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Climate change as a driver of change in the Great Lakes St. Lawrence River Basin

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ABSTRACT

Climate change in the Great Lakes–St. Lawrence River basin is affecting the socio-ecological system, including the residents who depend on the basin for drinking water, energy, and commerce. Over the past 50 years, air temperatures increased and heavier precipitation events became more frequent, and those trends are projected to continue. Climate change is expected to impact energy supply and demand, governance, and changes in demographics and societal values. More extreme events may exacerbate transport of biological and chemical contaminants and invasive species, and impact lake levels and water quality. We describe historical trends of the regional climate, examine global and regional climate model projections, and explore impacts of climate change with other key drivers of change defined by the Great Lakes Futures Project. Because reducing climate-related damages and economic losses is crucial; we offer three plausible future scenarios of mitigation and adaptation plans. Recommendations to reach a future Utopian scenario require immediate actions, such as improvements in energy conservation, efficiency and generation, curbs to emissions, preventative infrastructure upgrades, and investments in maintaining and monitoring a healthy ecosystem.

Introduction

The Great Lakes-St. Lawrence River basin forms the largest body of fresh water in the world. Water resources are used for drinking, agriculture, hydro-electricity production, shipping, recreation, and more. The basin moderates the region's temperatures (Gula and Peltier, 2012) providing a unique climate; however, climate-related ecological and societal changes can have far-reaching economic effects within the region and in the global economy.

Climate change due to increasing concentrations of greenhouse gases (GHGs) is an important issue and is explored as a driver of change in this paper. In its Fifth Assessment report, Working Group I of the Intergovernmental Panel on Climate Change (IPCC) has raised their consensus to it is “highly likely that human influence has been the dominant cause of the observed warming since the mid-20th century” (IPCC, 2013). It also stated “Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia. The atmosphere and ocean have warmed, the amounts of snow and ice have diminished… and the concentrations of greenhouse gases have increased” (IPCC, 2013). Global changes in climate are projected to continue and impact hydrology (Bates et al., 2008).

As part of the Great Lakes Futures Project (GLFP), two periods – historical changes in climate since 1963 and climate projections to 2063 – were chosen to provide context for exploring the implications of a changing climate on ecosystems and society within the Great Lakes-St. Lawrence River basin. This article also explores the interactions of climate change with the seven other priority driving forces (energy, economics, demographics and societal values, geopolitics and governance, aquatic invasive species, biological and chemical contaminants, and water quantity) established by the GLFP leadership team (Laurent et al., in this issue). Responding to climate change includes focusing on both mitigation (reducing or sequestering GHG emissions) and adaptation (reducing climate change impacts) and will require an

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[1] The Great Lakes Futures Project brought together graduate students and expert mentors from universities and institutions in Canada and the United States. Each paper required collaboration between a number of authors with many of them sharing co-leadership that we denote using a 1.

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approach that understands and addresses the interdependent nature of the driving forces and the impacts of climate change. To aid in future policy decisions, we highlight current regional trends in climate and explore three scenarios – status-quo, dystopian, and utopian futures – for the region based on the possible mitigation and adaptation strategies put in place. Recommended mitigation strategies include improving energy conservation, reducing carbon emissions, increasing sequestration of GHGs, as well as reducing energy and water demands, while adaptation strategies include improving infrastructure resilience, incorporating wetland flood control, and facilitating regional economic cooperation.

A look-back: climate change in the past

The historical changes in temperature and precipitation, both globally and within the Great Lakes-St. Lawrence River basin, are summarized in the following section, as well as the resulting impacts from these changes, specifically on the basin's ice cover, lake levels, sediment delivery, and pollution.

Air temperature

Average air temperature within the basin region increased by 0.7 °C (1.26 °F) from 1895 to 1999 (Hall et al., 2007; IJC, 2003). Minimum (i.e., nighttime) temperatures warmed more rapidly than maximum, and the range between daily minimum and maximum temperature has decreased (Bonsal et al., 2001; Zhang et al., 2000). The number of days with extreme low temperatures decreased while the number of days with extreme high temperature increased (Bonsal et al., 2001; Brown et al., 2010; Easterling et al., 2000). Additionally, the number of frost-free days increased and the potential growing season lengthened (Brown et al., 2010).

Air temperature increase has not been uniform across the Great Lakes region or the seasons (Kunkel et al., 2009). The northern portion of the basin has seen the largest increases of temperature in winter and early spring between 1900 and 1998 (Andresen et al., 2012; Zhang et al., 2000). However, in some areas of the region (e.g., Michigan), mean summer temperatures decreased with time, likely due to intensification of agriculture, where increased evapotranspiration suppresses daytime maximum temperatures (Andresen et al., 2012; Pan et al., 2004).

Precipitation

Total precipitation has increased and its distribution across seasons has changed. Total annual precipitation in the Great Lakes region has increased by 10.7 cm (~13%) between 1955 and 2004, with the majority of the change occurring during summer and winter (Andresen et al., 2012; Hodgkins et al., 2007). Specifically, the number of heavy events increased in summer, and the number of light events decreased in winter (Stone et al., 2000). The ratio of snow to total precipitation decreased (Karl et al., 2009; Zhang et al., 2000) which is consistent with warmer air temperature in late winter and early spring (Davis et al., 1999; Groisman and Easterling, 1994; Zhang et al., 2000).

Extreme precipitation events have become more frequent (Karl et al., 2009). For example, the annual number of days with precipitation exceeding 10.2 cm increased since 1910 over the US; the Great Lakes region, along with the Southwest, Midwest, and Southern Mississippi valley represent areas with the largest increases (Easterling et al., 2000). In the northeast and western Great Lakes regions, the precipitation amount with a 100-year recurrence interval increased 4 to 9% per decade from 1950 to 2007 (DeGaetano, 2009). The trend towards more intense precipitation in late winter and spring has contributed to an overall increased risk of flooding, although in some urban areas the increased flood risk was found to be more closely associated with land cover changes (e.g. more impervious surfaces) than climatological factors (Mao and Cherkauer, 2009). While the total annual precipitation increased, the number of dry periods also increased (Peterson and Baringer, 2009). In Canada, more areas were affected by extreme dry or wet conditions from the 1950–1998 period as compared to the 1900–1949 period (Zhang et al., 2000).

Impacts of climate change in the past and present

The basins play a key role in the climate of the region through exchange of heat and moisture with the atmosphere (Gula and Peltier, 2012). Changes in temperature and precipitation have affected and will continue to impact the physical, chemical, and biological processes of the basin. Several of these impacts are outlined below, and examined both in the historical and current context.

Ice cover

Winter ice duration and coverage have decreased over the period 1963–2001 (Austin and Colman, 2007), with potential impacts on winter evaporation and lake levels (IUGLS, 2009). This change is a result of warmer winter air temperatures, warmer lake water temperatures, as well as a reduced ratio of snow to total precipitation (IJC, 2003; Karl et al., 2009; Zhang et al., 2000). The lake ice season has shortened by one day per decade over the past 150 years, although the rate increased to 5.3 days per decade between 1975 and 2004 (Jensen et al., 2007). The five-year average of maximum ice cover has decreased steadily on the Great Lakes with Lake Superior showing the largest decrease (IUGLS, 2009). The average ice extent has decreased by more than 50% over the last two decades (Wang et al., 2012). While decreasing ice extent has been observed over the long-term, January 2014 was the 10th coldest in the Great Lakes region. Ice coverage reached 75% of the total Great Lakes surface area, the highest recorded coverage since 1996 (Ballinger et al., 2014; Kennedy, 2014). Changes in the Arctic Oscillation, La Nina, and increased melting of arctic ice may have contributed to anomalous cooling over the Great Lakes region influencing ice cover extent (Ballinger et al., 2014; Wang et al., 2010). Ice cover changes influence other physical properties of the basin. Desai et al. (2009) found that reduced ice cover on Lake Superior destabilizes the atmospheric surface layer, decreasing wind speeds by 5% per decade since 1985. Additionally, changes in ice cover extent and duration have influenced winter evaporation with potential impacts on basin water levels (IUGLS, 2009).

