H–P,LMP,LTMP.
[d] H–P,LMP.
[e] 1990–2009.
[f] LTMP.
[g] 1964–2005.
[h] 1992–2009.
[i] 1979–2009.
[j] LMP.
[k] LMP,LTMP.

estimated for 1990–1992 (Smeltzer and Quinn, 1996). Thus, changes in the rate of road salt application could plausibly account for the Cl^- trends seen in the lake. The 30% drop in road salt use since 1999 in Vermont state highway districts within the Lake Champlain Basin (Fig. 1b) appears to have produced a Cl^- decline in eastern (Vermont-side) regions of Lake Champlain after a lag time of about 5 years (Fig. 4).

Despite the long-term Cl^- increases observed in central and western areas of Lake Champlain, current levels (<25 mg/L) are well below the USEPA (1988) criterion of 230–860 mg/L established to protect

Fig. 4. Long-term trends in Na^+ (1964–2005), Cl^- (1992–2009), and Ca^{++} (1964–2005). Linear regression lines are shown for lake regions where the slope of the Na^+ or Ca^{++} vs. year relationship was significantly different from zero ($p<0.05$). LOWESS trend lines are shown for Cl^-. Note that the scales vary, and some data points were outside of the plot range.


Isle LaMotte
Grand Isle
Cumberland Bay
Main Lake
South Lake
Missisquoi Bay
St. Albans Bay
Northeast Arm
Malletts Bay
Shelburne Bay
Na^+ (mg/L)
Cl^- (mg/L)
Ca^{++} (mg/L)
Year
1960
1970
1980
1990
2000
2010
1995
2005

ambient aquatic life. However, just as Chapra et al. (2009) noted that Cl^- trends in the Great Lakes serve as "canaries in the coal mine," the Lake Champlain trends point to water quality changes in the smaller waterways of the basin. Recent studies in small Vermont streams have determined that Cl^- concentrations in some urban locations exceeded the USEPA chronic criterion of 230 mg/L between 60 and 80% of the time (Denner et al., 2010; Vermont DEC, unpublished data). The Adirondack Park region in New York has also been affected by winter road maintenance practices, with Cl^- exceeding 80 mg/L in some lakes (Langen et al., 2006).

Total phosphorus, chlorophyll-a, and total nitrogen

Trends in TP concentrations in Lake Champlain (Fig. 5) differed among the lake regions, with increases seen in the northeastern regions and stable or declining levels observed along the main axis of the lake (Table 2). A TP increase of 72% (20 μg/L) occurred in Missisquoi Bay over the 1979–2009 monitoring period. The Northeast Arm, Malletts Bay, and Shelburne Bay also had increasing trends during this period, although no trends were seen in St. Albans Bay. No overall trends were observed in the Main Lake or Isle LaMotte regions during the 1979–2009 monitoring period, although decreasing TP concentrations occurred in the Grand Isle, Cumberland Bay, and South Lake regions. A previous analysis limited to the LTMP data found statistically significant increasing linear trends in TP in the Missisquoi Bay, Northeast Arm, and Malletts Bay regions over the period of 1990–2008, but no significant trends in the other regions (Smeltzer et al., 2009).

Chl-a concentrations (Fig. 5, Table 2) showed few trends over the 1979–2009 monitoring period. Missisquoi Bay was an exception where Chl-a levels doubled over this period. A statistically significant decrease was seen in Cumberland Bay. Our findings of increasing TP and Chl-a in Missisquoi Bay since the late 1970s, and elevated but relatively stable levels in St. Albans Bay over this period, are consistent with paleolimnological evidence (Levine et al., 2012).

Given the substantial, long-term efforts to reduce phosphorus loading in the Lake Champlain Basin, the fact that TP and Chl-a concentrations have declined significantly in only a few lake regions and increased in others is disappointing to lake managers. Tributary TP monitoring during 1990–2009, including contributions from nonpoint sources, showed no overall lake-wide trend in total loadings (Smeltzer et al., 2009). Conversion of land during this period to higher phosphorus-yielding uses (Troy et al., 2007), and greater river flow rates in recent years, may have offset the gains from wastewater treatment. When tributary phosphorus concentrations and loads were normalized for temporal variations in flow (Medalie et al., 2012), decreasing trends were found in many rivers since 1999, suggesting that a watershed response to management efforts may have begun to occur.

There was a general lakewide trend of decreasing levels of TN over the LTMP monitoring period of 1992–2009 (Fig. 5, Table 2). Overall TN declines were about 18% in the Main Lake and adjoining lake regions during this period. TN declines in Missisquoi Bay, St. Albans Bay, and the South Lake were closer to 25% with most of the drop occurring in recent years.

The lakewide decreases in TN are not explained by changes in agricultural practices since nitrogen fertilizer sales and the amount of corn land harvested within the heavily agricultural Missisquoi Bay and St. Albans Bay watersheds both increased since 1990 (Fig. 1d). Reductions in atmospheric nitrogen deposition to the lake's surface or its watershed (Fig. 1e) may have accounted for some of the TN reduction seen in Lake Champlain, but the trends in tributary nitrogen loads during the 1990–2009 monitoring period were not consistent over time. Flow-normalized TN concentrations in nearly all tributaries to Lake Champlain declined since 1999, but these decreases followed a period of generally increasing loads during the prior decade (Medalie et al., 2012). Nitrogen mass balance modeling analyses should be conducted in order to more definitively evaluate the causes for the TN decline in Lake Champlain.

The decreasing TN trend in Lake Champlain contrasts with the increasing nitrate and TN concentrations in Lake Superior (McDonald et al., 2010). However, the Lake Superior trend was documented over a much longer time period (since 1900). Recent data and model scenarios suggest TN and nitrate in Lake Superior may have peaked or begun to decline as a result of reduced loadings or changes in internal processes (McDonald et al., 2010).

Zebra mussel veligers and calcium

After the first zebra mussel adult was discovered in the South Lake region of Lake Champlain in 1993, there was a very rapid increase in zebra mussel veliger densities northward through the Main Lake, Cumberland Bay, Grand Isle, and Isle LaMotte regions (Fig. 3). Season mean veliger densities exceeded 10,000/m^3 within the first few years and have generally stabilized in these regions since then. Veliger densities peaked in the South Lake at 40,000/m^3 in 1999 and have since declined. However, veliger monitoring ended in these regions in 2005. In northeastern lake regions (Missisquoi Bay, St. Albans Bay, Northeast Arm, and Malletts Bay), the veliger population increases were much slower and, with the exception of St. Albans Bay in 2008, season mean densities have not exceeded 1000/m^3.

