Dynamically Downscaled Projections of Lake-Effect Snow in the Great Lakes Basin

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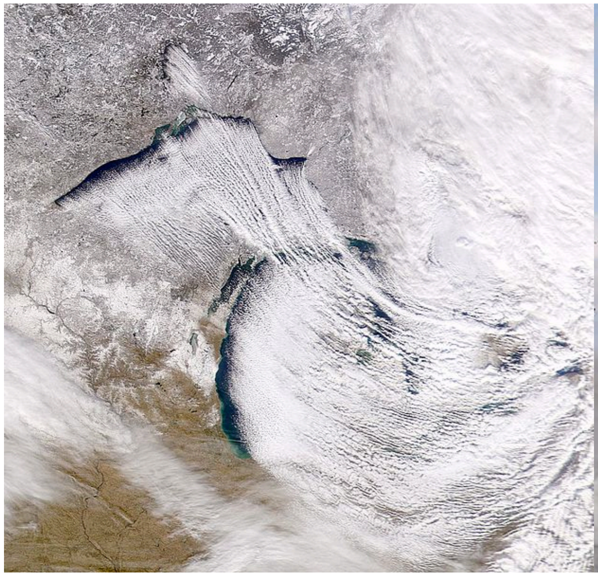


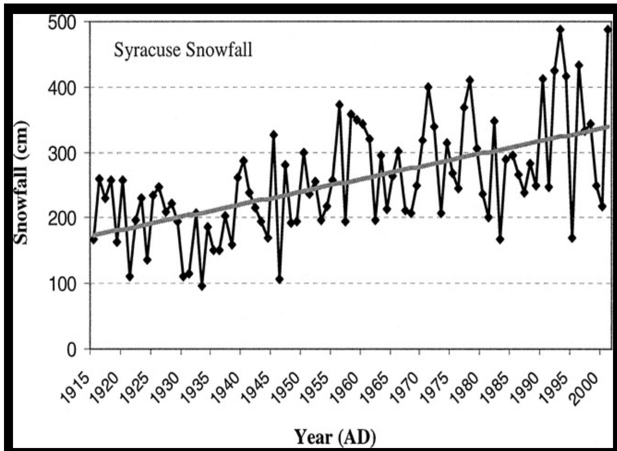
Key Questions

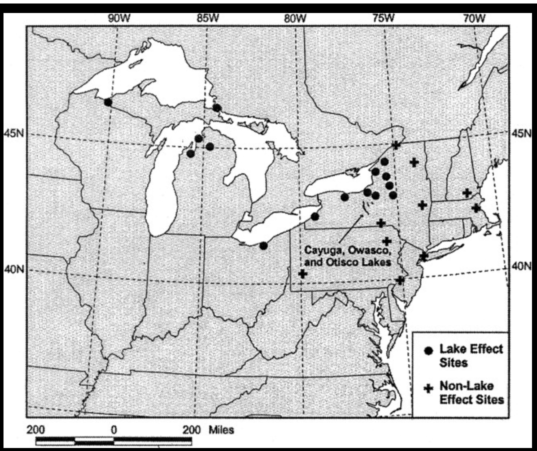
How well can RegCM4, coupled to an interactive 1D lake model, reproduce the spatial and temporal variability in lake-effect snow, lake ice, and additional climatic variables across the Great Lakes Basin? Is it trustworthy for future projections?

How will climate change impact the occurrence of heavy lake-effect snowstorms in the basin during the 21st century? Will warming lead to less snow, or will diminished lake ice support greater snow?

Historic Trends in Lake-Effect Snow

Observations have indicated a long-term positive trend in lake-effect snowfall within the Great Lakes Basin, likely due to warming lake surfaces and declining ice cover (Leathers and Ellis 1996; Burnett et al. 2003; Ellis and Johnson 2004; Kunkel et al. 2009).