Lake levels

Fluctuations of the basin water levels are influenced by changes in precipitation, evaporation, and evapotranspiration. For example, water levels typically progress from minima in late winter/early spring to maxima in the summer/early fall. An earlier onset of the rise in water levels in spring and a change in the amplitude of water levels have been documented (Argyilan and Forman, 2003; Lenters, 2004). This may be related to winter warming, changes in the form of the precipitation and earlier spring melt and runoff. Lake levels within the basin also exhibit inter-annual and inter-decadal fluctuations; however, the range for the period 1918–2012 has been within 2.0 m (varying by lake) (DFO, 2013a; Wilcox et al., 2007). The record high water levels since 1918 for the Great Lakes occurred in the mid-1980s with other high levels in the mid-1990s. Warm air temperatures and severe drought in 1988 and 1998 contributed to a rapid drop in water levels from their relatively high levels (Assel et al., 2004; Hall et al., 2007; IUGLS, 2009). Lakes Superior, Michigan, and Huron have been in a period of low water levels from 1998 to 2013, compared to the long-term mean. Record low monthly mean levels were set in 2007 (August and September) for Lake Superior (DFO, 2007) while Lakes Michigan and Huron attained record low levels in December 2012 and January 2013 (DFO, 2013b; EC, 2013). Climate change, vertical land movement (i.e. adjustment to retreat of glaciers), and human modification of the physical system

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(e.g., dredging in the connecting channels) have been identified as potential contributing factors (IUGLS, 2012).

Lamon and Stow (2010) and Sellinger et al. (2008) showed a downward trend in water levels, particularly since the end of the 20th century, potentially associated with changes in evaporation and net precipitation (overlake precipitation minus evaporation) – particularly on Lakes Michigan and Huron. The International Upper Great Lakes Study (2012) identified shifts in the hydro-climatic regime for the period 1948–2008. Evaporation from the Great Lakes-St. Lawrence River basin has increased since 1948 but a corresponding increase in overlake precipitation has offset this loss in most of the Great Lakes. However, while precipitation in the Lake Superior basin has remained relatively constant, evaporation increased and as a result water supplies have been declining. It is difficult to attribute observed changes in water levels, evaporation, and precipitation to human-caused climate change because most observed trends are within the range of natural variability (Hayhoe et al., 2010).

Chemical and biological pollution and sediment delivery

Weather and climate play significant roles in the transport and fate of chemicals, nutrients, pathogens, and sediment. Cyanobacteria, which can form harmful algal blooms, favor warmer temperatures and therefore are advantaged by a warming climate (Michalak et al., 2013; Paerl and Huisman, 2008). Lake Erie's largest harmful algal bloom took place in 2011 and was a result of long-term agricultural practices, increased precipitation, weak lake circulation and increased residence times (Michalak et al., 2013). These factors are expected to occur more frequently in a warming climate.

Combined sewer and storm water systems allow contaminants to flow directly into lakes and streams when heavy precipitation events overburden the system. While a portion of beach closures are from unknown sources, overflows from combined storm water and sewage systems due to heavy precipitation events have contributed to many beach advisories around the basin (McLellan et al., 2007).

Sedimentation and contaminated bottom sediments are of concern in the basin, although difficult to correlate with climate change. Sedimentation affects commercial navigation by reducing the allowed draft in channels and ports; approximately $20M per year is spent on dredging (Ouyang et al., 2005). Soil erosion data from the US National Resource Inventory show that agricultural land contributes 65 to 77% of the eroded soil in the basin, and that rates of erosion loss from agricultural lands have decreased in the US portion of the basin over the past 20 years due primarily to increased erosion control programs (GLC, 2008). Erosion of the bluffs and coastal shorelines of the basin is influenced by external controls such as precipitation, storm intensity and frequency, lake levels, and wave power. Erosion and bluff recession rates vary both spatially and temporally and lake levels appear to have the strongest correlation (Brown et al., 2005).

Climate impacts on other driving forces

A changing climate, with fluctuations in temperature, precipitation, ice cover and lake levels will influence the seven other priority drivers of change within the basin. Some key impacts are summarized in Table 1.

Impact of other driving forces on climate change

The primary driving forces that contribute to the severity of climate change are economic, societal, political and government actions that influence GHG emissions and the resulting concentrations in the atmosphere. These driving forces' impact on climate change is discussed in more detail in the following section, and all priority drivers are listed in Table 2.

Governance and geopolitics

Governance and geopolitics are keys to addressing climate change through policy creation at the global level. The United Nations Framework Convention on Climate Change (UNFCCC), and the associated Kyoto Protocol are the most significant global policy initiatives. The UNFCCC has 195 signatories, including the US and Canada (UNFCCC, 2012). However, the US did not sign on to the Kyoto Protocol setting out GHG reduction targets and Canada withdrew in 2011 (UNFCCC, 2012). Both countries have submitted non-binding emissions reduction pledges as part of the UNFCCC's 2009 Copenhagen Accord which aims to limit the global temperature increase to 2 °C above pre-industrial levels and to fund climate adaptation in developing countries (UNFCCC, 2009). However, both countries are still exceeding their emissions pledges.

The US and Canadian federal government positions on emission reductions can influence actions of other countries as well as impact decisions at home. Government climate policies can foster technical innovation and corporate environmental strategy (Selin and VanDeveer, 2010). Legislation as a tool can have a range of outcomes. For example, legislation did not markedly improve emission control practices for supply chain management (Tsireme et al., 2012), but lack of US GHG emissions standards contributed to the discontinuation of a carbon capture and storage initiative for coal-based power generation (AEP, 2011).

Providing funding for climate change science and research on mitigation and vulnerability, impacts, and adaptation is a way to understand the implications of climate change and drive innovative mitigation and adaptation strategies. The US government increased research funding in 2010 to just over $2B to the inter-agency US Global Change Research Program (USDS, 2010).

Fundamental, positive change often starts with small-scale modifications, and progress is being made on many initiatives for mitigation and adaptation at the regional and local levels within the basin. The Province of Ontario enacted the Green Energy and Green Economy Act of 2009, which plans to diversify energy supply with one-third renewables (OMoE, 2012). This initiative includes Ontario's Feed-In Tariff Program, which is North America's first comprehensive guaranteed pricing structure for renewable energy (OPA, 2010). It has attracted the single largest development of renewable energy generation in the province's history and is anticipated to provide 20,000 more jobs in the renewable energy sector (OMoE, 2012). The state of New York has a Climate Smart Communities program where individual communities are pledging to reduce emissions and receive expertise and funding to prepare for a variable climate future through infrastructure upgrades (NYSDEC, 2013). At the city level, Chicago's Climate Action Plan proposes to reduce emissions by 80% by the year 2050 (Hayhoe et al., 2010). Chicago also implemented a "Green Corps" program, which takes hard-to-employ former inmates and trains them in environmentally positive jobs such as improving home heating efficiency (Paehlke, 2010). The US Conference of Mayors (representing ~89 million citizens) presented a Climate Protection Agreement, which closely follows the Kyoto Protocol and has been signed by 277 mayors in the Great Lakes region (USCM, 2008). The Great Lakes and St. Lawrence Cities Initiative showcases cities within the basin transforming towards sustainability (GLSLCI, 2013). States, provinces, and municipalities are demonstrating leadership on climate change issues without federal leadership as they acknowledge that it will impact their bottom lines.