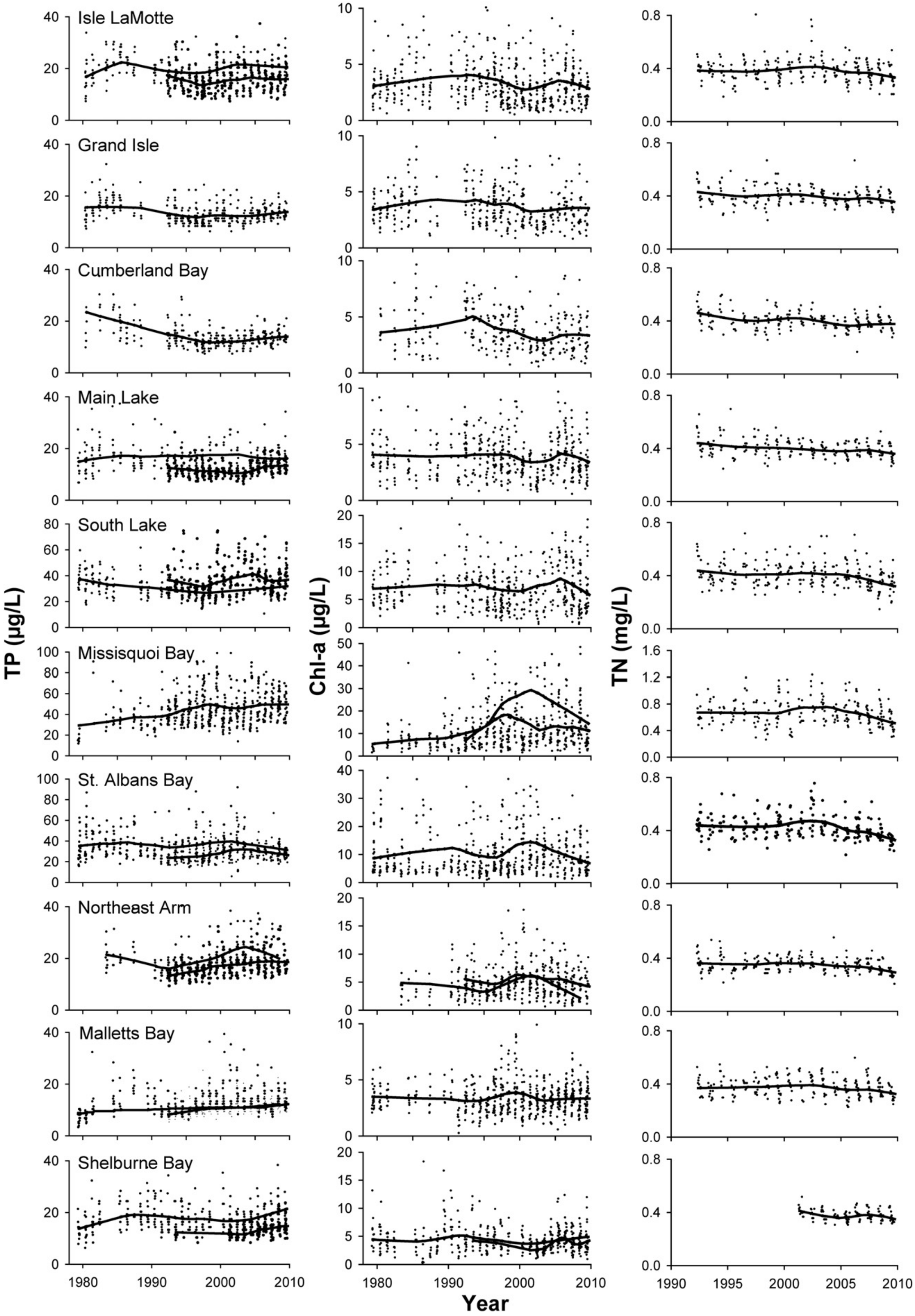
Lake Champlain has not responded as dramatically to zebra mussel invasion as have other lakes. Increases in SDT have been seen in many areas of Lake Champlain, but declines in TP and Chl-a have been limited in extent. Benthic macroinvertebrate communities in Lake Champlain responded positively to the presence of zebra mussels (Beekey et al., 2004), but incidences of nuisance filamentous green algae are rarely reported in the lake.

Filtration by adult zebra mussels is probably the major factor responsible for the increasing SDT trends. The mid-1990s timing of the largest transparency increases in the South Lake, Isle LaMotte, and Grand Isle regions (Fig. 3) corresponded to the explosive growth of zebra mussel populations in the lake as indicated by veliger densities. Transparency has not increased, or has decreased, in regions of Lake Champlain where zebra mussel veliger densities have remained relatively low (Missisquoi Bay, St. Albans Bay, the Northeast Arm, and Malletts Bay).

Barbiero et al. (2006) linked transparency increases in Lake Ontario to Ca^{++} uptake by zebra mussels and fewer calcite precipitation events, but no such declines in Ca^{++} have been observed in Lake Champlain. Ca^{++} concentrations in most regions of the lake showed little change between the H–P survey period of 1964–1974 and the LTMP monitoring period of 1992–2005 (Fig. 4, Table 2). However, small but significant positive trends were observed in the Isle LaMotte, Main Lake, St. Albans Bay, and Northeast Arm regions (linear regression lines were shown in Fig. 4 instead of LOWESS plots because of the discontinuity in the time series).

The reason for the much slower expansion of zebra mussel populations in the northeastern regions of Lake Champlain is not clear. Missisquoi Bay, the Northeast Arm, and Malletts Bay are each separated from adjoining lake regions by causeways, but openings in the causeways allow ample opportunity for the introduction of seed populations of veligers through water circulation. Missisquoi Bay and Malletts Bay have the lowest Ca^{++} concentrations among Lake Champlain regions, averaging less than 15 mg/L (Fig. 4). Low calcium is considered limiting to zebra mussels (Mellina and Rasmussen, 1994; Hincks and Mackie,

Fig. 5. Long-term trends in TP (1979–2009), Chl-a (1979–2009), and TN (1992–2009). Separate LOWESS curves were fit to the LMP and LTMP data in lake regions where statistically significant differences were found between monitoring programs during concurrently sampled years. Note that the scales vary, and some data points were outside of the plot range.


Isle LaMotte
Grand Isle
Cumberland Bay
Main Lake
South Lake
Missisquoi Bay
St. Albans Bay
Northeast Arm
Malletts Bay
Shelburne Bay
TP (µg/L)
Chl-a (µg/L)
TN (mg/L)
Year
1980
1990
2000
2010
1990
1995
2000
2005
2010

1997; Frischer et al., 2005). Whittier et al. (2008) considered invasion probability low in areas where Ca^{++} was less than 20 mg/L, noting also that some authors consider 20 mg/L Ca^{++} as being necessary to sustain a reproducing population.

Low calcium is most likely limiting zebra mussel spread in Malletts Bay, where there is sufficient hard substrate available for colonization. Substrate in Missisquoi Bay, St. Albans Bay, and the Northeast Arm is primarily soft, though native mussels, aquatic macrophytes, docks, and other infrastructure offer suitable attachment sites. Zebra mussels were slow to colonize soft sediment in other parts of Lake Champlain, but extensive mats were apparent in some locations by 2000 (Beekey et al., 2004). If the trend of increasing Ca^{++} concentrations in northeastern regions of Lake Champlain continues, then zebra mussel populations could expand because substrate is unlikely to be limiting in those areas. Quagga mussels (*Dreissena bugensis*) have not yet been found in Lake Champlain.

Phytoplankton

The LTMP phytoplankton cell count data were used to identify the dominant genera present in each region of Lake Champlain during 2006–2009, and compared in Table 3 with observations from previous studies. The earlier studies by Myer and Gruendling (1979) and Shambaugh et al. (1999) involved counts on whole-water samples, rather than 63 μm mesh net tows as used by the LTMP. Therefore, the dominant genera listed in Table 3 for the earlier time periods were restricted to those that would have been captured as net phytoplankton. Spring, summer, and fall data were combined to assess the dominant genera for these comparisons.

