National Park Service
U.S. Department of the Interior

Historical and Projected Climate Change and Ecological Change at Isle Royale National Park

Patrick Gonzalez, Ph.D.

Climate Change Response Program
Natural Resource Stewardship and Science
National Park Service
1201 I Street NW
Washington, DC 20005-5905 USA

November 5, 2012

Introduction

Greenhouse gas emissions from vehicles, power plants, deforestation, and other human activities have increased temperatures and changed precipitation patterns in the 20th and early 21st centuries (IPCC 2007a). Field observations from around the world show that climate change is fundamentally altering ecosystems by shifting biomes, leading to the extinction of some species, and causing numerous other changes (IPCC 2007b). To assist Isle Royale National Park (NP) in efforts to integrate climate change into resource management planning, this report summarizes peer-reviewed published scientific data on historical and projected climate, physical, and ecological changes. The report only uses information from peer-reviewed scientific publications and only presents results for Isle Royale NP or the nearby vicinity.

Historical Climate and Physical Changes

From 1901 to 2002, mean annual temperature increased across the Laurentian Great Lakes region (Figure 1; Gonzalez et al. 2010) and showed a statistically significant increase in the 50 km x 50 km area that includes Isle Royale NP (Figure 2, Table 1). From 1919 to 2010, temperature at the Grand Marais, Minnesota weather station also showed a statistically significant increase (Figure 2; data from National Oceanic and Atmospheric Administration).

For the Midwestern U.S., the statistically significant warming from 1895 to 2010 has been greatest in winter, the slight increase in the growing season from ~160 days to ~170 days has not been statistically significant, and no significant change in heat waves (4 days of 20% extreme or 1-in-20 year temperatures) has occurred (Kunkel et al. in review).

From 1901 to 2002, precipitation increased across most of North America (Figure 3; Gonzalez et al. 2010) and also showed a statistically significant increase in the Isle Royale area (Figure 4, Table 1). From 1919 to 2010, precipitation at the Grand Marais, Minnesota weather station did not show a statistically significant trend (Figure 3; data from National Oceanic and Atmospheric Administration). For the Midwestern U.S., the increase in precipitation has been greatest in summer (Kunkel et al. in review).

Mean annual snowfall of four quality-controlled weather stations upwind of Lake Superior (four in the Upper Peninsula, Michigan, and one in Wisconsin) showed a statistically significant increase of ~40% from 1899 to 2006 (Kunkel et al. 2009a). Historical records from 1900 to 2006 for four quality-controlled weather stations in Michigan, Minnesota, Wisconsin, and Iowa show no statistically significant change in extreme high snowfall seasons (10% extreme or 1-in-10 year winters) and a statistically significant decrease of 14% in extreme low snowfall seasons (10% extreme or 1-in-10 year winters) (Kunkel et al. 2009b). From 1901 to 2000, the weather station at Duluth, Minnesota recorded a statistically significant increase of 30% in total precipitation of the ten wettest days of the year (Kunkel et al. in review). Wind measurements from Lake Superior buoys show a 5% increase in wind speed from 1985 to 2008, possibly due to faster warming of water than land temperatures (Desai et al. 2009).

Lake Superior has shown some changes consistent with climate change. Water temperature at buoy ROAM4, off the west tip of Isle Royale, increased at a rate of 0.16 ± 0.1ºC y^{-1} (16 ± 10ºC $century^{-1}$) from 1979 to 2006 (Austin and Colman 2007). Analysis of water temperatures at buoy NDBC 45004, in eastern Lake Superior, showed a statistically significant increase of 25 days in summer water stratification from 1906 to 2005 (Austin and Colman 2008). Ice cover on Lake Superior decreased at a rate of 0.42 ± 0.20 $century^{-1}$ (42 ± 20% per century) from 1979 to 2005 (Austin and Colman 2007). Lake Superior water level has varied substantially over the period of instrumental measurements, with the level generally increasing from 1860 to 1980 and decreasing 30 cm from 1980 to 2007 (Lamon and Stow 2010). Dynamic linear modeling provides strong evidence that the trend is non-random. This is consistent with a slight decrease in net basin supply from 1948 to 2008 (MacKay and Seglenieks early). The seasonal maximum in lake level has shifted to earlier in the spring from 1860 to 1998 (Lenters 2001).

Observed Ecological Changes and Climate Change

Although no peer-reviewed publications have detected ecological changes on Isle Royale and attributed those changes to climate change, some studies have observed ecological changes consistent with climate change. Concerning vegetation distribution, conifer seedlings have shown a northward shift across the eastern U.S. between the 1970s and 2000s (Woodall et al. 2009). On the northern Lower Peninsula of Michigan, the ranges of mesic tree species (e.g. hemlock [*Tsuga canadensis*]) depends on lake-effect snow (Henne et al. 2007).

Although wildfire has increased in the western U.S. due to climate change (Littell et al. 2009), no significant change in fire frequency occurred from 1900 to 2000 in the 50 km x 50 km pixel that includes Isle Royale (Gonzalez et al. 2010). The area of boreal forest in Ontario at the same latitude as Isle Royale has shown a 0.07± 0.42 century^{-1} increase in the rate of area burned from 1959 to 1999 (Drever et al. 2008).

Several studies have examined the relationships among moose (*Alces alces*), wolves (*Canis lupus*), balsam fir trees (*Abies balsamea*), the North Atlantic Oscillation (a cycle of sea surface temperatures that bring high snow to the area in some years alternating with warmer periods in other years), and climate change. Field surveys on Isle Royale showed that tick-infested moose decreased by three-quarters from 1989 to 1994, possibly due to colder temperatures and more spring snow (Delgiudice et al. 1997). In the period 1958-1997, in times when the North Atlantic Oscillation brought more snow, wolf attacks increased, moose decreased, and balsam fir increased (Post et al. 1999). Because of the projected decease in snow in the region under future climate change, this trend may be opposite of that projected in the future. Research in the period 1959-1998 indicates that, after a crash of the wolf population due to an outbreak of canine parvovirus, moose increased, and the population variance showed a relation to the North Atlantic Oscillation (Wilmers et al. 2006). In northeastern Minnesota, temperature may have had a cumulative influence on moose survival from 2002 to 2008 due to the intolerance of moose for warm temperatures (Lenarz et al. 2009). In Algonquin Provincial Park and Wildlife Management Unit 49, Ontario, Canada, moose increased from 2006 to 2009, a trend that also may be opposite of that expected under climate change (Murray et al. 2012).

Some research on other animal species shows some changes consistent with climate change. Eight small mammal species in the Upper Peninsula and northern lower Peninsula, of Michigan showed a northward shift of ranges of up to 225 km from 1978 to 2008 (Myers et al. 2009). In Thunder Bay, Ontario, one bird species moved north out of area from 1974 to 2004, while two species moved northward into the area (La Sorte and Thompson 2007). Although lake trout and lake whitefish generally prefer colder waters, they increased in Lake Superior from 1970 to 2000, a trend that may be opposite of that expected under climate change (Bronte et al. 2003).

Future Climate and Physical Projections

The Intergovernmental Panel on Climate Change (IPCC) has coordinated research groups to project possible future climates under defined greenhouse gas emissions scenarios (IPCC 2007). The three main IPCC greenhouse gas emissions scenarios are B1 (lower emissions), A1B (medium emissions), and A2 (higher emissions). Actual global emissions are on a path above IPCC emissions scenario A2 (Friedlingstein et al. 2010).

For the three main IPCC emissions scenarios, general circulation models (GCMs) of the atmosphere project an increase in 21st century temperature four to seven times the amount of historical 20th century warming in the 50 km x 50 km area that includes Isle Royale NP (Table 1). Precipitation could increase under all three emissions scenarios in the 50 km x 50 km area around the park (Table 1).

Spatial analyses of the area within Isle Royale NP, using climate projections for IPCC emissions scenario A2 downscaled to 4 km x 4 km (data from Conservation International <http://futureclimates.conservation.org>, method of Tabor and Williams [2010]) show projected patterns of climate that may occur if we do not reduce greenhouse gas emissions. Mean annual temperature could increase 4.9 ± 1.1° C by 2100 AD (Figure 5). The temperature projections of the 18 GCMs are generally in close agreement, with a coefficient of variation (the standard deviation as a fraction of the mean) of 0.23, indicating that the temperature uncertainty is approximately one-fourth of the mean (Figure 6). Under emissions scenario A2, the length of the growing season in Northeast Minnesota could increase another 18-21 days between the periods 1980-2000 and 2041-2070 (Kunkel et al. in review).

Most of the GCMs project increased precipitation. The GCMs show an average 9 ± 6% increase in precipitation under IPCC emissions scenario A2 (Figure 7), with 16 of 18 GCMs projecting increases (Figure 8). The coefficient of variation of the precipitation projections is 0.61, indicating that the precipitation uncertainty is approximately two-thirds of the mean. Taken together, the temperature and precipitation projections from the 18 GCMs form a cloud of potential future climates (Figure 9). The ensemble mean reflects the central tendency of the projections, but the uncertainty for the precipitation projections is large.

Projections indicate potential changes in the frequency of extreme temperature and precipitation events. In Northeast Minnesota, modeling under emissions scenario A2 projects 19-21 fewer days with minimum temperature < 0°C and no change in consecutive days with maximum temperature > 35°C, between the periods 1980-2000 and 2041-2070 (Kunkel et al. in review). The same models project an increase of 20% in the number of days with precipitation > 2.5 cm and 4-6 fewer days with precipitation < 3 mm.

Models project decreases in snow and ice for the region. Under emissions scenario B1, the number of snow days across the State of Michigan could decrease by 25% between the periods 1961-1990 and 2070-2099 (Hayhoe et al. 2010), while the number of ice-free winters on Lake Superior cold increase from none in the period (1951-1995) to 7-43% of winters without ice by 2090 AD (Lofgren et al. 2002).

Models project other changes for Lake Superior. Under emissions scenario A2, the maximum water temperature could increase 6.7°C between the periods 1971-2000 to 2071-2100 (Trumpickas et al. 2009), summer stratification could increase (Fang and Stefan 2009), and the lake level could fall 0.1 ± 0.5 m between the periods 1970-1999 and 2080-2094 (Angel and Kunkel 2010), consistent with a projected slight decrease in net basin supply (MacKay and Seglenieks early).

Projected Ecological Changes

Only a few peer-reviewed publications have explicitly projected potential ecological changes at or near Isle Royale under climate change. These examine vegetation shifts and changes to freshwater fish.