Changing demographics and societal values

Societal values, technological innovation, economic development, and population trends influence GHG emissions as well as the severity of impacts and the potential to adapt (IPCC, 2007). Particularly on the Canadian side, the population has been increasing and more people are moving to urban and suburban areas from the countryside. The US portion of the basin is experiencing an out-migration of highly educated young people leaving behind an older, more vulnerable population with

Table 1
Selected list of potential impacts of climate change on other driving forces in the basin.

Divisions of climate change	Water quantity	Governance and geopolitics	Energy	Economy	Biological and chemical contaminants	Aquatic invasive species	Demographics and societal values
Climate change overall	Changes in precipitation and evaporation affect flow to the lakes, lake levels and the seasonal cycle.	Impacts from extreme conditions or events may prompt policy and regulations to adapt coastal and urban infrastructure and plans for floods, storms, drought.	Energy production and usage patterns may be altered; affecting supply capacity and reliability.	Agriculture, shipping, and tourism are all susceptible to variability in climate.	Weather and climate play a significant role in the transport and fate of chemicals, nutrients, pathogens, and sediment.	Changes in climate will influence the range and abundance of invasive species.	Changes in climate locally and globally will influence migration, population increase and demographics.
Precipitation/temperature	Warmer air temperatures and changes in amount, type and timing of precipitation affect hydrologic patterns, higher winter flows, lower summer flows, higher evaporation, and changes in spring peak flow.	Experiencing changes in climate and increased occurrences of events having damaging or harmful effects on people or economic activity may increase concern and motivate support for mitigation and adaptation planning.	Warmer summer temperatures increase peak load energy demand due to greater cooling requirements.[1] Warmer winters reduce energy use for heating.	Tourism activities are impacted by higher temperatures, changing optimal recreation seasons. Agricultural growing season may be longer, but precipitation changes (drought, timing) could reduce productivity of non-irrigated crops.[6] Higher summer temperatures can benefit some crops, but increased heat stress for livestock can reduce milk production and animal birth rates.[7]	More intense precipitation events can enhance erosion and increase entrainment of contaminants from agricultural and urban areas introducing more pollutants into receiving waters. Combined sanitary and stormwater sewers are especially vulnerable to heavy precipitation events and overflows of these systems can lead to chemical and biological contamination such as *E. coli.* [3] Warmer water temperatures can affect the rate of chemical reactions.	Warming lake temperatures may increase the thermal habitat for certain invasive species (e.g. zebra mussels).	The growing elderly population are more vulnerable to extreme events (e.g. floods) and heat related and respiratory illness.[8,9]
Lake levels/ice cover	Lake levels can drop dramatically following drought years. The thickness, duration and area of ice coverage declines due to warmer winter air and water temperatures, as well as a reduced snowfall.	Potential hydropower generation may require more extensive conservation programs and development of alternative sources of energy. Demands from drier regions and fluctuating water levels may challenge cooperative governance structures such as the Great Lakes–St. Lawrence River Basin Sustainable Water Resources Agreement.[10]	Fluctuations in flow affect hydropower generation.	With low lake levels ships have to reduce their cargo loads, but less ice would mean longer shipping season.[5]	Lower stream flows can lead to higher concentrations of chemicals and pollutants.	Fluctuating lake levels may promote the expansion of invasive species (e.g. *Phragmites australis*).[2]	Warmer temperatures will change recreational seasons and amenities. [4] Shorter winter recreation season will have an impact on cultural identity related to winter sports. Longer ice-free periods might increase summer recreation usage such as boating and fishing.

[1](Gotham et al., 2012), [2](Wilcox et al., 2007), [3](Patz et al., 2008), [4](Scott et al., 2002), [5](Millerd, 2005, 2011), [6](Kling et al., 2003), [7](Wolfe et al., 2008), [8](Sousounis and Bisanz, 2000), [9](Winkler et al., 2012), [10](Hall et al., 2007).

Table 2
Selected list of potential impacts of climate change on other driving forces in the basin.

Drivers	Changes in greenhouse gases	Changes in sequestration capacity
Water quantity	No significant direct link	No significant direct link
Governance and geopolitics	Policies and regulations (e.g. UNFCCC's Kyoto Protocol, Ontario's Green Energy Act, and statewide Renewable Portfolio Standards), and funding for climate mitigation research play a key role in supporting reduction of greenhouse gas emissions from local to global scales.	Policies, regulations and funding for climate change research can play a key role in devising and implementing methods to increase sequestration capacity. The Great Lakes Restoration Initiative provides funding to restore wetlands and other habitats that contribute to carbon storage.
Economy	Energy use associated with utilities, transportation, industry and agriculture within the basin contribute the most to GHG emissions. The continued transition from a manufacturing economy to a service-based economy may reduce industrial emissions and energy use. Commercial shipping on the lakes can reduce emissions per kg compared to trucking, but the fuels used emit more sulfur and particulates into the atmosphere. Agriculture accounted for 8% of Canada's emissions in 2010, with 60% coming from confined animal production.	Large scale logging without replanting can lead to significant changes in the forests' capacity to store carbon. Agricultural soils and crops have the ability to store and use carbon temporarily. "Conservation" and "No-Till" soil management, implemented in US and Canada, help to improve carbon storage in soil and maintain nutrients (and reduce water quality impairment).
Energy	GHG emissions from various energy forms (coal, oil, nuclear, biomass, wind, and natural gas) contribute to the overall emissions of the basin. Canadian coal-based energy production has been declining over the past 12 years, replaced by renewables. US coal-based energy production is also down slightly, but mostly replaced by natural gas. Both countries are likely to increase natural gas production that has been shown to have lower CO_2 but higher methane emissions.	Research on direct carbon storage for power plants and other large-scale emitters is ongoing and could have dramatic impacts on offsets; more research is needed on scalability and affordability.
Biological and chemical contaminants	Agricultural fertilizers are the largest source of nitrous oxide to the atmosphere (the second most common greenhouse gas).	No significant direct link
Aquatic invasive species	No significant direct link	No significant direct link
Demographic and societal values	The tendency towards less-dense suburban sprawl development promotes reliance on personal automobile use and GHG emissions. Strong rebuttal of findings from climate change science by skeptics in the US and Canada creates uncertainty in the population.	Continued development of greenspaces around cities reduces carbon sequestration. Engineered wetlands and park development in cities can sequester carbon.

less adaptive capacity and influencing the economic future of the basin (Austin and Affolter-Caine, 2006). The Great Lakes region faces many challenges as it transitions from a manufacturing hub to a more sustainable economy (Austin and Affolter-Caine, 2006). In addition, many US cities within the basin have lost population from their urban cores to suburban sprawl, with Detroit being a prime example. Suburban development promotes use of personal automobiles over public transit, increasing the region's GHG emissions (Paehlke, 2010).