Diatoms (Chrysophyta) were the dominant phytoplankton taxa present throughout Lake Champlain during 1970–1974 and 1991–1992, with the exception of St. Albans Bay where cyanobacteria dominated. Diatoms remain prevalent in most regions of the lake, but there has been a shift to increasing cyanobacteria dominance in northeastern lake regions during the recent time period of 2006–2009. Large colonial and filamentous cyanobacteria are now the dominant taxa in the Northeast Arm and Missisquoi Bay, as well as in St. Albans Bay. While Myer and Gruendling (1979) noted few cyanobacteria in Missisquoi Bay during the 1970s, the bay is now subject to blooms of *Aphanizomenon*, *Microcystis*, and *Anabaena* and the production of cyanotoxins such as microcystin (Watzin et al., 2011). These findings of relatively recent proliferation of cyanobacteria in Missisquoi Bay are consistent with fossil pigment evidence in sediment cores (Levine et al., 2012).

The observed shifts in the Lake Champlain phytoplankton community were likely influenced by a complex interaction of nutrient, food web, and other environmental changes in the lake and its watershed. Cyanobacteria tend to dominate by various competitive mechanisms in lakes where TN:TP ratios or dissolved inorganic nitrogen concentrations are low (Smith, 1983; Nurnberg, 2007). The increased presence of cyanobacteria in northeastern regions of the lake may be related to the decline in TN:TP ratios as a result of decreasing TN concentrations (Fig. 5). However, increases in TP in northeastern regions of Lake Champlain provide an alternate explanation for the greater cyanobacteria presence (Watson et al., 1997; Downing et al., 2001).

In shallow regions such as Missisquoi Bay, higher temperatures at the sediment–water interface could be accelerating internal phosphorus loading during the summer (Jensen and Andersen, 1992). Increased thermal stability resulting from the warmer summer surface water temperatures (Fig. 3) also facilitates cyanobacteria dominance (Wagner and Adrian, 2009). Zebra mussel filtration, and reduction in competition from green algae, have been linked to increases in cyanobacteria in some lakes, and to the proliferation of *M. aeruginosa* in particular (Makarewicz et al., 1999; Vanderploeg et al., 2001; Nichols et al., 2002; Raikow et al., 2004). However, locations in Lake Champlain such as Missisquoi Bay, the Northeast Arm, and Malletts Bay where *Microcystis* or other cyanobacteria have increased host relatively small populations of these mussels (Fig. 3). The introduction of alewife (*Alosa pseudoharengus*) to Lake Champlain in 2003 was linked with an observed loss of large zooplankton (Mihuc et al., 2012), a top–down food web effect that may release cyanobacteria from grazing by large daphnids and other zooplankton (Elser, 1999).

Table 3
Historical changes in the dominant genera of large-celled phytoplankton in Lake Champlain based on cell and colony density observations during spring, summer, and fall.

	Time period		
Lake region	1970–1974[a]	1991–1992[b]	2006–2009[c]
South Lake	*Microcystis*[d], *Aulocoseira*[e], *Stephanodiscus*[e], *Eudorina*[f], *Aphanizomenon*[d]	Large centric diatoms[e], Large pennate diatoms[e], *Aphanizomenon*[d]	*Aulocoseira*[e], *Aphanizomenon*[d], *Ulothrix*[f]
Shelburne Bay		*Asterionella*[e], *Aulocoseira*[e], *Dinobryon*[e]	*Fragilaria*[e], *Aulocoseira*[e], *Woronichinia*[d]
Main Lake	*Aulocoseira*[e], *Fragilaria*[e], *Anabaena*[d], *Asterionella*[e], *Synedra*[e]		*Fragilaria*[e], *Woronichinia*[d], *Asterionella*[e]
Malletts Bay	*Fragilaria*[e], *Synedra*[e], *Tabellaria*[e], *Peridinium*[g]	*Asterionella*[e], *Aphanizomenon*[d], *Fragilaria*[e]	*Woronichinia*[d], *Fragilaria*[e], *Aphanothece*[d]
Cumberland Bay		*Asterionella*[e], *Fragilaria*[e], *Aulocoseira*[e]	*Fragilaria*[e], *Aphanothece*[d], *Asterionella*[e]
Northeast Arm	*Fragilaria*[e], *Synedra*[e]	*Aphanizomenon*[d], *Fragilaria*[e], *Mougeotia*[f]	*Woronichinia*[d], *Fragilaria*[e], *Aphanizomenon*[d]
Grand Isle		*Asterionella*[e] *Fragilaria*[e] *Aulocoseira*[e]	*Fragilaria*[e] *Aulocoseira*[e] *Woronichinia*[d]
St. Albans Bay	*Anabaena*[d]	*Anabaena*[d], Unidentified trichome[d], *Microcystis*[d]	*Aphanizomenon*[d], *Anabaena*[d], *Aulocoseira*[e], *Fragilaria*[e]
Isle La Motte		Large pennate diatoms[e], *Asterionella*[e], *Aulocoseira*[e]	*Fragilaria*[e], *Microcystis*[d], *Aulocoseira*[e]
Missisquoi Bay	*Aulocoseira*[e], *Asterionella*[e], *Diatoma*[e], *Stephanodiscus*[e]	Large centric diatoms[e], *Microcystis*[d], *Pediastrum*[f]	*Aphanizomenon*[d], *Microcystis*[d], *Anabaena*[d]

[a] Myer and Gruendling (1979).
[b] Shambaugh et al. (1999).
[c] LTMP, this study.
[d] Cyanobacteria.
[e] Chrysophyta.
[f] Chlorophyta.
[g] Pyrrophyta.

Differences between sampling programs

There were several lake regions where the mean of the long-term annual means for SDT, TP, or Chl-a differed between the LTMP and the LMP sampling programs during the same monitoring period, and where LOWESS curves were therefore plotted separately for the two programs in Figs. 3 and 5. However, the directions of the trends indicated for these variables in the LOWESS plots were similar between the two monitoring programs, even where differences in the long-term mean values existed.

Restricting the LTMP data to the June–September season coincident with the LMP program data did not eliminate the bias for any lake region. The direction of the bias, when present, was not consistently positive or negative among the lake regions, which suggests that a difference in sampling technique between programs (Table 1) was probably not the major factor responsible for the bias.

Differences in navigation methods used by the LMP (visual landmarks) and the LTMP (electronic aids) could have led to samples being obtained from slightly different locations within these lake regions. Strong spatial water quality gradients are known to exist in some areas of Lake Champlain, particularly in the South Lake, Shelburne Bay, and St. Albans Bay, and errors in locating sampling locations might explain the discrepancies in the results for these areas. Providing citizen monitors with navigation aids such as global positioning system devices would be an appropriate way to eliminate this potential problem in future monitoring programs on Lake Champlain and other large lakes.