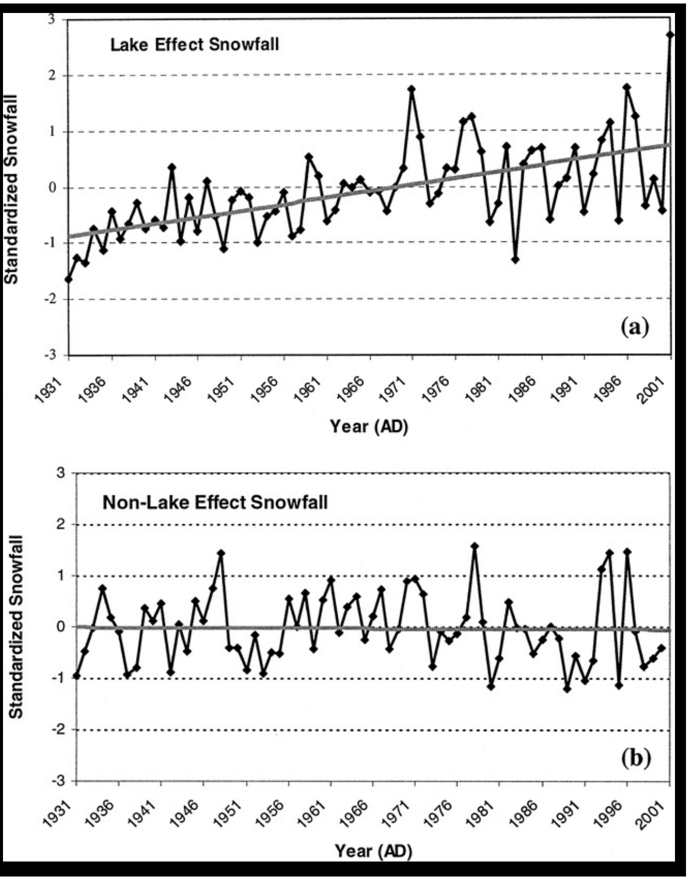




Burnett et al. (2003)

Annual snowfall in Syracuse, NY has doubled.

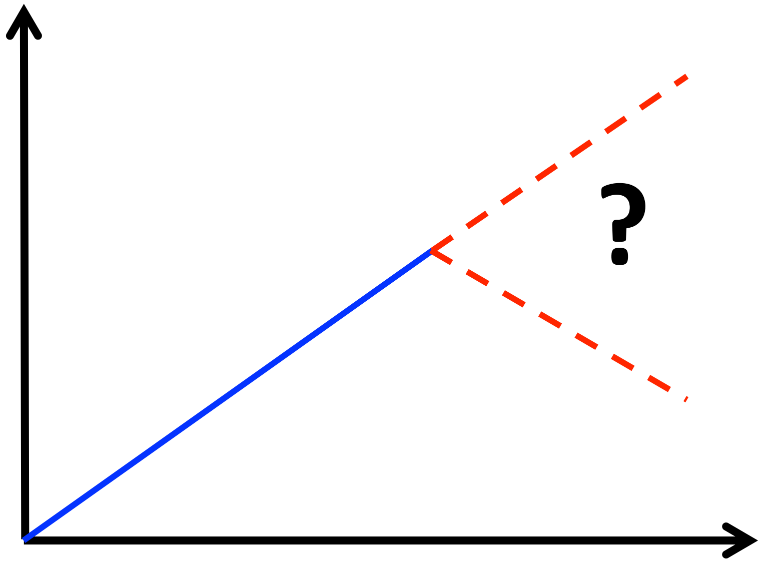
Annual snowfall has exhibited a positive trend at lake-effect site and no trend at non-lake-effect sites.



Opposing Hypotheses: Future of Lake-Effect Snow

Hypothesis 1

The observed positive trend in lake-effect snowfall will persist, as lake ice cover continues to decline in response to warming and lake evaporation increases, providing moisture to lake-effect episodes.



Hypothesis 2

The positive trend in lake-effect snowfall will reverse as extreme cold air outbreaks, which are key triggers of lake-effect snowstorms, become less common in response to anthropogenic climate change. According to a study by Vavrus et al. (2006) of CMIP3 global climate models, extreme cold-air outbreaks into North America are projected to decline in frequency by 74% (87%) by the mid- (late) 21st century.

International Centre for Theoretical Physics Regional Climate Model Version 4 (ICTP RegCM4) (Giorgi et al. 2012)

25-km grid spacing, 15 grid cell buffer zone

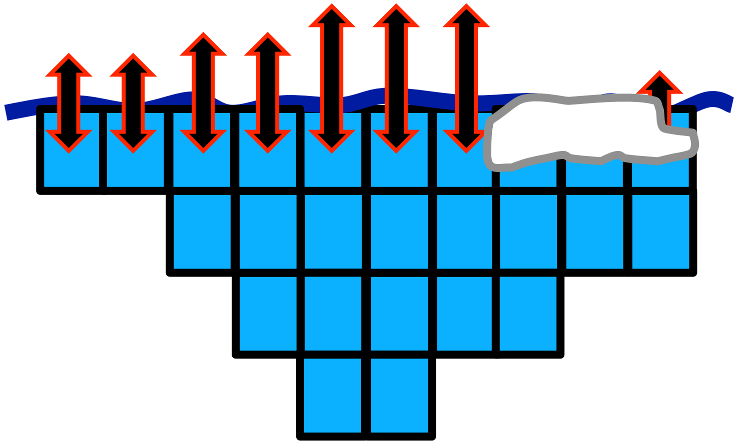
Interactively coupled to 1D energy-balance lake model (Hostetler and Bartlein 1990), with a lake ice submodel (Patterson and Hamblin 1988; Hostetler 1991)