There has been a greater reluctance in Canada and the US than in European and developing countries to address climate change (Diethelm and McKee, 2009). The media's requirement to present both sides of the climate change "debate" (i.e., giving equal weight to a dissenting opinion without an equally strong scientific basis to refrain from displaying bias) creates doubt among an unusually large percentage of the population (Painter and Ashe, 2012). The perception of controversy within the scientific community influences the decisions of millions of consumers (Ding et al., 2011) who choose not to invest in energy efficient vehicles or appliances or vote for emissions related policy such as light rail transportation and smog reduction, and continue to purchase real estate in areas at risk of water shortages and flooding.

The economy and energy

Energy use by utilities, transportation, and industry contributes the most GHG emissions (Kling et al., 2003). Eighty one percent of Canada's 2010 emissions (562 Mt CO_2 equivalents) and 79% of the US's 2007 emissions (5735 Mt CO_2 equivalents) came from energy, transport, and waste management (EC, 2010). Coal-based electricity generation peaked in 2000 in Canada and declined by 70% by employing

Table 3
SRES emissions families summary. IPCC Special Report Emissions Scenarios are widely used for modeling and assessing climate response to GHG emissions. Each scenario family makes assumptions about the driving forces in the first column and each is further broken down into 40 possible future scenarios of anthropogenic GHG emissions. Reproduced from: IPCC (2001).

Driving forces	A1FI	A2	B1
Population growth	Low	Low	Low
GDP growth	Very high	Very high	High
Energy use	Very high	High	Low
Land use change	Low-medium	Low	High
Oil/gas resource availability	High	Medium	Low
Technological change	Rapid	Rapid	Medium
Change favoring	Coal, oil and gas	Non-fossil fuel	Efficiency and dematerialization

more renewable energy (OMoE, 2012). Coal-fired energy in the US declined from 51.7% of total generation in 2000 to 48% in 2008, primarily due to generation plants switching to natural gas (USDS, 2010).

Agriculture accounted for 8% of Canada's total GHG emissions in 2010. Agriculture was also the most significant contributor of methane, primarily from confined animal production (EC, 2010). The manufacture, use, and breakdown of nitrate-based fertilizers are the largest source of nitrous oxide, the second most common GHG, with 300 times the warming impact of CO_2 (USEPA, 2012). Conservation and no-till soil management that improves the soil's capacity to store carbon and maintain nutrients are now implemented on more than 40% of the agricultural acreage in the US (Eagle and Olander, 2012) and over 70% in Canada (SC, 2007). Historically, clear-cutting forests for agriculture has removed carbon storage, replacing it with agricultural activities that export GHG. The US has launched 13 projects related to tree planting in the region since 2010 (GLRI, 2010) and Ontario's Private Land

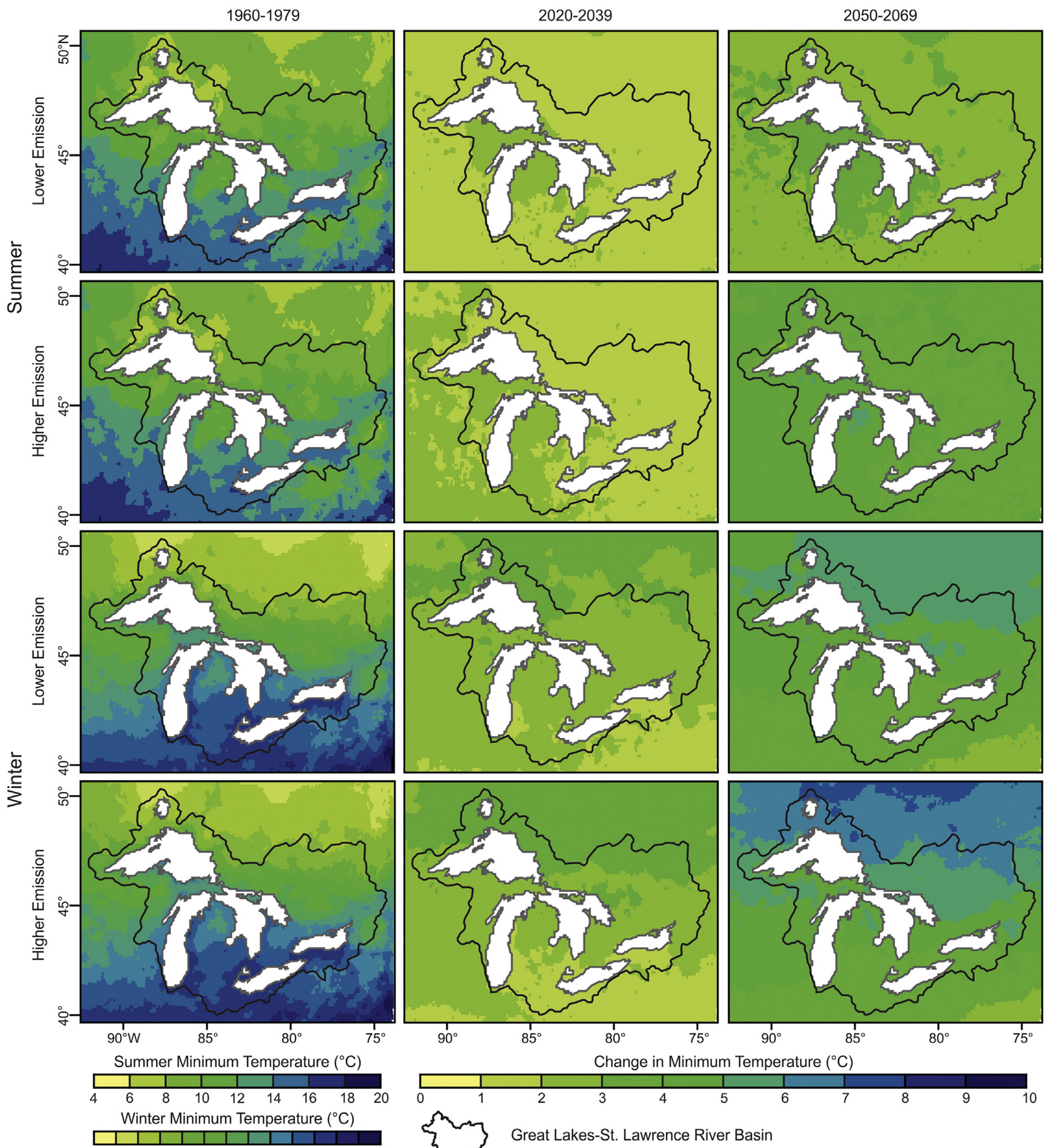

Fig. 1. Average daily minimum temperature values. The first column shows the absolute value for the time period 1960–1979 in ^{0}C while the second column shows the projected relative temperature increase by 2020–2039 (relative to 1960–1979), and the third column shows the projected relative temperature increase by 2050–2069 (relative to 1960–1979), for both a higher emissions scenario (A1FI) and a lower emissions scenario (B1). The maps were generated by downscaling GCM outputs to land-based observations at a one-eighth degree resolution according to Stoner et al. (2013) and taking an average of the four GCMs used (CCSM3, GFDL CM2.0, HadCM3 and PCM). Reproduced from the US Geological Survey (USGS) High-Resolution National Climate Change Dataset (Hayhoe, 2013).

Afforestation Program is encouraging farmers to reforest land that is marginal agricultural land (Bird and Boysen, 2007).