Conclusions

The "long-term" monitoring window of 18–46 years for the data presented here represents an extremely brief period of time relative to the 9000 years that Lake Champlain has existed in its present geologic form. The fact that measureable environmental trends were observed during the monitoring period suggests that anthropogenic influences were primarily responsible. However, the changes in the lake did not always occur as predicted from trends in environmental stressors and management activities. The spread of zebra mussels has been slower than expected in northeastern lake regions and may be limited by low Ca^{++} concentrations. There was no proliferation of cyanobacteria species such as *M. aeruginosa* that could be linked to zebra mussels, as has occurred in some of the Great Lakes. TP and Chl-a declined in some areas of the lake but not in the more eutrophic northeastern lake regions, despite significant management efforts at controlling point and nonpoint sources in the watershed. The lakewide decline in TN was a surprising finding, given the increases in corn production and fertilizer use in the watershed, and might have been due in part to regional reductions in atmospheric nitrogen deposition rates.

The scope and sometimes unexpected nature of environmental changes that have occurred in Lake Champlain illustrate the importance of continuing the long-term monitoring programs. The awareness and understanding of alterations in the lake's ecosystem gained from monitoring can be used to direct management responses in a more timely and effective manner. Lake Champlain experienced historically unprecedented flooding during the spring of 2011, followed by destructive river flows from Tropical Storm Irene in August, 2011. The data provided by the ongoing monitoring programs will be invaluable in assessing the environmental effects of these extreme weather events.

This paper presents only a limited subset of the variables and monitoring sites encompassed in the current monitoring databases, and numerous research questions remain. The authors hope that the availability of the Long-Term Monitoring Program dataset on the internet may stimulate further analyses and investigation of ecological changes in Lake Champlain.

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Climate Change Adaptation White Paper Series

Climate Change in Vermont

Alan K. Betts, June 2011 (edited 10/29/2011)

Vermont's climate has changed substantially in the past fifty years. Continuing change is certain, as the Earth's climate is being driven towards a warmer state by the increase of greenhouse gases in the atmosphere. The primary driver is the increase of atmospheric CO_2 from the burning of fossil fuels, which reduces the cooling of the Earth to space. The small warming from the increase of CO_2 is amplified several times[1] because atmospheric water vapor, another powerful greenhouse gas, increases as temperature increases. Reductions in snow and sea-ice cover at northern latitudes also amplify the warming, because less of the sun's energy is reflected.

We have two complementary reference frameworks when planning for the future:

1) Regional projections from climate models
2) Climate trends in Vermont and New England in recent decades

Global model projections help us look into an uncertain future and explore humanity's options. For example, we can estimate how the patterns of temperature and precipitation will change, and see how reducing greenhouse gas emissions give a smaller temperature rise by the end of this century. Our models for the Earth's climate system necessarily contain simplifications, but they are continually revised as understanding improves. In 2007, a major synthesis was completed by an international team of 500 lead authors and 2,000 expert reviewers for the Intergovernmental Panel on Climate Change. This Fourth Assessment Report (IPCC-AR4)[2] documented the global and regional changes in temperature and precipitation expected this century. This report contains results from regional studies for the United States and New England that were based on the IPCC-AR4 report. Some 800 experts are now working on the next update, the Fifth Assessment Report, expected to be finished in 2014.

Our biggest challenge is that our ability to predict the future climate in detail is limited. So it is very helpful to examine climate trends in Vermont and New England in recent decades as a guide for the future. These recent observational trends are familiar to local communities and can help us understand the relationship between the local climate change that we are experiencing and projected global climate changes.

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How does predicting climate differ from forecasting weather?

Predicting climate is very different from forecasting weather. With global models we can forecast the day-to-day weather for about a week – generally forecast skill lasts a few days longer in winter than in summer. Further into the future we can only predict the general climate.

For example, we can predict with certainty that next July will be warmer than it was in January – because the sun heats the Earth more when it is high in the sky – but we can't forecast whether it will rain on the 4th of July. Furthermore, even though the sun follows the same path in the sky every year, some summers are drier and warmer or wetter and cooler than 'usual.' This is because regional weather patterns vary widely, depending, for example, on the position and movement of the jet streams. Scientists say the climate system has a lot of internal variability.

Similarly as CO_2 rises in the atmosphere, we know this will push the Earth towards a warmer climate, because CO_2 is a greenhouse gas that traps the Earth's heat. And as the earth warms, more water evaporates – and because water vapor is another greenhouse gas, the warming is further amplified. And as the Earth warms, ice and snow cover are reduced, so less sunlight is reflected. This amplifies the warming further. So we can predict that the Arctic (and northern winters) will warm faster as the reflective snow and sea ice decrease. In contrast, the Antarctic ice sheets are thousands of feet thick and will take hundreds to thousands of years to melt as the Earth warms.

We can also predict that the continents will warm faster than the oceans. As the climate warms, heat is only conducted down a short distance into the ground over land. But the oceans circulate heat down to the ocean depths, so they warm more slowly.

While we can predict a broad warming climate trend as atmospheric greenhouse gases rise, we cannot predict the detailed future weather. We must expect the large variability from year to year to continue; in fact, it may increase.

Regional projections from climate models

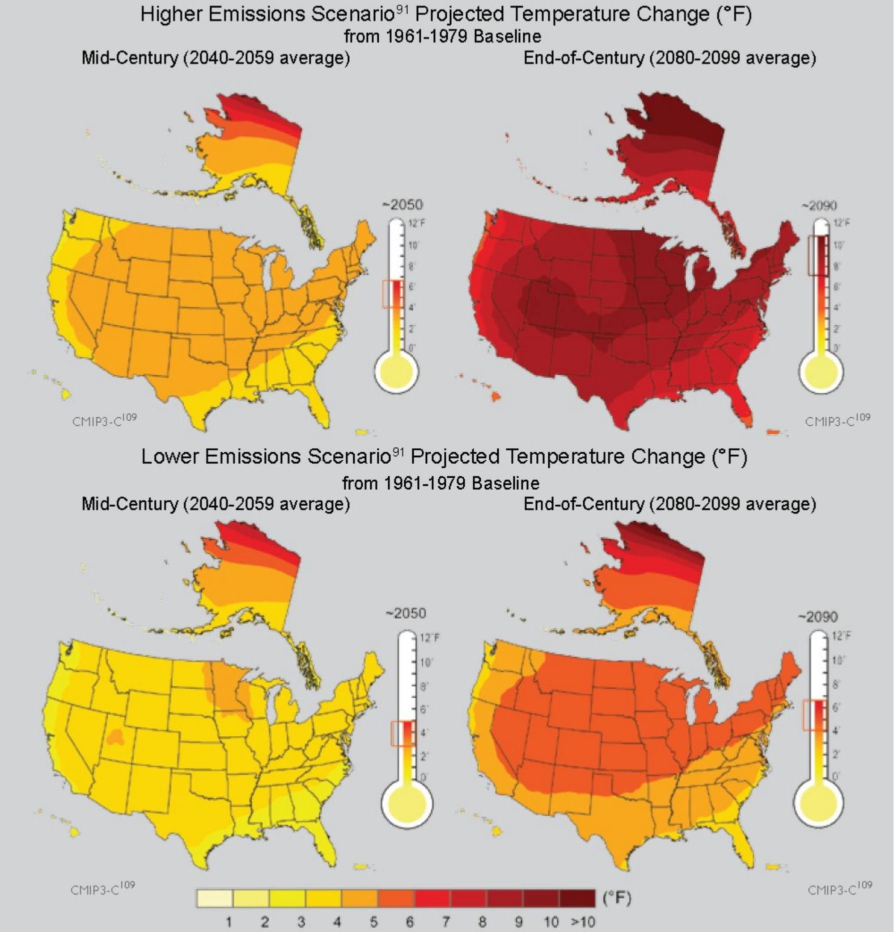
USGCRP (2009) - pp 29

Based on the IPCC-AR4 model projections, the US Global Change Research Program produced a report, *Global Climate Change Impacts in the United States.* [3]

This map shows the projected mean annual temperature increases for North America for mid century and end of century for both higher and lower greenhouse gas ‘emissions scenarios.’ For the lower emissions scenario, the projected temperature change for Vermont is about 3°F by 2050, and about 5°F by late century. For the higher emissions scenarios, these increases in temperature are larger: 4°F and 9-10°F, respectively.