Modeling of the distribution of ten tree species across the Great Lakes projected northward shifts between the periods 1951-1980 and 2090-2099 (Walker et al. 2002). Spatial analyses of 1901-2002 historical climate and 2071-2100 projected vegetation and classification using the IPCC vulnerability framework (Table 2) indicate that the 50 km x 50 km area of Isle Royale is highly vulnerable to a northward shift of boreal conifer forest, including balsam fir, replaced by temperate conifer forest (Figures 10-13, Gonzalez et al. 2010). Across eastern North America, niche models project a northward shift of ranges of 120 tree species, with 66 species increasing and 54 species decreasing the area of their potential range at least 10% from 1990 to 2099 (Iverson et al. 2008). Concerning wildfire, a dynamic global vegetation model projects no change in fire frequency from 2000 to 2100 (Gonzalez et al. 2010).

In Lake Superior, modeling indicates that the mobilization of the toxic organic compound PCB-77 from sediments by warmer waters could increase bioaccumulation in round goby, mottled sculpin, and lake trout by 1-5% by 2100 (Ng and Gray 2011). Across the Great Lakes, warmer water temperatures may cause a northward and downward shift of cool-water species (e.g. lake trout, walleye) in favor of warm-water species (e.g. smallmouth bass) (Lynch et al. 2010).

Tables 3 and 4 summarize the climate, physical, and ecological changes reviewed in this report.

Table 1. Historical and projected climate (mean ± standard deviation (SD)) trends for the 50 km x 50 km square area that includes Isle Royale NP (Mitchell and Jones 2005, IPCC 2007a, Gonzalez et al. 2010). Historical trends also given for the Grand Marais, Minnesota, weather station. The climate projection under IPCC emissions scenario A2 for the 50 km x 50 km square area is consistent with the climate projection downscaled to 4 km x 4 km for the area of the park (data from Conservation International using method of Tabor and Williams [2010]). Note "century^{-1}" is the fractional change per century (-0.01 century^{-1} is a decrease of 1% in a century).

	mean	SD	units
Historical			
temperature 1901-2002 annual average	2.4	1.0	ºC
temperature 1901-2002 linear trend	0.7	3.2	ºC century^{-1}
temperature 1919-2010 annual average (station)	3.9	0.9	ºC
temperature 1919-2010 linear trend (station)	1.4	3.2	ºC century^{-1}
precipitation 1901-2002 annual average	640	120	mm y^{-1}
precipitation 1901-2002 linear trend	0.37	0.54	century^{-1}
precipitation 1919-2010 annual average (station)	640	120	mm y^{-1}
precipitation 1919-2010 linear trend (station)	-0.01	450	century^{-1}
Projected			
IPCC B1 scenario (lower emissions)			
temperature 1990-2100 annual average	2.8	1.1	ºC century^{-1}
precipitation 1990-2100 annual average	0.06	0.06	century^{-1}
IPCC A1B scenario (medium emissions)			
temperature 1990-2100 annual average	4.1	1.1	ºC century^{-1}
precipitation 1990-2100 annual average	0.05	0.06	century^{-1}
IPCC A2 scenario (higher emissions)			
temperature 1990-2100 annual average	4.9	1.1	ºC century^{-1}
precipitation 1990-2100 annual average	0.09	0.06	century^{-1}

Table 2. Intergovernmental Panel on Climate Change (IPCC 2007a) treatment of uncertainty.

Confidence	Degree of confidence in being correct
Very high	At least 9 out of 10 chance
High	About 8 out of 10 chance
Medium	About 5 out of 10 chance
Low	About 2 out of 10 chance
Very low	Less than 1 out of 10 chance

Table 3. Historic and Projected Climate and Physical Changes around Isle Royale National Park

Patrick Gonzalez

National Park Service

November 5, 2012

			Projected 21st Century Change		
Climate or Physical Variable	**Trend**	**Historical 20th Century Change**	**Lower Emissions Scenario (IPCC B1)**	**Higher Emissions Scenario (IPCC A2)**	**Confidence in Scientific Understanding (IPCC Terms)**
Temperature	↑	Isle Royale: mean ± SE = +0.7 ± 0.3°C/century, 1901-2002, statistically significant (Mitchell and Jones 2005, Gonzalez et al. 2010); Midwest: warming greatest in winter (Kunkel et al. in review)	Isle Royale: mean ± SD = +2.8 ±1.1°C/century, 1961-90 to 2071-2100 (Gonzalez et al. 2010, IPCC 2007)	Isle Royale: mean ± SD = +4.9 ± 1.1°C/century, 1961-90 to 2071-2100 (Gonzalez et al. 2010, IPCC 2007); Northeast Minnesota: warming greatest in winter (Kunkel et al. in review)	Very High (IPCC 2007)
Precipitation	↑	Isle Royale: mean ± SE = +30 ± 5%/century, 1901-2002, statistically significant (Mitchell and Jones 2005, Gonzalez et al. 2010); Midwest: increase greatest in summer (Kunkel et al. in review)	Isle Royale: mean ± SD = +6 ± 6%/century, 1961-90 to 2071-2100 (Gonzalez et al. 2010, IPCC 2007)	Isle Royale: mean ± SD = +9 ± 6%/century, 1961-90 to 2071-2100 (Gonzalez et al. 2010, IPCC 2007); Northeast Minnesota: increaase greatest in winter (Kunkel et al. in review)	High (IPCC 2007)
Growing season length	↑	Midwest: + ~10 days, 1895-2010 (Kunkel et al. in review)		Northeast Minnesota: +18-21 days, 1980-2000 to 2041-2070 (Kunkel et al. in review)	High
Extreme temperature events	↔	Midwest: No significant change in heat waves (4 days of 20% extreme or 1-in-20 year temperatures), 1895-2010 (Kunkel et al. in review)		Northeast Minnesota: -19-21 days with minimum temperature < 0°C, no change in consecutive days with maximum temperature > 35°C, 1980-2000 to 2041-2070 (Kunkel et al. in review)	Medium
Extreme precipitation events	↑	Duluth, MN: +30% total precipitation of 10 wettest days, statistically significant, 1901-2000 (Kunkel et al. in review)		Northeast Minnesota: +20% days with precipitation > 2.5 cm, -4 to -6 days with precipitation < 3 mm, 1980-2000 to 2041-2070 (Kunkel et al. in review)	High (IPCC 2007)

Table 3. Historic and Projected Climate and Physical Changes around Isle Royale National Park

Patrick Gonzalez

National Park Service

November 5, 2012

			Projected 21st Century Change		
Climate or Physical Variable	**Trend**	**Historical 20th Century Change**	**Lower Emissions Scenario (IPCC B1)**	**Higher Emissions Scenario (IPCC A2)**	**Confidence in Scientific Understanding (IPCC Terms)**
Wind	↔	Lake Superior: +5% increase in wind speed measured at buoys 1985-2008 (Desai et al. 2009)			Low
Snowfall	↔	Upper Peninsula: + ~40%, 1899-2006, statistically significant, -14% low snowfall seasons (10% extreme or 1-in-10 year winters), statistically significant, 1900-2006 (Kunkel et al. 2009b)	Michigan: -25% snow days, 1961-1990 to 2070-2099 (Hayhoe et al. 2010)		Low
Lake temperature	↑	west end of Isle Royale: +0.16 ± 0.1ºC/y (+16 ± 10ºC/century), 1979-2006 (Austin and Colman 2007); eastern Lake Superior: +25 days summer stratification, statistically significant, 1906-2005 (Austin and Colman 2008)		Lake Superior: +6.7ºC, maximum temperature, 1971-2000 to 2071-2100 (Trumpickas et al. 2009); increase in summer stratification (Fang and Stefan 2009)	High
Lake ice cover	↓	Lake Superior -42 ± 20%/century, 1979-2005 (Austin and Colman 2007)	Lake Superior: no ice-free winters (1951-1995) to 7-43% of winters without ice (2090 AD) (Lofgren et al. 2002)		High
Lake level	↓	Lake Superior: level increasing 1860-1980, 30 cm decrease 1980-2007, strong evidence for non-random trend (Lamon and Stow 2010); Shift to earlier spring maximum, 1860-1998 (Lenters 2001); slight decrease in net basin supply 1948-2008 (MacKay and Seglenieks early)		Lake Superior: -0.1 ± 0.5 m, 1970-1999 to 2080-2094 (Angel and Kunkel 2010); continued slight decrease in net basin supply (MacKay and Seglenieks early)	Medium (Angel and Kunkel 2010)

Table 4. Observed Ecological Changes Consistent with Climate Change and Projected Vulnerabilities at Isle Royale National Park

Patrick Gonzalez

National Park Service

November 5, 2012

Resource or Process	20th Century Observations Consistent with Climate Change, unless noted	21st Centrury Projections Higher Emissions Scenario (IPCC A2)	Confidence in Scientific Understanding (IPCC Terms)
Vegetation distribution	eastern U.S.: Northward shift of conifer seedlings 1970s-2000s (Woodall et al. 2009); northern Lower Peninsula, Michigan: Lake-effect snow maintains mesic species (e.g. hemlock) (Henne et al. 2007)	Area around Isle Royale: Northward shifts of ten tree species, 1980-2099 (Walker et al. 2002); Area of 50 km x 50 km that includes Isle Royale: High vulnerability to northward shift of boreal conifer forest, replaced by temperate conifer forest, 1990-2100 (Gonzalez et al. 2010); eastern North America: northward shift of ranges of 120 species, with 66 spp. increasing and 54 spp. decreasing range ≥10%, 1990-2099 (Iverson et al. 2008)	High
Wildfire	Area of 50 km x 50 km that includes Isle Royale: no significant change in fire frequency, 1900-2000 (Gonzalez et al. 2010); Ontario, same latitude as Isle Royale, 7± 42%/century burned, 1959-1999 (Drever et al. 2008)	Area of 50 km x 50 km that includes Isle Royale: no projected change in fire frequency, 2000-2100 (Gonzalez et al. 2010)	Low
Moose	Isle Royale: tick-infested moose decreased by 3/4, 1989-1994, possibly due to colder temperatures and more spring snow (Delgiudice et al. 1997), after crash of wolf population due to virus, moose increased, population variance related to North Atlantic Oscillation, 1959-1998 (Wilmers et al. 2006); northeastern Minnesota: 2002-2008 temperature may have a cumulative influence on survival (Lenarz et al. 2009); Algonquin Provincial Park, WMU49, Ontario: trend opposite of climate change - increasing population, 2006-2009 (Murray et al. 2012)		Low
Wolves	Isle Royale: trend perhaps opposite of climate change - North Atlantic Oscillation, more snow, more wolf attacks, fewer moose, more balsam fir trees, 1958-1997 (Post et al. 1999)		Low

Table 4. Observed Ecological Changes Consistent with Climate Change and Projected Vulnerabilities at Isle Royale National Park

Patrick Gonzalez

National Park Service

November 5, 2012

Resource or Process	20th Century Observations Consistent with Climate Change, unless noted	21st Centrury Projections Higher Emissions Scenario (IPCC A2)	Confidence in Scientific Understanding (IPCC Terms)
Small mammals	Upper Peninsula, northward lower Peninsula, Michigan: Northern shift of ranges of 8 small mammal species, up to 225 km, 1978-2008 (Myers et al. 2009)		Medium
Birds	Thunder Bay, Ontario: One species moved north out of area, two species moved northward into area 1974-2004 (La Sorte and Thompson 2007)		Medium
Fish	Lake Superior: trend opposite of climate change - increase in lake trout and lake whitefish, 1970-2000 (Bronte et al. 2003)	Lake Superior: mobilization of PCB-77 by warmer waters from sediments, +1-5% bioaccumulation in round goby, mottled sculpin, and lake trout, ~2000-2100 (Ng and Gray 2011); Great Lakes: northward and downward shift of cool-water species (e.g. lake trout, walleye) in favor of warm-water species (e.g. smallmouth bass) (Lynch et al. 2010)	High

Figure 1.