Emissions from the world's shipping fleet were estimated to be 3.3% of anthropogenic emissions in 2007 (IMO, 2009). While there are no specific measurements of emissions from the basin's inland navigation, there are efforts to “green” the fleet (Lloyd's Register, 2012). The North American Emission Control Area policy, established under international maritime law, includes the waters of the Great Lakes and the St. Lawrence Seaway, and went into effect in August 2012. Among other measures, it requires that fuel sulfur content cannot exceed 1%, significantly reducing ship emissions (Lloyd's Register, 2012). While the majority of trade between Canada and the US occurs by truck and rail, marine shipping is the most fuel efficient way of transporting goods to global markets.

A look forward: climate over the next 50 years and future impacts

This article surveys the most recent peer-reviewed literature to provide a summary of the future climate (temperature, precipitation) and selected physical effects. Climate projections are based on both global climate model (GCM) and regional climate model (RCM) simulations using emissions scenarios from the IPCC Special Report on Emissions Scenarios (SRES) (Table 3) (IPCC, 2000). Three key emissions scenarios are explored: A2 (high population growth, economic development regionally oriented), A1FI (business as usual, high fossil fuel use and emissions, economic focus on global integration), and B1 (plateauing population growth, global emphasis on environmental cooperation, improved technology). This article uses an ensemble of outputs from GCMs (e.g. 21 GCMs in IPCC AR4) and RCMs from the North American Regional Climate Change Assessment Program to explore a range of climate futures for the basin since no single combination of climate model and emission scenario can accurately project future outcomes. For the IPCC Fifth Assessment report, four new GHG emission and concentration scenarios were developed called Representative Concentration Pathways and used in climate projections (IPCC, 2013). Future regional impact assessments in the Great Lakes-St. Lawrence River basin will use climate modeling results based on Representative Concentration Pathways to develop climate change scenarios.

Temperature

The mean annual temperature across the basin is expected to increase 2 to 3 °C by mid-century under A1FI and B1 scenarios respectively (Hayhoe et al., 2010; Winkler et al., 2012). Seasonal changes may be greater (Kling et al., 2003) and are obscured by the use of annual averages (Hayhoe et al., 2010). Summer and winter temperatures may increase by 7 °C to 8 °C respectively (Winkler et al., 2012). Generally winters will be warmer, and summers will be moderately warmer, with greater variability of temperatures for spring and fall. Fig. 1 depicts seasonal average daily minimum temperature for the time periods 1960–1979 (absolute value), 2020–2039 (change relative to 1960–1979), and 2050–2069 (change relative to 1960–1979), for both the highest emissions scenario (A1FI) and a lower emissions scenario (B1). There is significant variability across the region, particularly by 2063, and it is during winter where the warming trend is most apparent. Annual average warming will likely be 1 °C to 3 °C lower directly over the lakes than the increases over the northwestern and southwestern areas of the basin. While winter warming is expected to be the greatest at higher latitudes, summer warming will be greater in the southern and western parts of the basin (Kling et al., 2003).

Trumpickas et al. (2009) found that lake water temperature changes were closely correlated to seasonal air temperature changes and projected water temperature increases from 1.5 °C to 3–4 °C across the basin. The implications were an earlier breakup and an earlier onset of summer lake stratification shortening the overturn period, which circulates critical dissolved oxygen to deeper waters for fish and zooplankton species (Jensen et al., 2007). The period of summer lake stratification could be lengthened by 42 days (Lake Erie under low emissions influence) to 90 days (Lake Superior under higher emissions influence) (Trumpickas et al., 2009), leading to low dissolved oxygen levels in bottom waters and potential summer die-off events.

The trend of the frequency and duration of extreme temperatures is likely to continue into the future. The frequency of days below freezing is anticipated to decrease; for example, simulations from RCMs project 22 fewer days below freezing by mid-century (Winkler et al., 2012). The occurrence of days above 35 °C is projected to increase by 5 to 25 days by mid-century (Winkler et al., 2012). These temperature extremes vary regionally with greater increases within the southern portion of the basin.

Precipitation

Projections of precipitation changes over the basin have a higher degree of uncertainty than temperature. Annual total precipitation is projected to slightly increase over the first half of the 21st century, with a change of −2 to +10% (Winkler et al., 2012). However, by the end of the century the projected annual total precipitation shows an increase of up to 20% across the region (Hayhoe et al., 2010; Vavrus and Van Dorn, 2010; Winkler et al., 2012).

Similar to temperature, changes in precipitation differ seasonally and regionally. By 2063, the projections from a range of models show consistent increases in precipitation (November to March) across the region, while projections of summer precipitation show increases and decreases (Winkler et al., 2012). For example, precipitation projections for Wisconsin and Michigan do not appear to change significantly in summer, whereas in Illinois and Indiana precipitation is projected to decrease by up to 24% (Cherkauer and Sinha, 2010). Fig. 2 depicts seasonal cumulative precipitation for 1960–1979 (absolute value), 2020–2039 (percent change from 1960 to 1979), and 2050–2069 (percent change from 1960 to 1979), for both the high emissions scenario (A1FI) and a lower emissions scenario (B1). It also demonstrates the precipitation variability across the basin, particularly from north to south, but also the projected shift in many areas of more summer precipitation and less winter precipitation by 2050–2069.

With a warming climate, more winter precipitation is likely to fall in the form of rain rather than snow. Gula and Peltier (2012) project that by 2050–2060 compared to 1979–2001, a greater decrease in snowfall, up to 20% decrease, in the earlier months of winter (September to December) will occur compared to 10% decrease from January to April. This will also vary spatially with a greater decrease occurring in the southern portion of the Great Lakes basin. While the overall proportion of precipitation, as snowfall is likely to decrease, the snowbelt region located downwind from the Great Lakes basin might have greater snowfall. Lake-effect snow is anticipated to increase with warming through mid-century, as warmer surface waters and a decrease in ice cover release more heat and moisture flux to the atmosphere (Gula and Peltier, 2012).

Warmer temperatures and more evaporation lead to an increase in atmospheric moisture contributing to more intense precipitation (Winkler et al., 2012). The extent of change in increased intensity of precipitation events is highly variable depending on the GHG emissions scenario (Winkler et al., 2012). Most models project increases in the frequency and intensity of extreme precipitation events ranging from 20 to 30% for B1 and A2 emissions scenarios respectively (Mackey, 2012). Higher emissions scenarios generate a greater percentage of more intense precipitation events. For example, precipitation events greater than 4 cm per day in Chicago are likely to increase from 25% under low GHG emissions scenarios to over 60% in high emission scenarios (Vavrus and Van Dorn, 2010).

Ice cover

The current overall trend of reduction in lake ice cover is projected to continue within each of the Great Lakes with climate warming,