(These are annual mean increases; the northeast is likely to see larger temperature increases in winter than summer.)

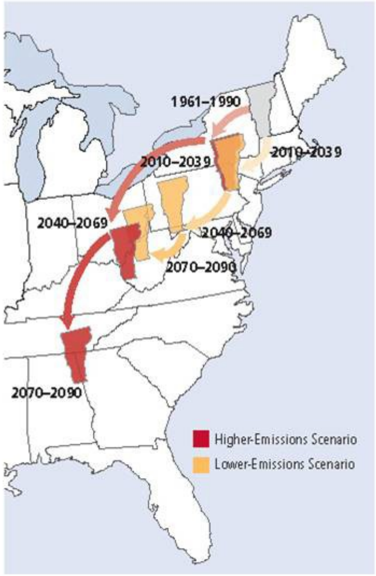
The lower emissions scenario is based on the assumption that the global community makes major reductions in greenhouse gas emissions.



The maps on this page and the previous page are based on projections of future temperature by 16 of the Coupled Model Intercomparison Project Three (CMIP3) climate models using two emissions scenarios from the Intergovernmental Panel on Climate Change (IPCC), *Special Report on Emission Scenarios* (SRES).[91] The “lower” scenario here is B1, while the “higher” is A2.[91] The brackets on the thermometers represent the likely range of model projections, though lower or higher outcomes are possible. Additional information on these scenarios is on pages 22 and 23 in the previous section, *Global Climate Change*. These maps, and others in this report, show projections at national, regional, and sub-regional scales, using well-established techniques.[110]

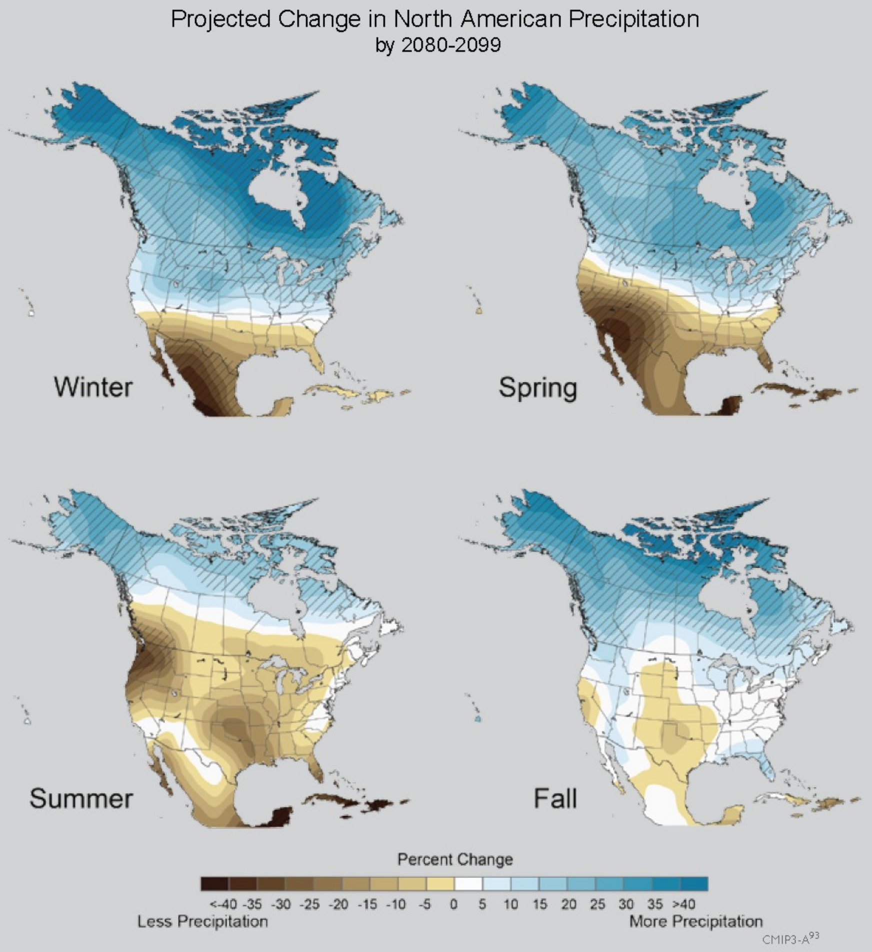
This map from the Northeast Climate Impacts Assessment[4] gives a visualization of what summers in Vermont will feel like over the course of this century with high and low greenhouse gas emissions.

If current high emissions continue, Vermont’s summer climate by 2080 will feel similar to the climate of northwest Georgia for the period 1961-1990. However, if emissions are greatly reduced, the climate of Vermont will more closely resemble the climate of southeastern Ohio.



Migrating State Climate

Changes in average summer heat index—a measure of how hot it actually feels, given temperature and humidity—could strongly affect quality of life in the future for residents of Vermont. Red arrows track what summers in Vermont could feel like over the course of the century under the higher-emissions scenario. Yellow arrows track what summers in the state could feel like under the lower-emissions scenario.


Projected Change in North American Precipitation
by 2080-2099

The maps show projected future changes in precipitation relative to the recent past as simulated by 15 climate models. The simulations are for late this century, under a higher emissions scenario.[91] For example, in the spring, climate models agree that northern areas are likely to get wetter, and southern areas drier. There is less confidence in exactly where the transition between wetter and drier areas will occur. Confidence in the projected changes is highest in the hatched areas.

USGCRP (2009) – pp 31

This map shows the projected seasonal changes in North American precipitation by the end of the century for continued high emissions. [3]

For Vermont the projected increases are about 15% in winter, 10% in spring, 5% in fall, and no change in summer. The lightest precipitation is projected to decrease, while the heaviest precipitation will increase.