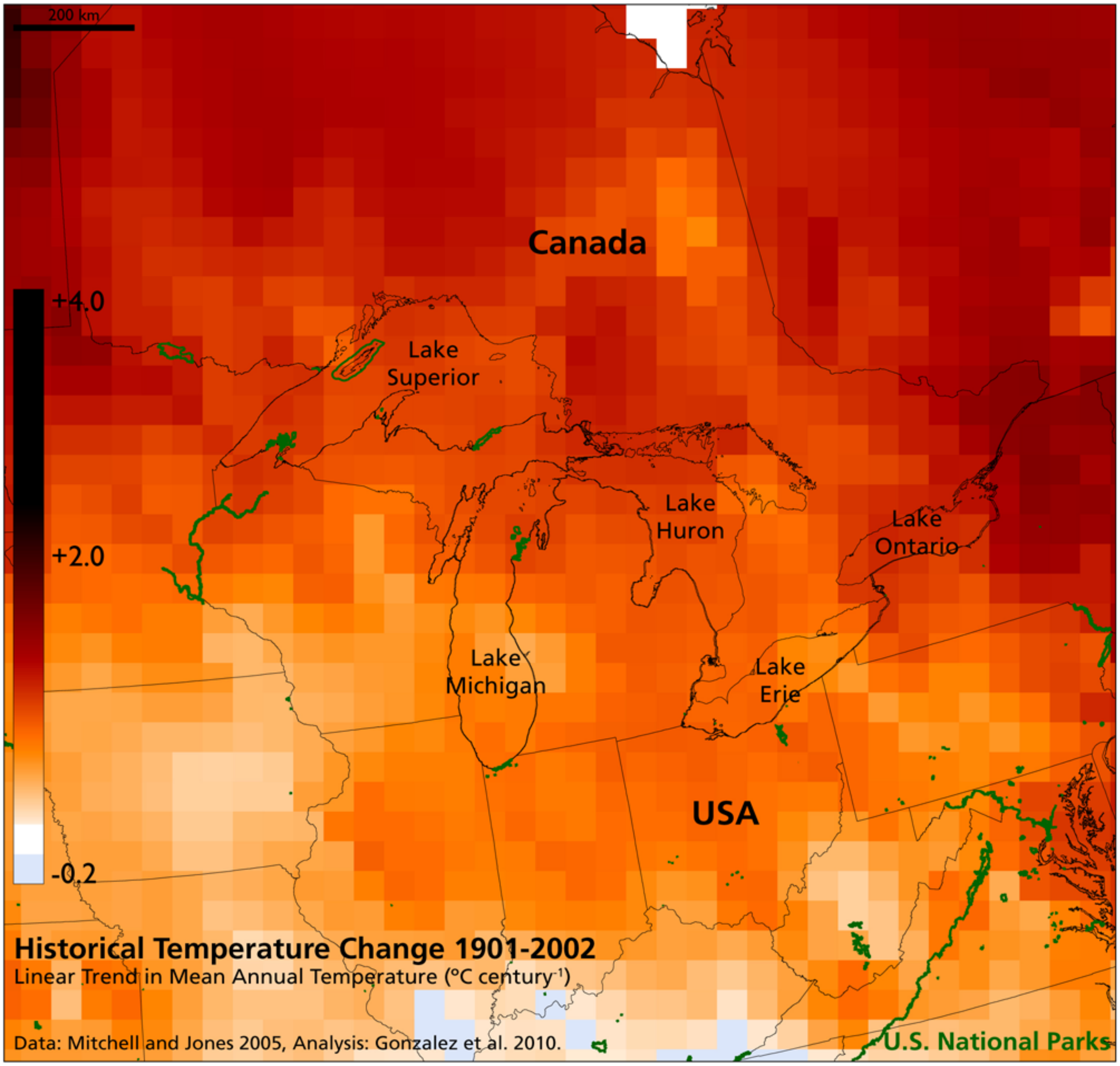

200 km
+4.0
+2.0
-0.2
Canada
Lake Superior
Lake Huron
Lake Ontario
Lake Michigan
Lake Erie
USA
Historical Temperature Change 1901-2002
Linear Trend in Mean Annual Temperature (°C century⁻¹)
Data: Mitchell and Jones 2005, Analysis: Gonzalez et al. 2010.
U.S. National Parks

Figure 2.

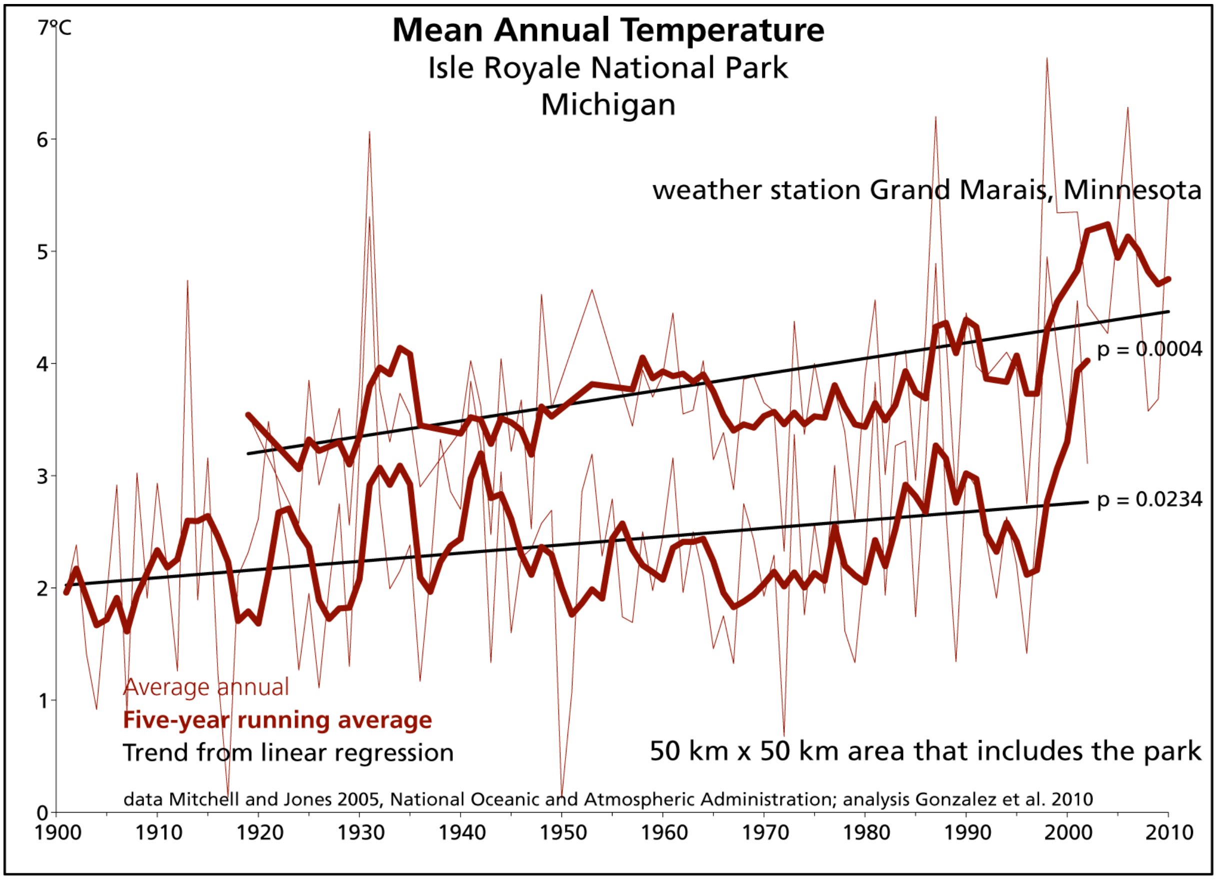

Mean Annual Temperature
Isle Royale National Park
Michigan
weather station Grand Marais, Minnesota
p = 0.0004
p = 0.0234
Average annual
Five-year running average
Trend from linear regression
50 km x 50 km area that includes the park
data Mitchell and Jones 2005, National Oceanic and Atmospheric Administration; analysis Gonzalez et al. 2010
7°C
6
5
4
3
2
1
0
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010

Figure 3.