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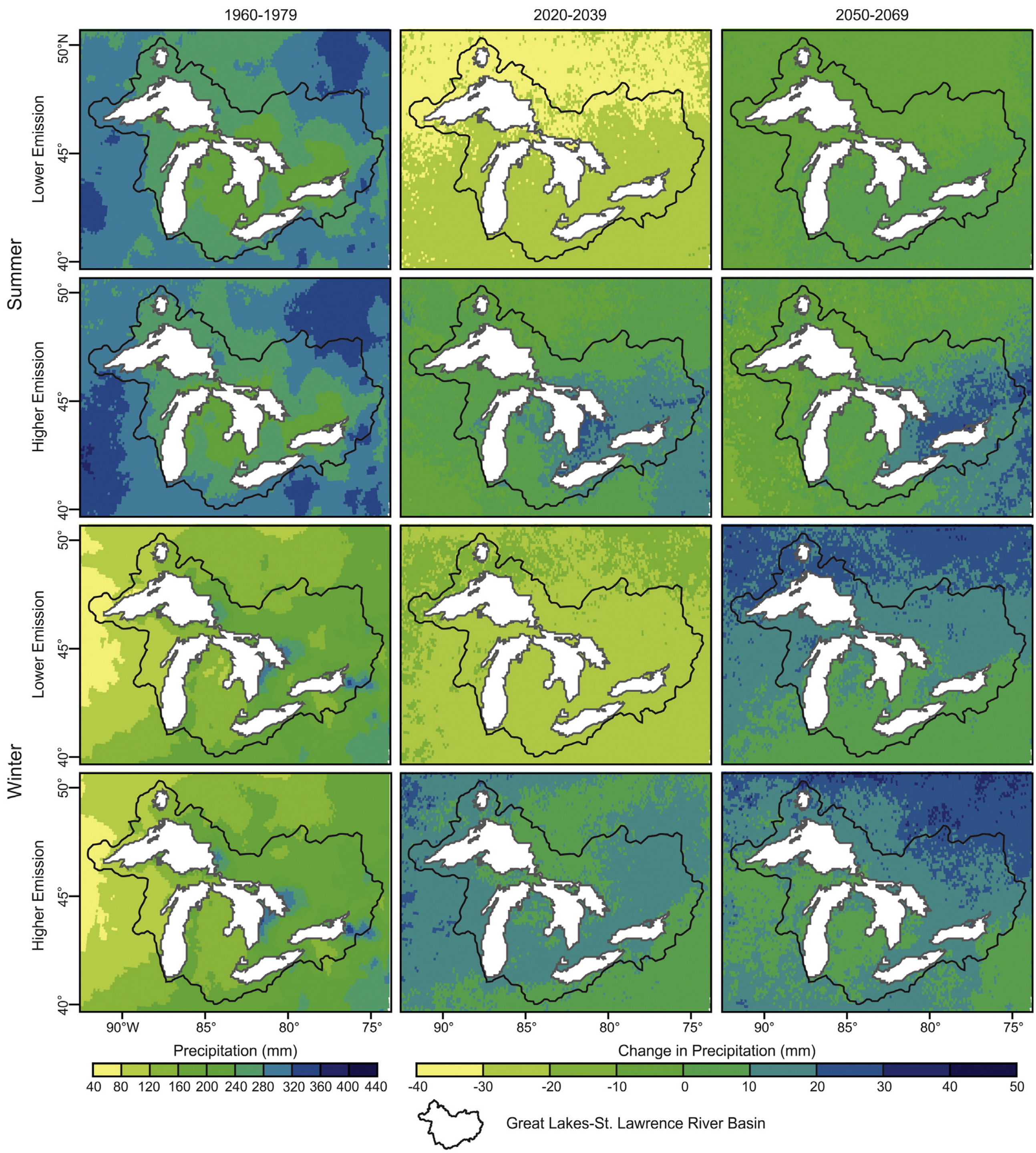

Fig. 2. Cumulative precipitation. The first column shows the absolute value for the time period 1960–1979 in mm while the second column shows the projected relative percent change in precipitation by 2020–2039 (relative to 1960–1979), and the third column shows the projected relative percent change in precipitation by 2050–2069 (relative to 1960–1979), for both a higher emissions scenario (A1FI) and a lower emissions scenario (B1). The maps were generated by downscaling GCM outputs to land-based observations at a one-eighth degree resolution according to Stoner et al. (2013) and taking an average of the four GCMs used (CCSM3, GFDL CM2.0, HadCM3 and PCM). Reproduced from the USGS High-Resolution National Climate Change Dataset (Hayhoe, 2013).

despite interdecadal variability providing ice cover in some years. The southern lakes are projected to have more pronounced changes in ice breakup (Jensen et al., 2007). Lake Michigan could be ice-free as early as 2020, and annual average ice cover across all the lakes could fall to near zero by 2050 (Hayhoe et al., 2010). Ice formation on the Great Lakes themselves is a major control of the climate of the region.

Lake levels

A range of future lake levels is projected for the Great Lakes basin. While the majority of hydrologic simulations across all emissions scenarios indicate water level declines, higher water levels are also a possibility (Angel and Kunkel, 2010; IUGLS, 2012). For example, future lake level changes for the 2050–2064 period on Lakes Michigan and Huron range from a decline of around 1.5 m to an increase of more than 1 m (Angel and Kunkel, 2010). Modeling future lake level changes is constrained by the high degree of uncertainty in estimating lake evaporation and watershed evapotranspiration. Previous climate change assessments may have overestimated increases in evaporation and associated decreases in lake levels (IUGLS, 2012). A recent climate change assessment used an energy-balance approach, coupling the hydrologic cycle with land, air and water (Lofgren and Gronewold, 2012). These preliminary projections showed similar or slightly increased lake levels due to an increased frequency of precipitation events for the lower Great Lakes. Nevertheless, the IUGLS (2012) indicated that while future lower water levels are likely, the possibility of higher levels must also be incorporated in water management and planning.

Water and sediment delivery

Increased occurrences of both floods and droughts are expected by 2063 and will influence runoff and sediment delivery (Hayhoe et al., 2010). Average annual total runoff is projected to increase by approximately 7 to 9% over the Great Lakes basin for A1, B1 and A1B emissions scenarios (Cherkauer and Sinha, 2010). Areas impacted by lake-effect precipitation will experience larger increases in mid-winter melt and spring melt runoff relative to the rest of the Great Lakes basin by the end of the century (Cherkauer and Sinha, 2010). Summer and fall runoff is more inconsistent and is dependent on emissions scenario. Cherkauer and Sinha (2010) projected that on an annual average basis, regional precipitation in winter and spring would be sufficient to erase summer water deficits, but noted that it would leave the region susceptible to drought conditions into the spring wet season.

Land use change can also influence runoff in a basin. In the Midwest US, many natural forest and grassland ecosystems became agricultural and urban landscapes (Lofgren and Gronewold, 2012). Increased impervious surfaces associated with urban development and exposed agricultural soils tend to decrease the amount of rainfall that percolates and is absorbed by soil and vegetation. Changes in agricultural practices (e.g., a shift to irrigation-dependent agriculture due to reduced summer precipitation), might influence the amount of runoff as well (Hall et al., 2007). Irrigation is a consumptive water use, and most water withdrawn does not return to the basin, thus increased irrigation use will reduce recharge to groundwater aquifers (Hall et al., 2007).

Sediment delivery to the Great Lakes basin includes sediment loads from contributing tributaries, the land surface and erosion along the coastline. Extreme precipitation events and projected increases in runoff can increase surface and in-stream erosion that is delivered to the Lakes – particularly in the winter and spring when runoff is anticipated to be greater. Coastal bluff erosion is a concern in the basin as it can often threaten infrastructure stability along developed shorelines. Reduced winter ice cover is anticipated to increase wind and wave turbulence, accelerating coastal bluff erosion during the winter months (Mackey, 2012) while potentially lower lake levels could leave bluffs less vulnerable to erosion. Polluted sediments are also the main cause of food web contamination in fish advisory warnings.

Biological and chemical contamination

Chemical contaminants can be transported via sediment, water, and atmospheric deposition into the waters of the Great Lakes basin. Projected changes in temperature, precipitation, and atmospheric circulation are likely to impact how pathogens and chemicals are transported and dispersed into the environment (Boxall et al., 2009). Increases in precipitation intensity will exacerbate the loss of nutrients and pesticides from the landscape and promote lake eutrophication (Daloglu et al., 2012). More intense precipitation events interspersed with longer dry spells would affect the dilution and residence times of these and other pollutants such as metals and pathogens in water bodies (Whitehead et al., 2009). This will most likely occur in spring, when higher precipitation is projected and vegetation cover is low (Dempsey et al., 2008). The resulting excess level of nutrients can lead to abundant algae and eutrophication, affecting drinking water treatment facilities, recreational water activities and biota.