Precipitation is not as easy to predict as temperature, but these model projections reflect an increase of precipitation with warming at high northern latitudes, as well as a reduction of precipitation across the southern US. This reduction is associated with a poleward shift of the subtropical dry zones, which we are already observing. [5]

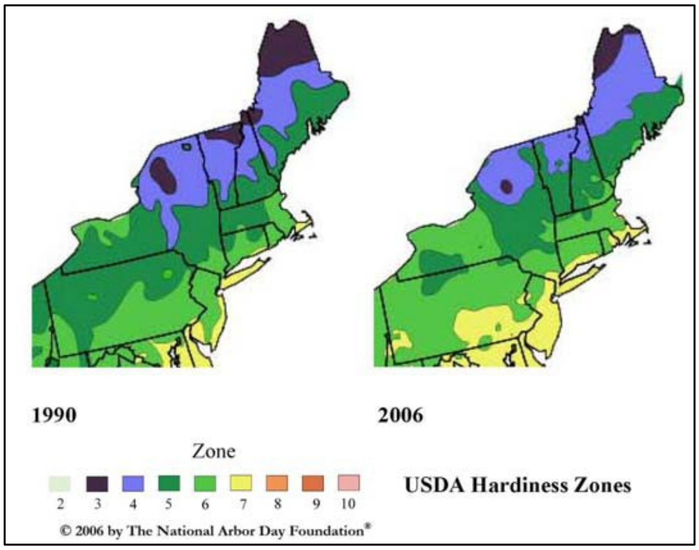
Evaporation increases with temperature; therefore in regions where precipitation decreases, an increase in drought frequency is likely.[6] In New England, earlier snowmelt, and more runoff from heavier summer rainfall, coupled with increased evaporation, are expected to increase the frequency of summer droughts – if high emissions continue.[7]

Climate trends in New England in recent decades

These projected changes are consistent with the climate trends seen in the Northeast in recent decades.[3,7,8,9,10] Since 1970 the annual average temperature in the Northeast has increased by 2°F, with winter temperatures rising twice this much. Warming has resulted in many other climate-related changes, including:

- More frequent days with temperatures above 90°F
- A longer growing season
- Increased heavy precipitation
- Less winter precipitation falling as snow and more as rain
- Reduced snowpack in some winters
- Earlier breakup of winter ice on lakes and rivers
- Earlier spring snowmelt resulting in earlier peak river flows
- Rising sea surface temperatures and sea level in coastal states

Temperatures have risen the most in winter. The USDA winter hardiness zones are determined by average minimum winter temperatures and are used to tell what plants, shrubs and trees can survive a typical winter. As the climate has warmed in winter across the whole of the Northeast, Vermont has gone from mostly Zone 4 to mostly zone 5 between 1990 and 2006; while Massachusetts has become mostly Zone 6. [11]



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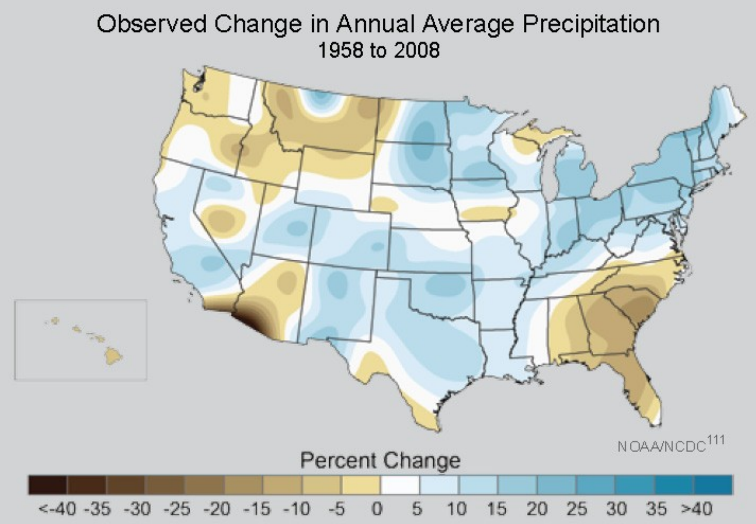
Observed changes in precipitation

Precipitation has increased in Vermont by 15-20% in the past fifty years, with increasing trends throughout much of the year. Heavy downpours have increased in frequency and intensity across most of the U.S., especially in the Northeast, where there has been a 67% increase in the amount falling during very heavy precipitation events. Water management has traditionally been based on historical precipitation statistics, but this assumption is no longer valid. [12]

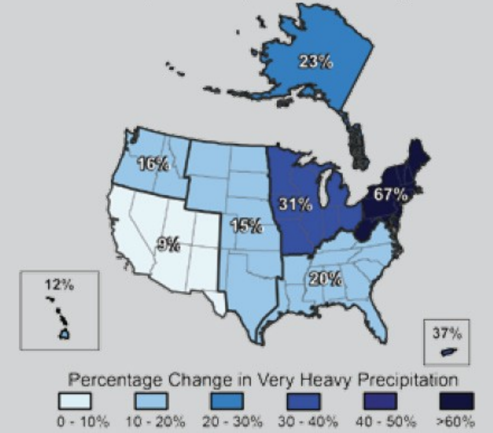
The USGS has recently developed a framework for a hydrologic climate-response program in Maine, which is being extended to other New England states.[13] Preliminary results for Vermont show increases in annual mean stream flow have occurred in the past fifty years, with significant increases in monthly mean flows in the period July through December. [14]

Observed Change in Annual Average Precipitation
1958 to 2008



While U.S. annual average precipitation has increased about 5 percent over the past 50 years, there have been important regional differences as shown above.

Increases in Amounts of Very Heavy Precipitation (1958 to 2007)



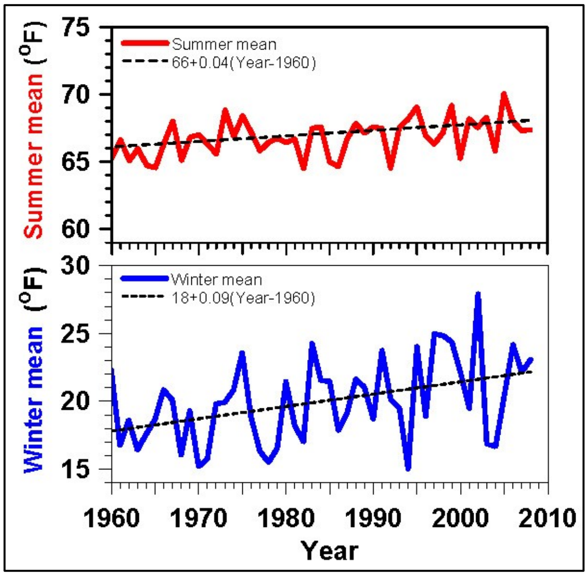
Updated from Groisman *et al.*[113]

The map shows percent increases in the amount falling in very heavy precipitation events (defined as the heaviest 1 percent of all daily events) from 1958 to 2007 for each region. There are clear trends toward more very heavy precipitation for the nation as a whole, and particularly in the Northeast and Midwest.