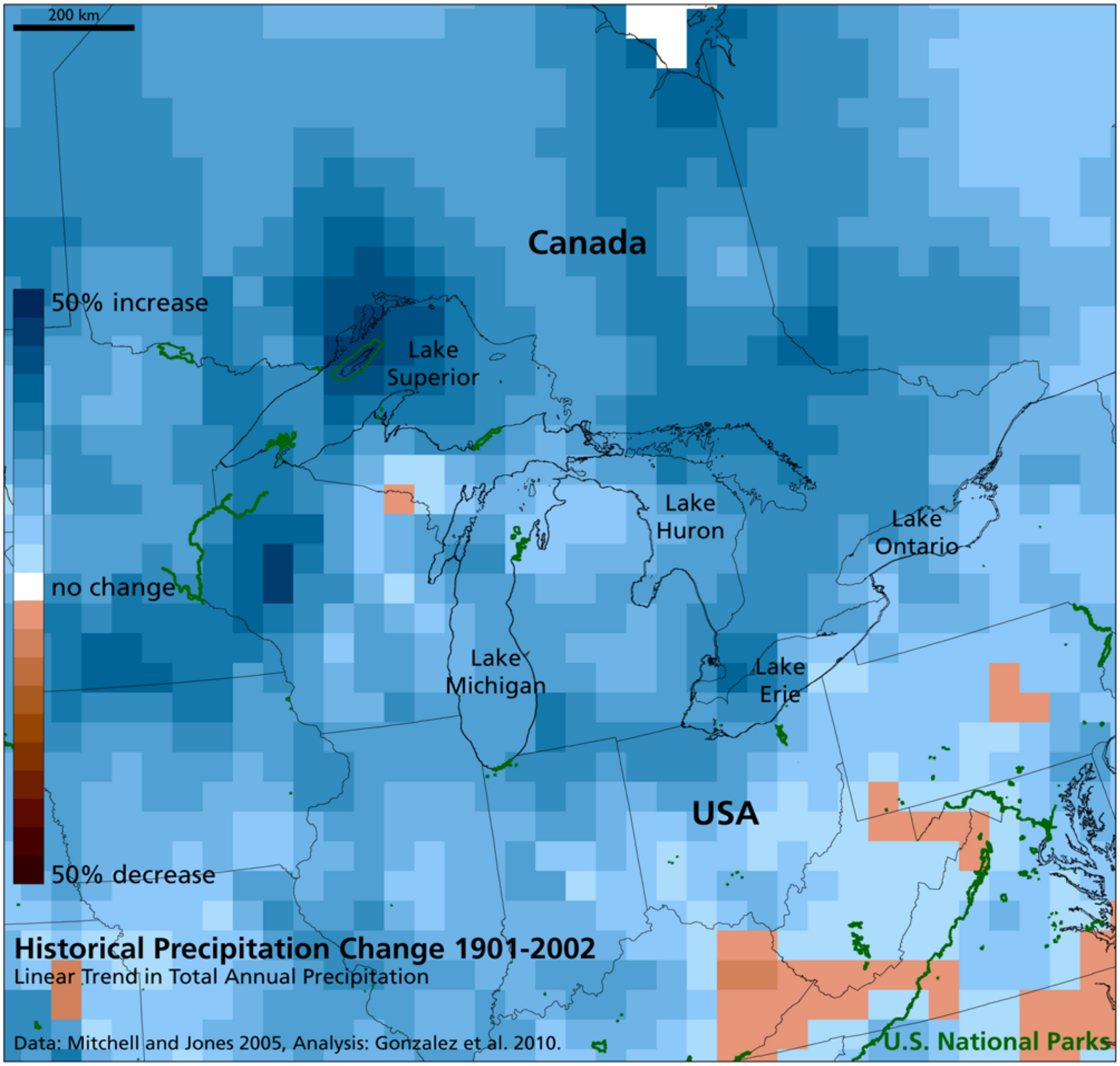

200 km
Canada
50% increase
no change
50% decrease
Lake Superior
Lake Huron
Lake Ontario
Lake Michigan
Lake Erie
USA
U.S. National Parks
Historical Precipitation Change 1901-2002
Linear Trend in Total Annual Precipitation
Data: Mitchell and Jones 2005, Analysis: Gonzalez et al. 2010.

Figure 4.

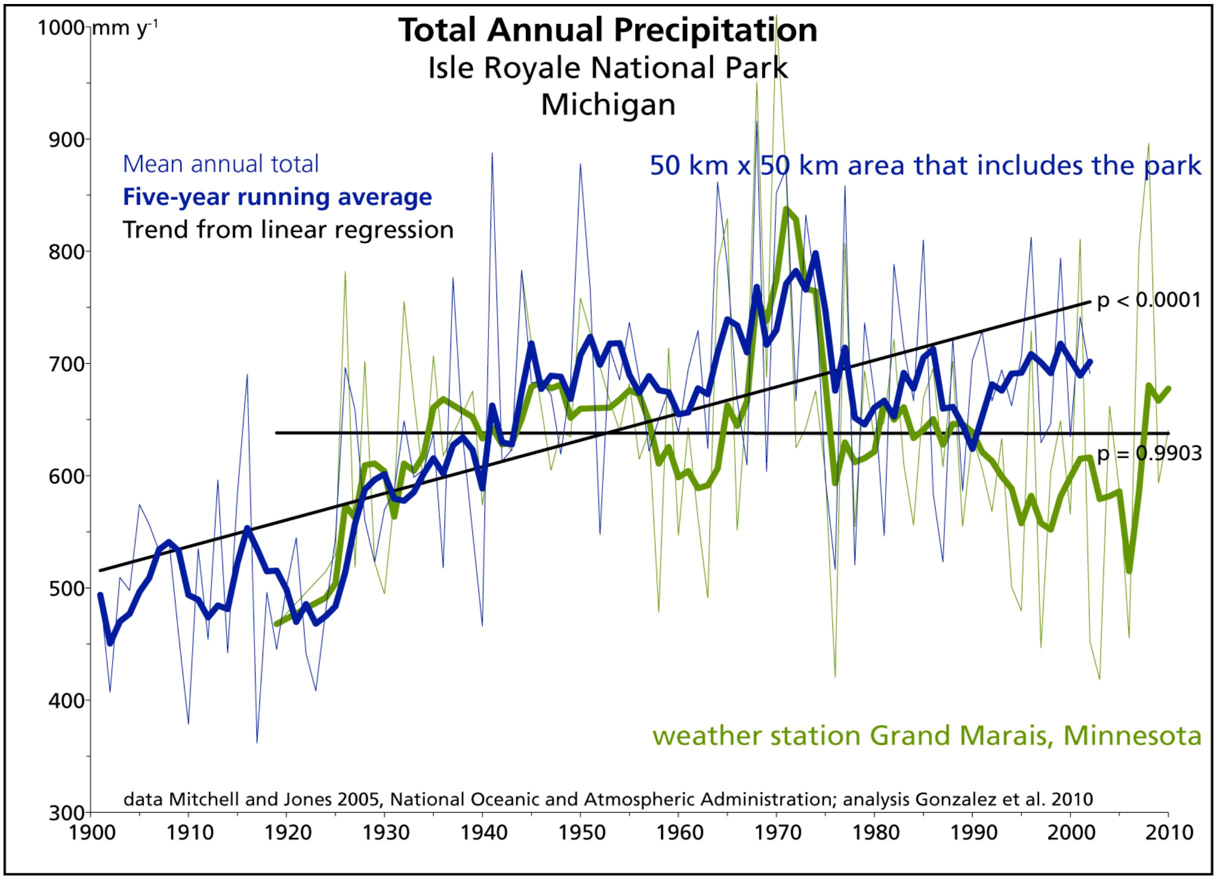

Total Annual Precipitation
Isle Royale National Park
Michigan
1000 mm y-1
900
800
700
600
500
400
300
Mean annual total
Five-year running average
Trend from linear regression
50 km x 50 km area that includes the park
p < 0.0001
p = 0.9903
weather station Grand Marais, Minnesota
data Mitchell and Jones 2005, National Oceanic and Atmospheric Administration; analysis Gonzalez et al. 2010
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010

Figure 5.

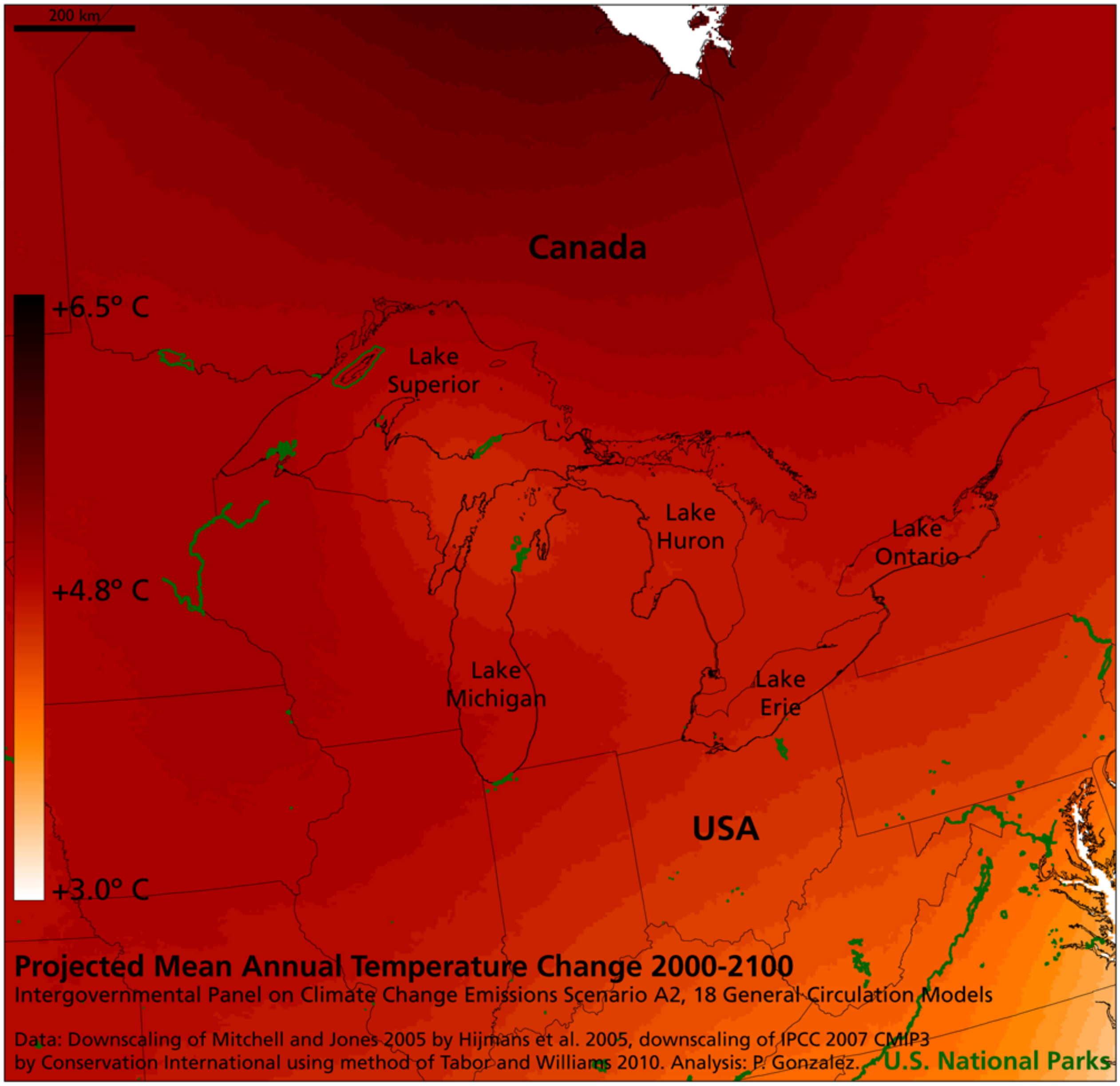

200 km
Canada
+6.5° C
+4.8° C
+3.0° C
Lake Superior
Lake Huron
Lake Ontario
Lake Michigan
Lake Erie
USA
Projected Mean Annual Temperature Change 2000-2100
Intergovernmental Panel on Climate Change Emissions Scenario A2, 18 General Circulation Models
Data: Downscaling of Mitchell and Jones 2005 by Hijmans et al. 2005, downscaling of IPCC 2007 CMIP3
by Conservation International using method of Tabor and Williams 2010. Analysis: P. Gonzalez.
U.S. National Parks

Figure 6.