Increases in extreme precipitation events can also overburden combined sewage overflow systems in the Great Lakes region (which exist in over 180 communities), allowing untreated discharge to enter water bodies (Patz et al., 2008). Contamination events typically occur when precipitation amounts exceed 5 to 6.4 cm within a 24-hour period (exceedances that are projected to increase in the future). In an assessment for Chicago, the frequency of overflow occurrences is expected to increase from one event every other year to 1 to 1.2 events per year based on lower and higher GHG emissions scenarios, respectively (Patz et al., 2008). It is possible that overflows will lead to an increase of contaminants (e.g. metals, bacteria, pathogens, and pesticides) in water bodies, causing health concerns (e.g. waterborne diseases) and impacts to the recreational economy (e.g., beach advisories, recreational fishing) (Patz et al., 2008).

Ecological impacts on wildlife and vegetation

Changing climate has implications for the flora and fauna of the basin. The distribution, abundance, and range of species including fish, mammals, and birds will likely be affected by warming lake and air temperatures. For example, there will be more habitats for warm-water fish species (native and non-natives) and less for cold-water species; cold-water species will be more stressed (Cline et al., 2013; Magnuson et al., 1997). Changes in ice cover play a significant role in the winter mixing within the lakes, impacting fish and zooplankton communities who rely on winter mixing for the delivery of oxygen and food sources to the deeper reaches of the lakes (Jensen et al., 2007; Sharma et al., 2011). Ice cover tends to protect near-shore regions from waves and erosion (Wang et al., 2010) and acts as an insulator to keep water temperature steady. Near-shore stress from shoreline erosion and fluctuating water levels can have negative ecological impacts on many fish species due to high turbidity loads and sedimentation impacts on spawning and nursery habitats (Mackey, 2012).

Increased temperature and CO_2 concentrations can change the productivity and distribution of plant species within the Great Lakes basin. At present, the basin is 60% forest cover, (51% forest on the US portion and 73% on the Canadian portion) and forest management can lead to significant changes in carbon storage (Wormstead et al., 2009). Millar et al. (2007) suggest that adaptively managing forest resistance to impacts, resilience in the face of disturbance, and response in the face of changing climate will enable forests to thrive under rapidly changing conditions. Climate change might also have significant impacts on agricultural production and crop yield. Longer growing seasons and increased CO_2 can increase certain crop yields, while extreme climate events may reduce yields and increase dependence on irrigation (Hall, 2012).

Future scenarios

The Great Lakes Futures Project assembled stakeholders from the basin for a workshop in January 2013 to explore how different decisions on mitigation and adaptation implementation could unfold over the next 50 years (Laurent et al., in this issue). Three future histories, from the perspective of the year 2063 are developed to present status quo, dystopian, and utopian conditions that we have termed “The Fog”, “The Wreckage”, and “The Lighthouse”, respectively. Each future history presents a story line consisting of a summary of current conditions and the mitigation and adaptation options that were utilized or dismissed within the region. The resultant future impacts that were discussed earlier in this article are seen to have emerged due to the interaction of climate change with other drivers.

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Status quo: "The Fog"

GHG emissions growth slowed, but did not level off or decrease, which resulted in atmospheric concentrations continuing to increase. For decades, the international and national political environments hindered significant changes directed at mitigating climate change. Many GHG reduction initiatives in the region faded after a few years due to dwindling public interest and budget cuts. Global emissions reductions maintained early 21st century GHG concentration levels, slowing the upward trend without reversing it; average air temperatures are now 3 °C warmer in the basin.

Mitigation

Mitigation efforts were started early in the 21st century, but were not aggressive enough to provide significant changes in emissions or to slow increasing energy demand. Provinces and states enacted renewable energy portfolio standards requiring a reduction in carbon emissions by switching 10 to 30% of energy generation to renewable resources by 2020 or 2030. However, increased energy demand, particularly in summer months, continued to require the use of coal and natural gas to meet peak loads. Several states met their new portfolio requirements and demand by purchasing renewable energy from outside of the basin instead of decreasing their fossil fuel generation. Natural gas production reduced more expensive coal use for energy. However, natural gas production came at the expense of low-carbon renewables as it was more competitively priced due to unchanged fuel subsidies and no implementation of a continental carbon market. Without a strong consensus to implement stricter carbon emission policies, regional and global GHG emissions continued to increase CO_2 in the atmosphere.

Adaptation

A warming of several degrees and other associated changes in climate had a significant impact on the basin. Without strong, coordinated initiatives at all scales of governance; adaptation was ad hoc, slow and difficult. Increased incidence and severity of pests, disease and forest fires reduced forest land cover and damaged field crops. Farmers had to increase pest management efforts, which increased input costs and impacted water quality. Imported fruits and vegetables became more expensive due to drought and productivity declines in other regions. This created opportunities for local farmers who took advantage of drip irrigation methods and higher commodity prices and converted to greenhouse farming. Urban populations continued to grow in the region but sprawl was more common than dense development. Cities used "green infrastructure" to absorb runoff from heavy precipitation events by retaining stormwater and filtering contaminants but most natural shoreline wetland ecosystems were developed, reducing biodiversity. Warmer lake temperatures created thermal habitat conducive to the spread of established invasive species and many native cold water fish populations were outcompeted by aggressive invasives. The commercial and sports fisheries struggled to remain economically viable despite expensive efforts at managing invasive species and restocking. The summer recreation industry welcomed longer boating seasons but was affected by lower water levels closing many marinas. Warmer, but highly variable winter temperatures affected most outdoor ice skating rinks and reduced cross country skiing opportunities. Support for large-scale changes to energy generation and conservation was not evident until many decades into the new century, once changes became too large to dispute and economic losses were mounting across industries.

A dystopian future: "The Wreckage"

Despite dire warnings from climate scientists, very little progress was made in reducing GHG emissions or preparing for an unpredictable future climate within the basin. GHG emissions continued on their early-century trajectory with atmospheric GHG concentrations setting even higher records than expected, raising annual average temperatures by 5 °C. This coincided with a lack of public and government support for immediate and lasting changes to the status quo for climate change mitigation. Hope had been placed on finding new GHG reducing technologies, but with minimal investment in research and innovation, very little has materialized. Similarly, investment in local adaptation preparation was insufficient. Actual temperature increases, precipitation changes and extreme events (e.g., droughts and heavy rain storms) were more significant locally than projections from GCMs and RCMs using the IPCC SRES scenarios. Fragmented and unenforced governmental policy meant the failure of binational cooperation such as the Great Lakes Water Quality Agreement. The basin has experienced many greater than anticipated impacts.

Mitigation

Progress on climate change policies was prevented by sluggish economies and partisan politics. Without federal leadership, the basin's regional communities did not uphold non-binding emissions reduction targets in industry or energy production. More broadly, developing countries used fossil fuels for short-term economic development offsetting gains in emissions reductions by other developed nations. Population growth, in conjunction with more summer heat waves, increased cooling demand and energy consumption has exceeded development of renewable energy sources.