USGCRP (2009) – pp 30 and 32

Seasonal climate trends in Vermont in recent decades

Summer and winter temperature trends since 1960



This figure shows the mean trends in Vermont summer temperatures and winter temperatures since 1960 from an average of four Vermont climate stations in Burlington, Cavendish, Enosburg Falls and St. Johnsbury.[15] From 1960-2008:

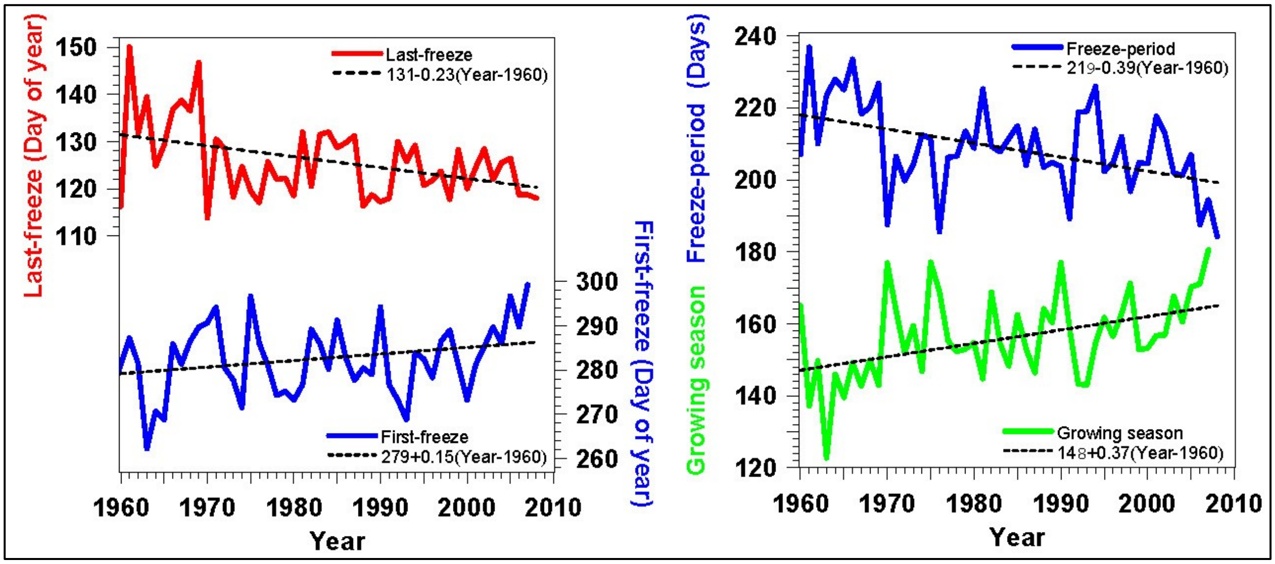
- Summer temperature trend is 0.4 (±0.12)°F per decade
- Winter temperature trend is 0.9 (±0.28)°F per decade

The upward trend in winter temperature is about twice as large as in summer. The annual mean trend for Vermont is the same as for New England, about 0.5 °F per decade. Note that the variability from year to year in winter is more than twice as large as in summer. In fifty years, mean winter temperatures in Vermont have risen about 4.5 °F; while in summer, mean temperatures have risen about 2 °F.

If we extrapolate the observed mean annual warming trend for Vermont of 0.5°F per decade from 1970 out to 2050, we get a 4°F warming, which is consistent with the model projections shown earlier.

Length of Vermont's growing season

These warming trends are affecting the timing and nature of the Vermont seasons.[15,16]
First and last freeze dates are changing, and the length of the growing season is increasing.



There is large variability from year to year, as first and last frosts are single night events, but the trend lines show that on average:

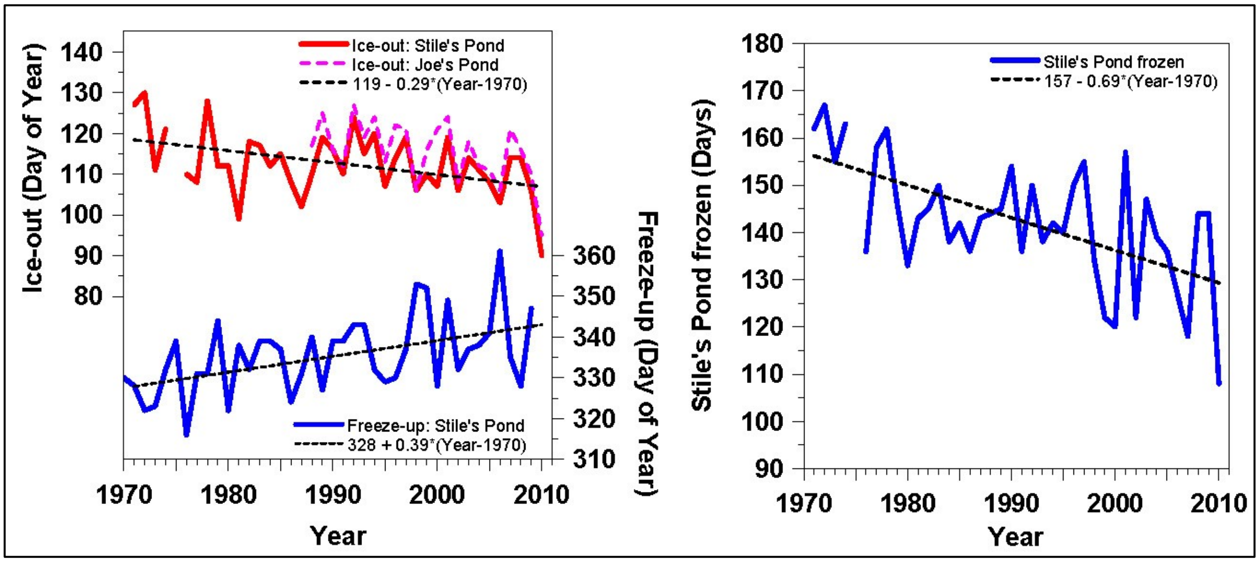
- Last spring freeze has come earlier by 2.3 (±0.7) days per decade
- First autumn freeze has come later by 1.5 (±0.8) days per decade
- Freeze-period has decreased 3.9 (±1.1) days per decade
- Growing season has increased 3.7 (±1.1) days per decade

These trends show that in the past forty years, the growing season for frost-sensitive plants has increased by about 2 weeks.

Freeze-up, ice-out and freeze-length for small lakes

The freeze and ice-out dates for small lakes are good integrated climate indicators for the length and severity of the cold season in Vermont.[15] The date of freeze-up depends on lake and air temperatures over many weeks in the fall; ice thickness depends on the severity of the winter; and the date of spring melt/ice-out depends on ice thickness and air temperatures in spring. These dates are important for the ecology of the lakes, and the frozen period and ice thickness matter to the public for winter recreation, including ice fishing.

The freeze-up and ice-out dates for Stile's Pond in Waterford, Vermont have been recorded since 1971 by the Fairbanks Museum in St. Johnsbury. There has been an annual contest to guess the ice-out date on Joe's Pond in West Danville, Vermont, and these dates have been recorded since 1988. Joe's Pond melts about 4 days later than Stile's Pond, because it is 676 ft higher in elevation.