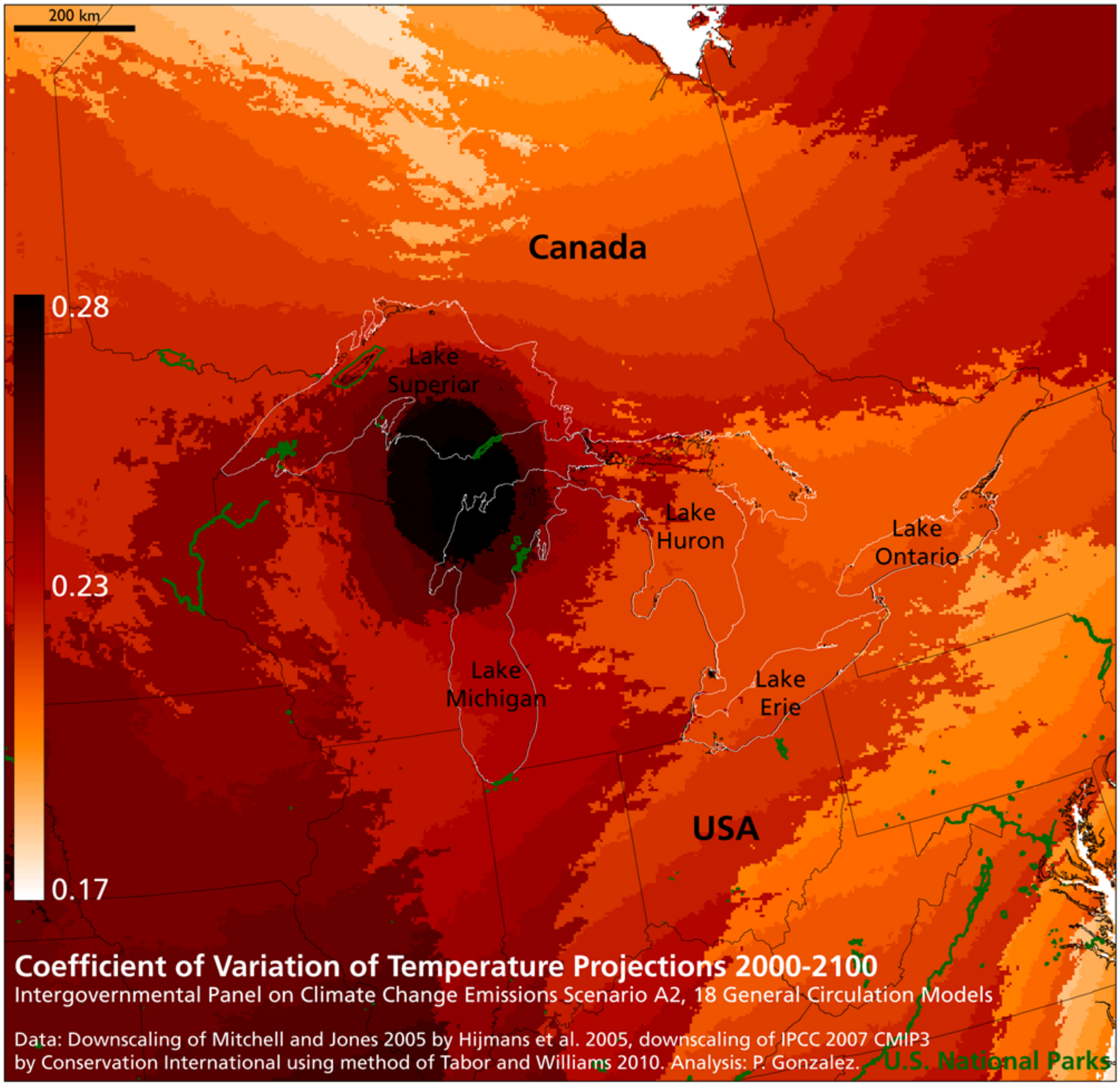

200 km
Canada
0.28
0.23
0.17
Lake Superior
Lake Huron
Lake Ontario
Lake Michigan
Lake Erie
USA
Coefficient of Variation of Temperature Projections 2000-2100
Intergovernmental Panel on Climate Change Emissions Scenario A2, 18 General Circulation Models
Data: Downscaling of Mitchell and Jones 2005 by Hijmans et al. 2005, downscaling of IPCC 2007 CMIP3
by Conservation International using method of Tabor and Williams 2010. Analysis: P. Gonzalez.
U.S. National Parks

Figure 7.

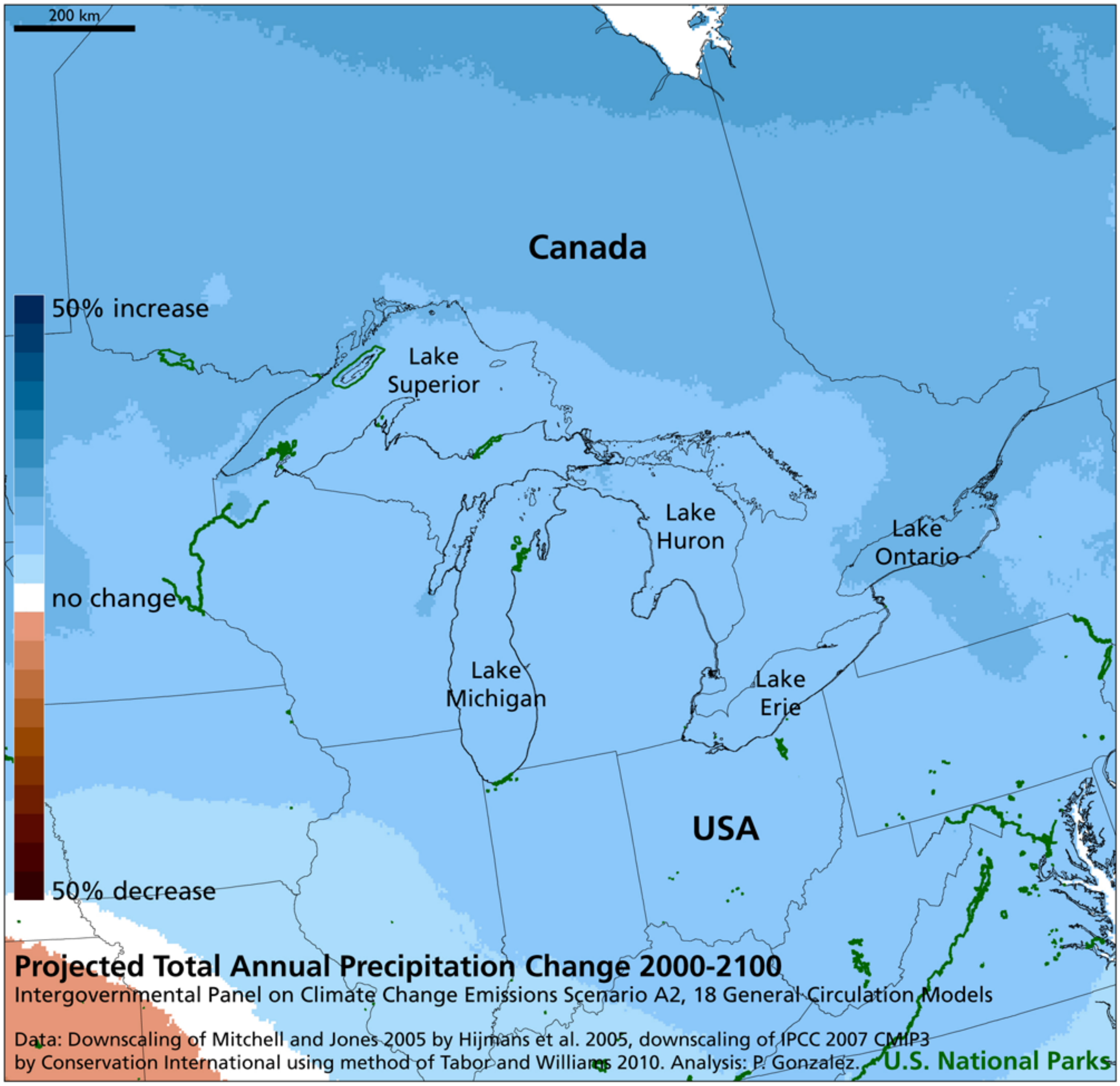

200 km
Canada
50% increase
no change
50% decrease
Lake Superior
Lake Huron
Lake Ontario
Lake Michigan
Lake Erie
USA
Projected Total Annual Precipitation Change 2000-2100
Intergovernmental Panel on Climate Change Emissions Scenario A2, 18 General Circulation Models
Data: Downscaling of Mitchell and Jones 2005 by Hijmans et al. 2005, downscaling of IPCC 2007 CMIP3
by Conservation International using method of Tabor and Williams 2010. Analysis: P. Gonzalez.
U.S. National Parks

Figure 8.