Adaptation

While the Great Lakes-St. Lawrence River basin is relatively wealthy, its adaptive capacity is low as there was little investment in research, training or implementation of innovative change. In addition, the basin absorbed climate refugees from within North America as well as other countries affected by rising sea levels, severe storms, and water stress. Climate changes and effects have been significant. The demographics of the basin became biased towards the very young and old who struggled with respiratory and heat related illness, while young graduates left for better jobs elsewhere. Innovative ideas for coping with the drastic weather changes have been ignored or not implemented where most needed. Chronic low lake levels have impacted commercial shipping, hydropower generation, and access and amenity of lakefront properties. Beaches and marinas are now separated by mudflats from the water, and farmers are restricted from lake water irrigation, forcing them to dig deeper for groundwater. Cities around the basin were required to invest in upgrading drinking water treatment and moving lake intakes at great expense due to declining lake water levels and quality. Many cities that did not upgrade their stormwater management facilities had to spend many times more recovering from damage due to flash floods and collapsed sewers caused by more intense storm events. Additionally, costs associated with repairing property and infrastructure damage from severe weather events such as flooding has affected many communities and individuals. Families that could afford them bought household treatment systems to cope with more frequent boil water advisories. Municipal hospitals became overwhelmed with treating rising cases of water-borne illnesses such as *E.coli* after more frequently occurring flood events. Urban sprawl in coastal cities continues unabated and is consuming the remaining wetlands in the region, further removing the abilities of the lakes to absorb increased nutrient and contaminant loading from industrialized agriculture. Cold water fish species were replaced by warm water and invasive species, causing a total collapse of what was left of the fishing industry. Job supply is decreasing as many employers leave the basin for other regions that invested in the future by modernizing infrastructure and welcoming renewable energy.

A utopian future: "The Lighthouse"

The Lighthouse future represents a concerted global effort to respond seriously and rapidly to the threat of climate change through mitigation resulting in a significant reduction in GHG emissions, and an eventual decline in GHG concentrations. The magnitude and rate of climate change were reduced with average warming of only 2 °C. New technology provided more effective, low-cost solutions to reducing emissions and improving resilience to climate change. Grassroots support for climate change action allowed for governmental and business sector change; the region has become a leader in energy conservation and significantly reducing GHG emissions.

Mitigation

The Lighthouse was achieved by improving energy efficiency, reducing GHG emissions through improved technology and pricing structures and was buoyed by significant sequestration programs. Building codes in the region were changed to implement new ultra-efficient standards such as the Passivhaus and Zero-Energy Building standards (Musall et al., 2010; Wahlström et al., 2012). Local governments provided incentives for renovating and retrofitting commercial and residential buildings to reduce energy use by more than half. To compel improvements in efficiency, governments created realistic pricing structures for energy and water use in the region including infrastructure, delivery, and water treatment. A new, non-energy intensive method for sequestration and post-carbon capture reduced the carbon footprint of many industries including power plants. Great Lakes states followed Québec and Ontario's leads and joined the Western Climate Initiative and a cap and trade market (MDDEP, 2002). Carbon pricing allows the renewable energy sector to be market-competitive and significant funding of carbon sequestration technology research was provided to achieve commercial success. Managed development of the changing forests using species diversity controlled disease and fire losses and contributed to sequestration. Changes in climate are still affecting ecosystems and society, but the strict emission reductions helped curb the rate and magnitude of change and lessened drastic impacts.

Adaptation

As a society, the Great Lakes basin had significant human and financial capital to apply to the changing climate relative to other areas of the world. Investing in multi-disciplinary research expanded the adaptive knowledge base for the communities and fostered new and innovative technology and ideas, with an emphasis on environmental resilience. A dense, long-term environmental monitoring network supported regional environmental impact modeling and early-detection of risk factors. Integrated water resources management made for a community-determined, adaptive approach, which used climate models to plan infrastructure resilience projects such as water treatment plants, dam and levee maintenance, bridges, and roadways. Separating the aging combined sewer and storm drainage systems reduced water treatment costs and prevented combined sewer overflows. Natural storm water and flood control methods, such as wetlands, helped to protect shoreline habitats and personal property. Consumers became aware of their water use and carbon footprint through key initiatives. Widespread installation of digital water metering systems helped to reduce water demand. Development of the smart-grid for energy transmission significantly reduced transmission loss. Adaptive planning significantly benefited the region's economy. The states, provinces and First Nations communities have developed a holistic, trans-boundary economy facilitating the cross-border movement of goods taking advantage of each community's strengths in manufacturing and labor thereby improving the economic strength of the region. Removing obstacles to economic cooperation improved overall transboundary governance, allowing a continent-wide carbon market to be put in place. There was recognition that surface waters were best managed binationally on a basin scale instead of existing political boundaries ensuring strong, cooperative, cross-boundary management of shared waters and improving water security for the entire region (Zubrycki et al., 2011). Redevelopment of brownfield sites in the former “Rust Belt” region boosted local economies and idle industrial-zoned land was repurposed instead of developing natural areas. Factories were converted to manufacture items related to renewable energy, such as solar arrays, wind turbines, and new technologies, increasing the viability of renewable energy in the region and providing well-paid jobs. The entire region united and supported change. The foresight resulted in a region with a growing economy, rich in well-paying, green jobs, a safer and cleaner environment than 2013, and regional pride in giving our children a promising future.

Conclusions and recommendations

The evidence of climate change in the Great Lakes basin can already be seen in reduced lake ice extent and warmer air and water temperatures. Projections indicate that those trends will continue and might become more extreme in the future. A warmer climate with more severe precipitation events will exacerbate existing water resource management issues such as flooding, infrastructure failure, transport of sediment and contaminants, water quality degradation, combined sewer overflows, shoreline erosion, and temporary water shortages. The associated damages and economic losses will involve substantial monetary costs. The implementation of mitigation and adaptation strategies will be crucial in shaping the ecological, social and economic future of the basin.

Achievement of the Utopian Lighthouse future depends on many global factors, however with the right approach, the citizens of the basin can have a significant impact on their future and foster hope and change at a continental if not global scale. Most importantly, this requires implementing immediate and continuing mitigation and adaptation strategies. Energy consumption must be reduced through energy conservation in homes, buildings and factories' lighting, heating and cooling. Raising fuel efficiency and emissions standards can reduce emissions from vehicles. To encourage both energy conservation and improvements in efficiency, a government action such as creating a unified carbon market across the basin would price the true cost of fossil fuels and level the playing field for more sustainable energy sources. An improved environmental monitoring network across the basin can assist with future modeling but also help with near-term risk-assessment such as flash flooding. Infrastructure upgrades must incorporate the implications of a changing climate. This will involve upgrades to urban stormwater systems for dealing with heavy rains, improving water treatment plants' capacities, and reexamining drinking water treatment plants' intakes originating within the lakes. Critical infrastructure such as power plants, transportation (bridges, roads, railways) and hospitals will need to be sited and retrofitted for protection against natural hazard events such as flooding. Additionally, there needs to be emergency planning and preparation for dealing with regional disasters. Evidence suggests that prevention is much cheaper than a cure; the Federal Emergency Management Agency demonstrated that for every dollar spent on natural hazard mitigation, four dollars were saved from damages averted (MMC, 2005). Investments in energy conservation, efficiency, and infrastructure can immediately boost the economy of the region and reduce costs in the long term and should not be seen as costly expenses by business and government interests. An adaptive management approach will help the region iteratively incorporate lessons learned into the planning and policy process. A sustainable Great Lakes region will require a knowledgeable and engaged society, with changes in governance and the energy sector that promote responsible strategies for maintaining a healthy economy and ecosystem.

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