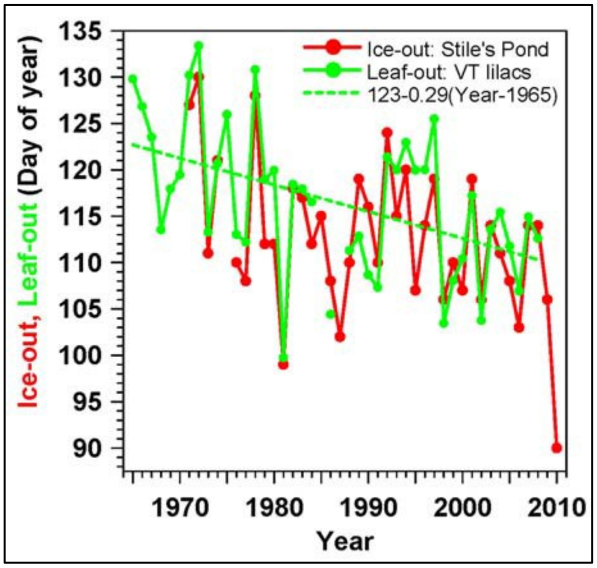
Despite the large variability from year to year, trends are clear. For Stile's Pond over the past forty winters:

- Freeze-up has occurred later by 3.9 (±1.1) days per decade.
- Ice-out has come earlier by 2.9 (±1.0) days per decade.
- Lake frozen duration has decreased by 6.9 (±1.5) days per decade.

These results show that as our northern climate has warmed substantially in fall, winter and spring, Stile's Pond is frozen for 4 weeks less on average than forty years ago. (Note that the downward trend in frozen lake duration is larger than for the winter freeze period, when a frost is likely.)

Changes in spring phenology

As lakes are melting earlier and the last frost is coming earlier, spring is arriving sooner in Vermont. The leaf-out date of lilacs, which have been tracked in Vermont since 1965 as a measure of early spring, closely follow the ice-out date of Stiles Pond in most years (a few years are missing).[15] So the leaf-out of lilacs in early spring is also coming earlier by about 3 days per decade.



Summary of expected changes in the climate of Vermont

The observed changes in Vermont's climate over the past fifty years match those seen in New England. These changes are also consistent with the changes projected by global climate models through 2050. Winter temperatures are rising fastest, so the winter season is shrinking and becoming less severe. Spring is coming earlier and fall later, so the summer growing season is lengthening. As the climate warms, total precipitation in Vermont is expected to increase in all seasons except summer. The frequency of heavy precipitation events is likely to increase in all seasons, with the heaviest precipitation events occurring in the summer season. Stream flow is likely to increase.

Although we cannot predict in detail the changes in weather patterns resulting from climate change, we can summarize the seasonal changes we are likely to see in Vermont in the coming decades:

In winter:
- Later arrival of winter
- Warmer winters: upward shift of USDA climate zones
- More overwintering of pests
- Shortened ski, snowmobile, ice-fishing, and snowshoeing season
- Increased winter precipitation
- More wet snow and freezing rain
- Multiple melt events in the winter with possible flooding

In spring:
- Reduced productivity of sugar maples
- Earlier end to sugaring season
- Earlier spring melt and run-off; possibly larger stream flows
- Earlier arrival of spring
- Earlier bloom dates of many plant species
- Earlier last spring frost
- Earlier ice-out of lakes and ponds

In summer:
- Hotter summers
- Reduced productivity of cold-weather crops
- Reduced productivity of dairy cows
- Longer growing season
- More heavy rain events
- More frequent floods and associated flood damage
- Greater frequency of 1-2 month droughts
- Increased warm-weather pest species, such as mosquitoes, ticks, and algae
- Increased threats to cold-water fish and wildlife species
- Increased hazards to human health, including heat waves and the spread of disease
- Increased hazards to human safety, such as landslides, flooding, and violent storm events
- Increased threat to infrastructure, such as roads and bridges near streams and rivers
- Worsening air quality in some areas

In fall:
- Later first fall frost
- Warmer fall temperatures
- Later fall color
- Increased fall precipitation and stream flow

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Document available at http://www.anr.state.vt.us/anr/climatechange/Adaptation.html

Scientific Article Worksheet

Title:

Authors:

Journal:

Year:

The Basics:

1. What hypothesis or research question does the paper address?

2. What experiments were done to test the hypothesis or investigate the research question?

3. What are the major conclusions?

4. What evidence supports each of the conclusions?

The Critique:

1. Is the paper well written? How do you know?

2. Do the conclusions seem logical given the data presented? Why or why not?

3. Why are the conclusions important?

4. What were the best aspects of the research presented, and how could it be improved?

Additional Resources:

1. What are the basic concepts that you need to know to understand the science presented in your paper?

2. Identify a chapter/section in a textbook that outlines these basic concepts. Is reading this helpful to your understanding?

3. What other information or resources would help you better understand the paper?

Further Questions:

Write *at least* five comments or questions about the article to discuss with your mentor.

1.

2.

3.

4.

5.

From Branchaw, J.L., Pfund, C., and Rediske, R. (2010), *Entering Research: A Facilitator's Manual: Workshops for Students Beginning Research in Science*, W.H. Freeman & Company.

Below is a list of resources and emergency contact information that you should keep with you in case anything happens while you are in Vermont this summer.

In any emergency: Call 9-1-1
University of Vermont Police Services: 802.656.3473
Burlington Police Department: 802.658.2704

Groceries

- Price Chopper off Williston Road: 41 Hinesburg Rd, South Burlington, VT 05403
  - Take Bus 1 towards Airport or Walmart
- Market 32 Shelburne Road: 595 Shelburne Rd, Burlington, VT 05401
  - Take Bus 6
- Shaw's Shelburne Road: 570 Shelburne Rd, Burlington, VT 05401
  - Take Bus 6
- Hannaford University Mall: 217 Dorset St, South Burlington, VT 05403
  - Take Bus 1 towards UMall, Airport or Walmart (as long as it stops at the mall, where the store is)
- City Market: 82 S Winooski Ave, Burlington, VT 05401
  - Take Bus 1 into downtown Burlington
  - Walk
- Healthy Living: 222 Dorset St, South Burlington, VT 05403
  - Take Bus 1 towards UMall, Airport or Walmart (as long as it stops at the mall)
  - Get off at the mall and cross to Dorset St.
- Trader Joe's: 200 Dorset St, South Burlington, VT 05403
  - Take Bus 1 towards UMall, Airport or Walmart (as long as it stops at the mall)
  - Get off at the mall and cross to Dorset St.

Pharmacy

- Rite Aid Downtown Burlington: 158 Cherry St, Burlington, VT 05401
- CVS Downtown Burlington: 35 Church St, Burlington, VT 05401
- CVS South Burlington: 1 Dorset St, South Burlington, VT 05403

House goods

- (Bus 6) TJ Maxx: 595 Shelburne Rd, Burlington, VT 05402
- (Bus 6) HomeGoods: 595 Shelburne Rd, Burlington, VT 05402
- (Bus 1) Walmart: 863 Harvest Ln, Williston, VT 05495
- (Bus 1) Bed, Bath and Beyond: 115 Trader Ln, Williston, VT 05495
- (Bus 1) Christmas Tree Shops: 100 Cypress St, Williston, VT 05495
- (Bus 2) Big Lots Essex Junction: 70 Pearl St, Essex Junction, VT 05452

Hospitals/Emergency Rooms

- University of Vermont Medical Center: 111 Colchester Avenue, Main Campus, West Pavilion, Level 1, Burlington, VT 05401

As a reminder, if you are injured on the job, you are covered by Saint Michael's College workers' compensation and the first point of contact should be SMC Public Safety: (802) 654-2374. You should also promptly inform the CWDD office and your mentor. Ask your mentor for their contact information and keep it in your cell phone directory in case of emergency. You can search the UVM Directory (https://www.uvm.edu/**directory**) for their office contact.