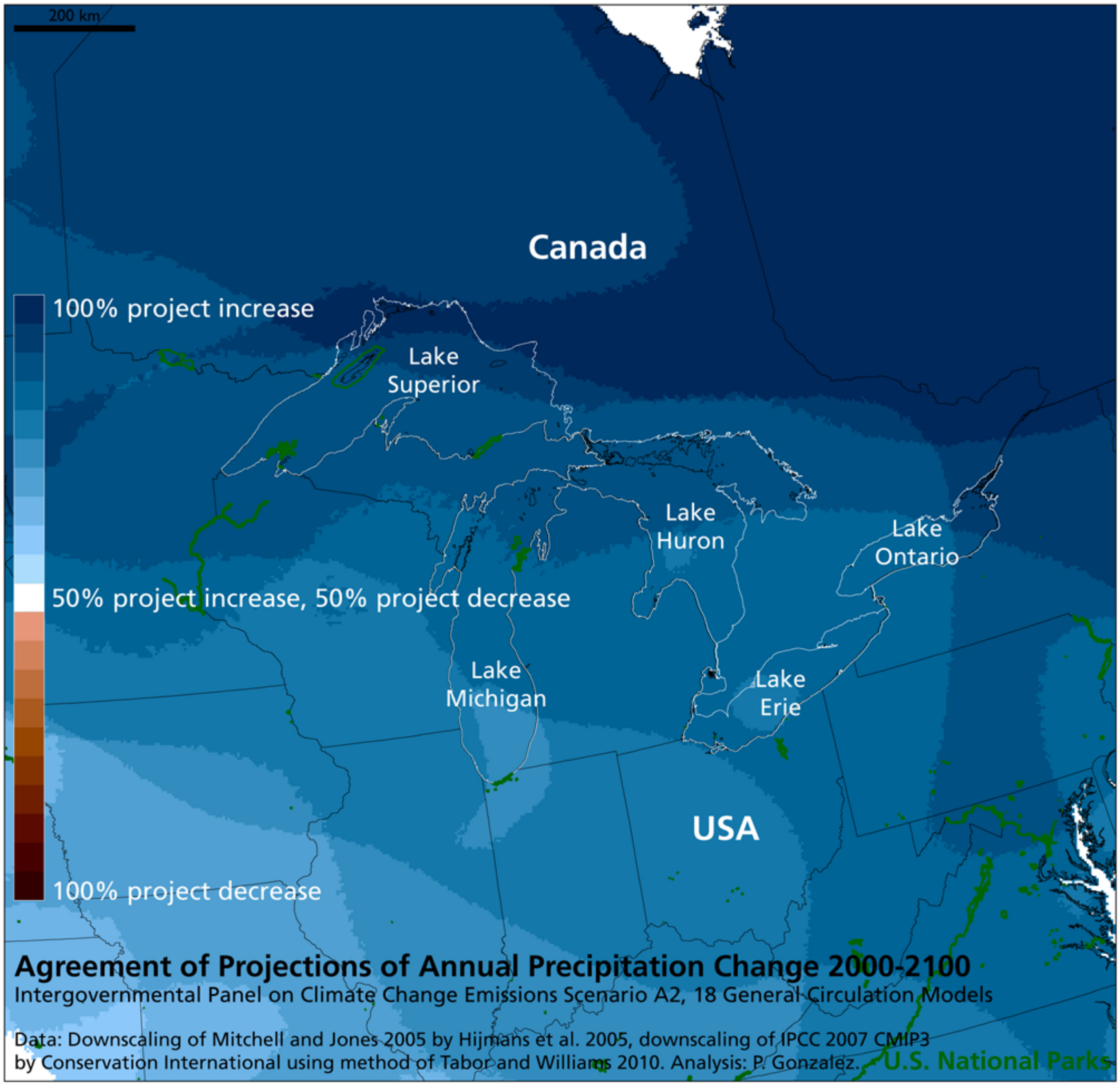

200 km
Canada
100% project increase
Lake
Superior
Lake
Huron
Lake
Ontario
50% project increase, 50% project decrease
Lake
Michigan
Lake
Erie
USA
100% project decrease
Agreement of Projections of Annual Precipitation Change 2000-2100
Intergovernmental Panel on Climate Change Emissions Scenario A2, 18 General Circulation Models
Data: Downscaling of Mitchell and Jones 2005 by Hijmans et al. 2005, downscaling of IPCC 2007 CMIP3
by Conservation International using method of Tabor and Williams 2010. Analysis: P. Gonzalez.
U.S. National Parks

Figure 9.

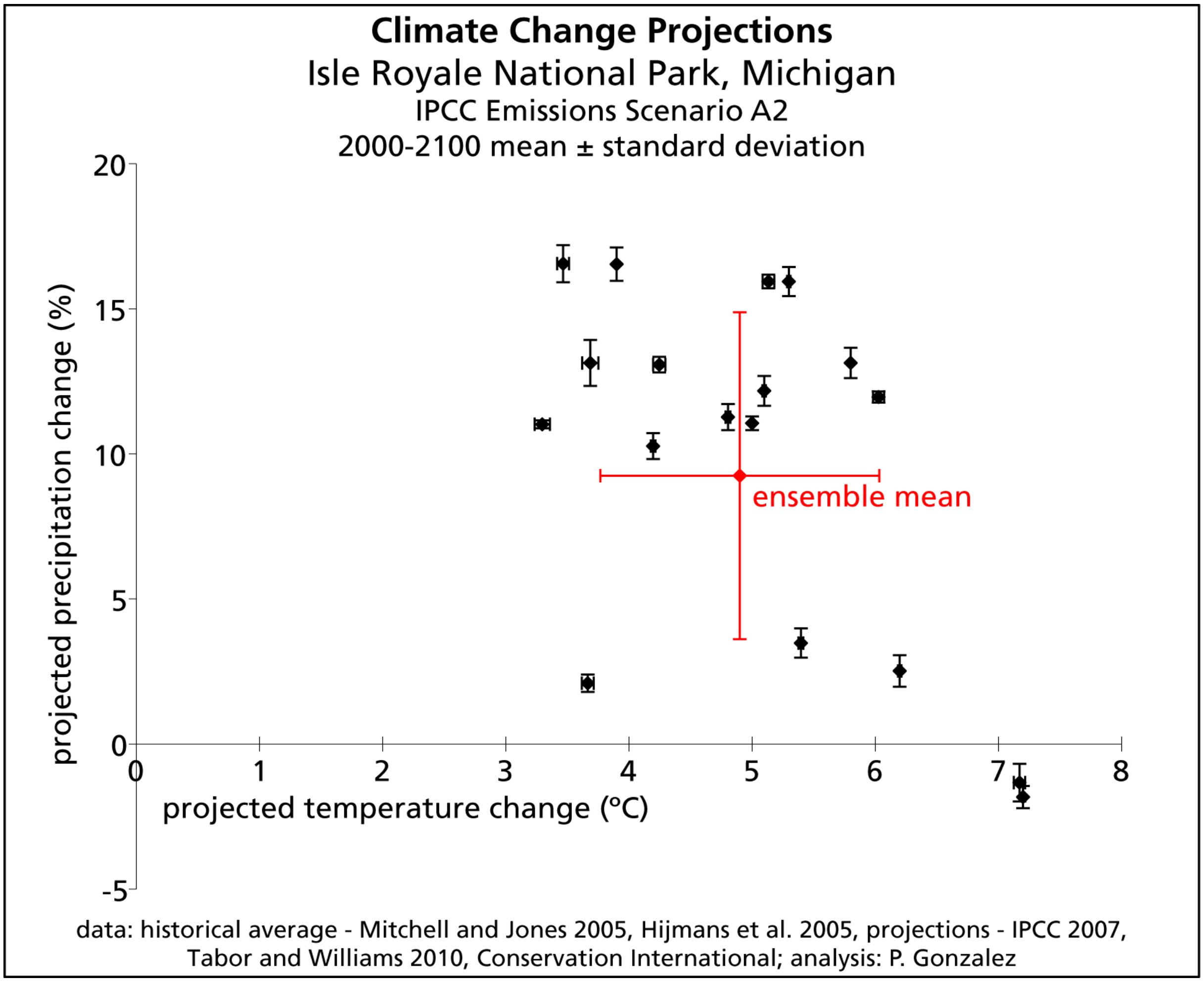

Climate Change Projections
Isle Royale National Park, Michigan
IPCC Emissions Scenario A2
2000-2100 mean ± standard deviation
projected precipitation change (%)
projected temperature change (°C)
ensemble mean
20
15
10
5
0
-5
0
1
2
3
4
5
6
7
8
data: historical average - Mitchell and Jones 2005, Hijmans et al. 2005, projections - IPCC 2007,
Tabor and Williams 2010, Conservation International; analysis: P. Gonzalez

Figure 10.

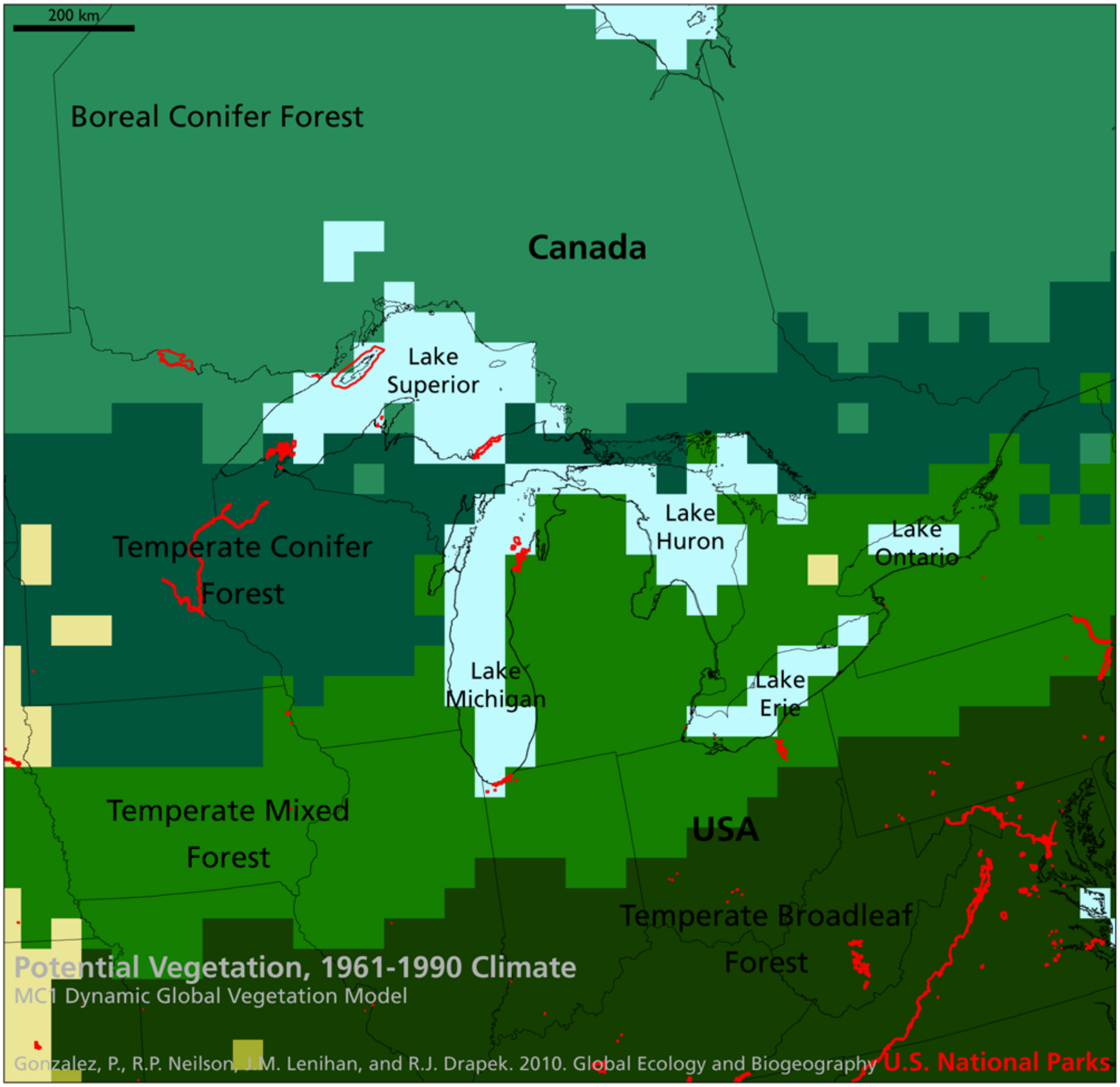

200 km
Boreal Conifer Forest
Canada
Lake Superior
Temperate Conifer Forest
Lake Huron
Lake Ontario
Lake Michigan
Lake Erie
Temperate Mixed Forest
USA
Temperate Broadleaf Forest
Potential Vegetation, 1961-1990 Climate
MC1 Dynamic Global Vegetation Model
Gonzalez, P., R.P. Neilson, J.M. Lenihan, and R.J. Drapek. 2010. Global Ecology and Biogeography
U.S. National Parks

Figure 11.

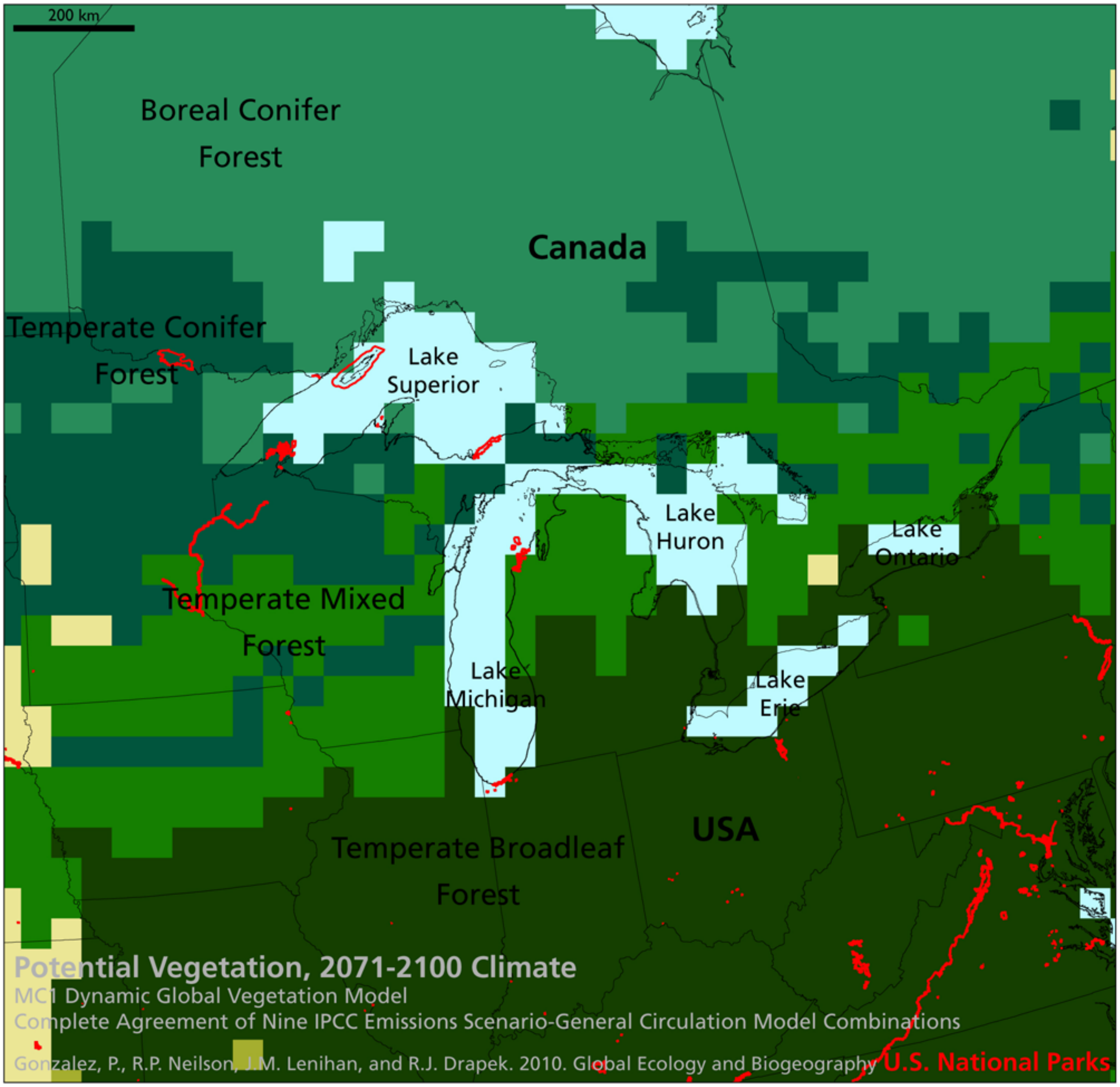

200 km
Boreal Conifer Forest
Canada
Temperate Conifer Forest
Lake Superior
Lake Huron
Lake Ontario
Temperate Mixed Forest
Lake Michigan
Lake Erie
USA
Temperate Broadleaf Forest
Potential Vegetation, 2071-2100 Climate
MC1 Dynamic Global Vegetation Model
Complete Agreement of Nine IPCC Emissions Scenario-General Circulation Model Combinations
Gonzalez, P., R.P. Neilson, J.M. Lenihan, and R.J. Drapek. 2010. Global Ecology and Biogeography
U.S. National Parks

Figure 12.

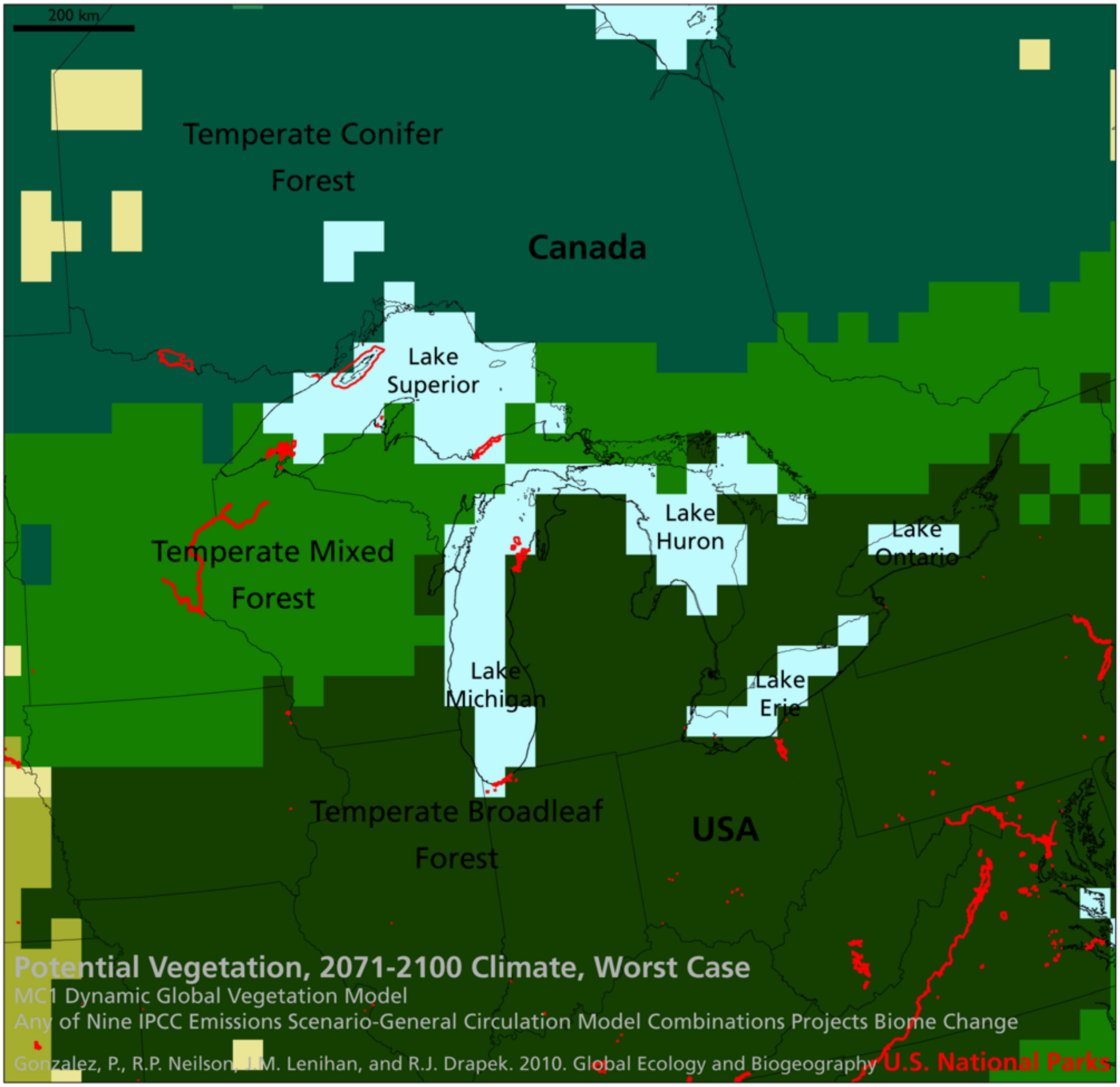
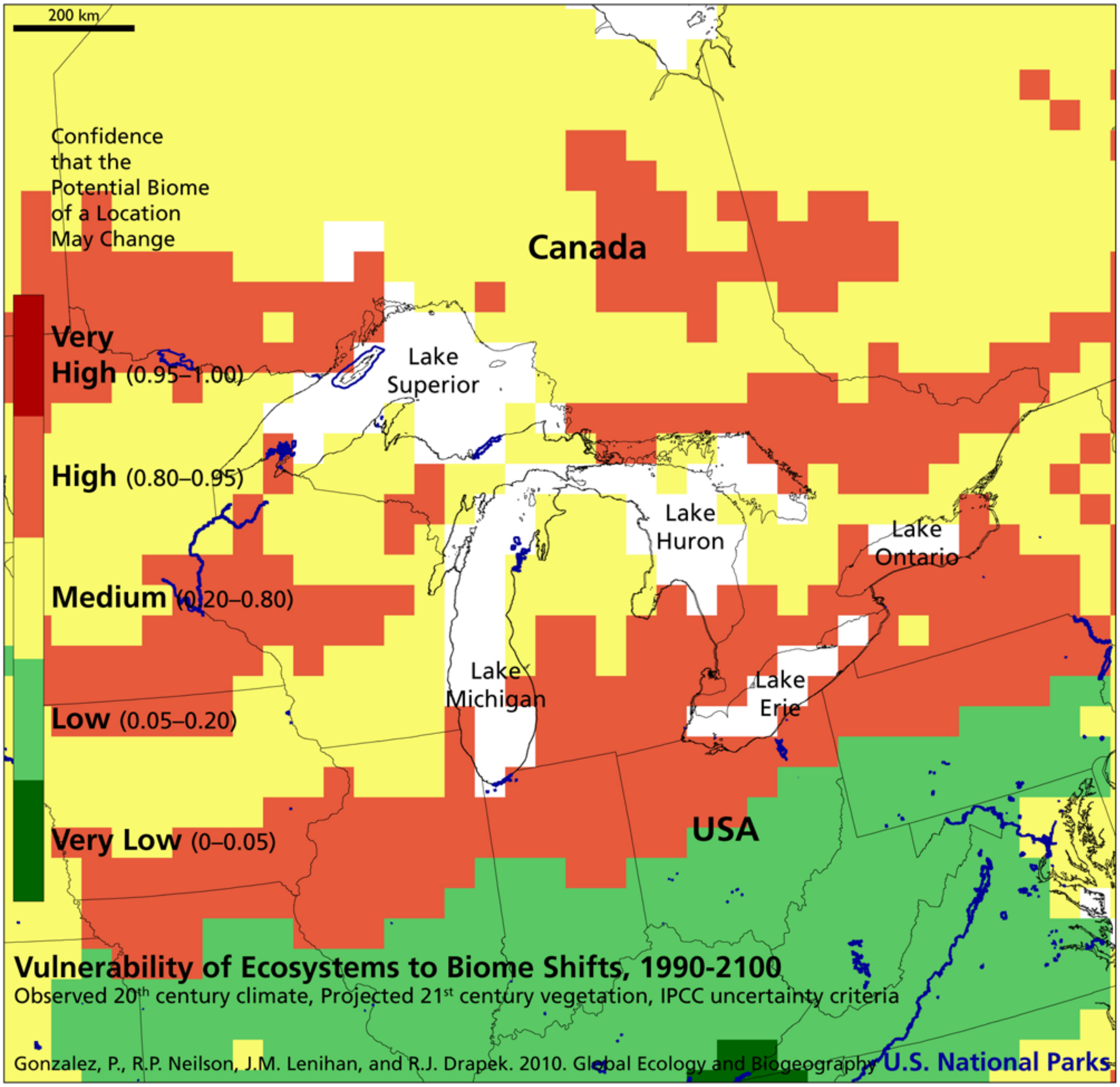

200 km
Temperate Conifer Forest
Canada
Lake Superior
Temperate Mixed Forest
Lake Huron
Lake Ontario
Lake Michigan
Lake Erie
Temperate Broadleaf Forest
USA
Potential Vegetation, 2071-2100 Climate, Worst Case
MC1 Dynamic Global Vegetation Model
Any of Nine IPCC Emissions Scenario-General Circulation Model Combinations Projects Biome Change
Gonzalez, P., R.P. Neilson, J.M. Lenihan, and R.J. Drapek. 2010. Global Ecology and Biogeography
U.S. National Parks

Figure 13.


200 km
Confidence that the Potential Biome of a Location May Change
Very High (0.95–1.00)
High (0.80–0.95)
Medium (0.20–0.80)
Low (0.05–0.20)
Very Low (0–0.05)
Canada
USA
Lake Superior
Lake Michigan
Lake Huron
Lake Ontario
Lake Erie
Vulnerability of Ecosystems to Biome Shifts, 1990-2100
Observed 20th century climate, Projected 21st century vegetation, IPCC uncertainty criteria
Gonzalez, P., R.P. Neilson, J.M. Lenihan, and R.J. Drapek. 2010. Global Ecology and Biogeography
U.S. National Parks

References

Angel, J.R. and K.E. Kunkel. 2010. The response of Great Lakes water levels to future climate scenarios with an emphasis on Lake Michigan-Huron. Journal of Great Lakes Research 36 (S2): 51-58.

Austin, J.A., and S.M. Colman. 2007. Lake Superior summer water temperatures are increasing more rapidly than regional air temperatures: A positive ice-albedo feedback. Geophysical Research Letters 34: L06604. doi:10.1029/2006GL029021.

Austin, J. and S. Colman. 2008. A century of temperature variability in Lake Superior. Limnology and Oceanography 53: 2724-2730.

Bronte, C.R., M.P. Ebener, D.R. Schreiner, D.S. DeVault, M.M. Petzold, D.A. Jensen, C. Richards, and S.J. Lozano. 2003. Fish community change in Lake Superior, 1970–2000. Canadian Journal of Fisheries and Aquatic Sciences 60: 1552-1574.

Delgiudice, G.D., R.O. Peterson, and W.M. Samuel. 1997. Trends of winter nutritional restriction, ticks, and numbers of moose on Isle Royale. Journal of Wildlife Management 61: 895-903.

Desai, A.R., J.A. Austin, V. Bennington, and G.A. McKinley. 2009. Stronger winds over a large lake in response to weakening air-to-lake temperature gradient. Nature Geoscience 2: 855-858.

Drever, C.R., M.C. Drever, C. Messier, Y. Bergeron, and M. Flannigan. 2008. Fire and the relative roles of weather, climate and landscape characteristics in the Great Lakes St. Lawrence forest of Canada. Journal of Vegetation Science 19: 57-66.

Fang, X. and H.G. Stefan. 2009. Simulations of climate effects on water temperature, dissolved oxygen, and ice and snow covers in lakes of the contiguous United States under past and future climate scenarios. Limnology and Oceanography 54: 2359-2370.

Friedlingstein, P., R.A. Houghton, G. Marland, J. Hackler, T.A. Boden, T.J. Conway, J.G. Canadell, M.R. Raupach, P. Ciais, and C. Le Quéré. 201. Update on CO2 emissions. Nature Geoscience 3: 811-812.

Gonzalez, P., R.P. Neilson, J.M. Lenihan, and R.J. Drapek. 2010. Global patterns in the vulnerability of ecosystems to vegetation shifts due to climate change. Global Ecology and Biogeography 19: 755-768.

Hayhoe, K., J. VanDorn, T. Croley, N. Schlegal, and D. Wuebbles. 2010. Regional climate change projections for Chicago and the US Great Lakes. Journal of Great Lakes Research 36 (S2): 7-21.

Henne, P.D., F.S. Hu, and D.T. Cleland. 2007. Lake-effect snow as the dominant control of mesic-forest distribution in Michigan, USA. Journal of Ecology 95: 517-529.

Hijmans, R.J., S.E. Cameron, J.L. Parra, P.G. Jones, and A. Jarvis. 2005. Very high resolution interpolated climate surfaces for global land areas. International Journal of Climatology 25: 1965-1978.

Intergovernmental Panel on Climate Change (IPCC). 2007a. Climate Change 2007: The Physical Science Basis. Cambridge University Press, Cambridge, UK.

Intergovernmental Panel on Climate Change (IPCC). 2007b. Climate Change 2007: Impacts, Adaptation, and Vulnerability. Cambridge University Press, Cambridge, UK.

Iverson, L.R., A.M. Prasad, S.N. Matthews, and M. Peters. 2008. Estimating potential habitat for 134 eastern US tree species under six climate scenarios. Forest Ecology and Management 254: 390-406.

Kunkel, K.E., L. Ensor, M. Palecki, D. Easterling, D. Robinson, K.G. Hubbard, and K. Redmond. 2009a. A new look at lake-effect snowfall trends in the Laurentian Great Lakes using a temporally homogeneous data set. Journal of Great Lakes Research 35: 23-29.

Kunkel, K.E., M.A. Palecki, L. Ensor, D. Easterling, K.G. Hubbard, D. Robinson, and K. Redmond. 2009b. Trends in twentieth-century U.S. extreme snowfall seasons. Journal of Climate 22: 6204-6216.

Kunkel, K.E., L.E. Stevens, S.E. Stevens, E. Janssen, S. Hilberg, M. Timlin, L. Stoecker, and N. Westcott. in review. Climate of the Midwest U.S.; National Climate Assessment. U.S. Global Change Research Program, Washington, DC.

La Sorte, F.A. and F.R. Thompson. 2007. Poleward shifts in winter ranges of North American birds. Ecology 88: 1803-1812.

Lamon, E.C. and C.A. Stow. 2010. Lake Superior water level fluctuation and climatic factors: A dynamic linear model analysis. Journal of Great Lakes Research 36: 172-178.

Lenarz, M.S., M.E. Nelson, M.W. Schrage, and A.J. Edwards. 2009. Temperature mediated moose survival in northeastern Minnesota. Journal of Wildlife Management 73: 503-510.

Lenters, J.D. 2001. Long-term trends in the seasonal cycle of Great Lakes water levels. Journal of Great Lakes Research 27: 342-353.

Littell, J.S., D. McKenzie, D.L. Peterson, and A.L. Westerling. 2009. Climate and wildfire area burned in western U.S. ecoprovinces, 1916–2003. Ecological Applications 19: 1003-1021.

Lofgren, B.M., F.H. Quinn, A.H. Clites, R.A. Assel, A.J. Eberhardt, and C.L. Luukkonen. 2002. Evaluation of potential impacts on Great Lakes water resources based on climate scenarios of two global circulation models. Journal of Great Lakes Research 28: 537-554.

Lynch, A.J., W.W. Taylor, and K.D. Smith. 2010. The influence of changing climate on the ecology and management of selected Laurentian Great Lakes fisheries. Journal of Fish Biology 77: 1764-1782.

MacKay, M. and F. Seglenieks. early. On the simulation of Laurentian Great Lakes water levels under projections of global climate change. Climatic Change. doi:10.1007/s10584-012-0560-z.

Mitchell, T.D. and P.D. Jones. 2005. An improved method of constructing a database of monthly climate observations and associated high-resolution grids. International Journal of Climatology 25: 693-712.

Murray, D.L., K.F. Hussey, L.A. Finnegan, S.J. Lowe, G.N. Price, J. Benson, K.M. Loveless, K.R. Middel, K. Mills, D. Potter, A. Silver, M.J. Fortin, B.R. Patterson, and P.J. Wilson. 2012. Assessment of the status and viability of a population of moose (Alces alces) at its southern range limit in Ontario. Canadian Journal of Zoology 90: 422-434.

Myers, P., B.L. Lundrigan, S.M.G. Hoffman, A.P. Haraminac, and S.H. Seto. 2009. Climate-induced changes in the small mammal communities of the Northern Great Lakes Region. Global Change Biology 15: 1434-1454.

Ng, C.A. and K. Gray. 2011. Forecasting the effects of global change scenarios on bioaccumulation patterns in Great Lakes species. Global Change Biology 17: 720-733.

Post, E., R.O. Peterson, N.C. Stenseth, and B.E. McLaren. 1999. Ecosystem consequences of wolf behavioural response to climate. Nature 401: 905-907.

Tabor, K. and J.W. Williams. 2010. Globally downscaled climate projections for assessing the conservation impacts of climate change. Ecological Applications 20: 554-565.

Trumpickas, J., B.J. Shuter, and C.K. Minns. 2009. Forecasting impacts of climate change on Great Lakes surface water temperatures. Journal of Great Lakes Research 35: 454-463.

Walker, K.V., M.B. Davis, and S. Sugita. 2002. Climate change and shifts in potential tree species range limits in the Great Lakes region. Journal of Great Lakes Research 28: 555-567.

Wilmers, C.C., E. Post, R.O. Peterson, and J.A. Vucetich. 2006. Predator disease out-break modulates top-down, bottom-up and climatic effects on herbivore population dynamics. Ecology Letters 9: 383-389.

Woodall, C.W., C.M. Oswalt, J.A. Westfall, C.H. Perry, M.D. Nelson, and A.O. Finley. 2009. An indicator of tree migration in forests of the eastern United States. Forest Ecology and Management 257: 1434-1444.