Does not consider horizontal heat transfer between neighboring lake points

Vertical resolution of lake model is 1 m, with spatially-varying bathymetry

Historical simulation: May 1975-December 2002
Lateral boundary conditions: NCEP-NCAR Reanalysis and UK Met Office GISST

GCM-forced simulations:
1980-1999, 2040-2059, 2080-2099



Lateral boundary conditions:
CMIP5 (CNRM-CM5, MIROC5) – RCP8.5
(selected due to performance, resolution, and range of projected warming)

Evaluation of Historical Reanalysis-Forced Simulation

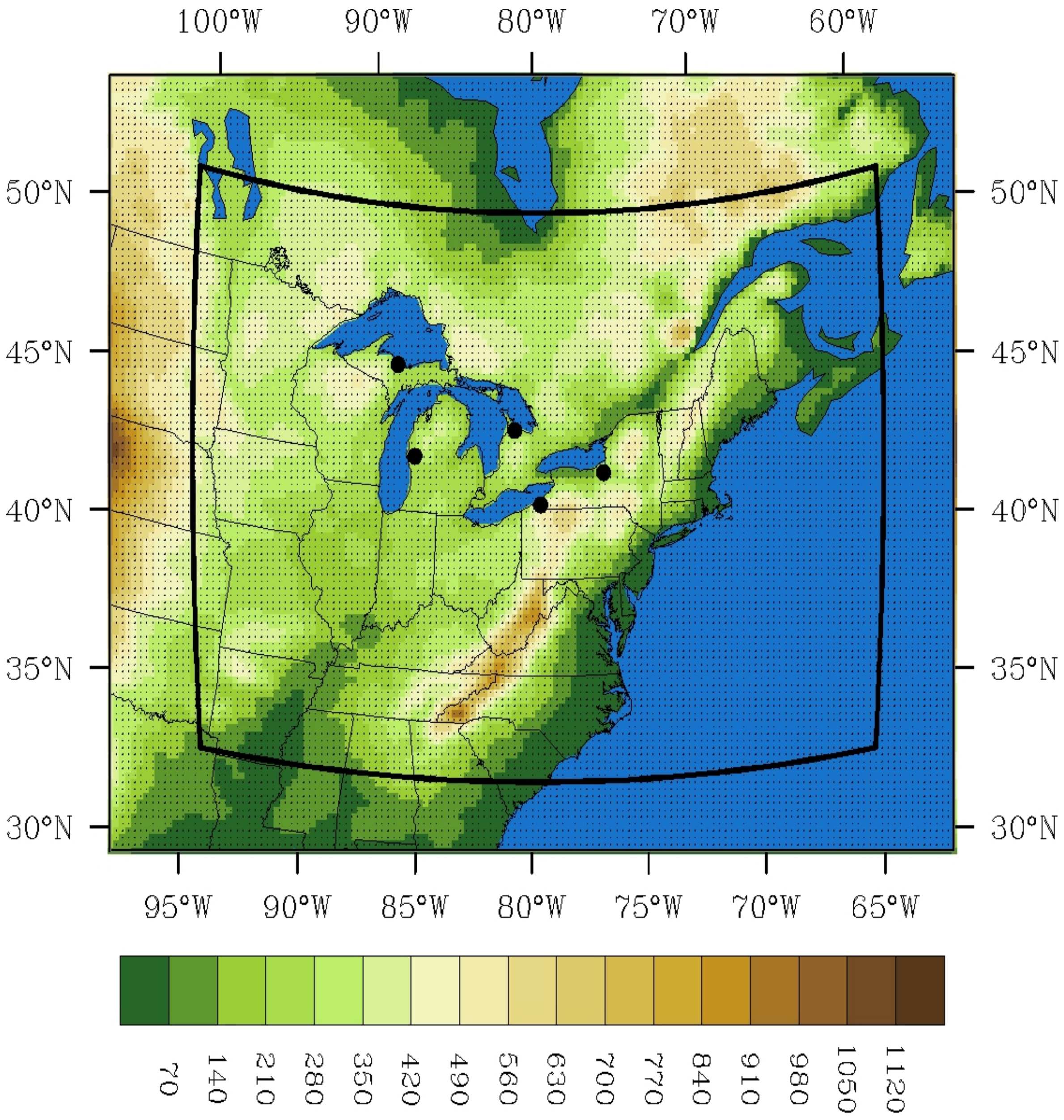
Shading = Elevation (m)

Small dots = 25-km grid

Great Lakes = 410 grid cells

20-30 km horizontal resolution permits a successful simulation of lake-effect snow at meso-beta scale (Hjelmfelt and Braham 1983; Warner and Seaman 1990; Sousounis and Fritsch 1994; Ballentine et al. 1998)

Domain for Reanalysis-Forced Simulation



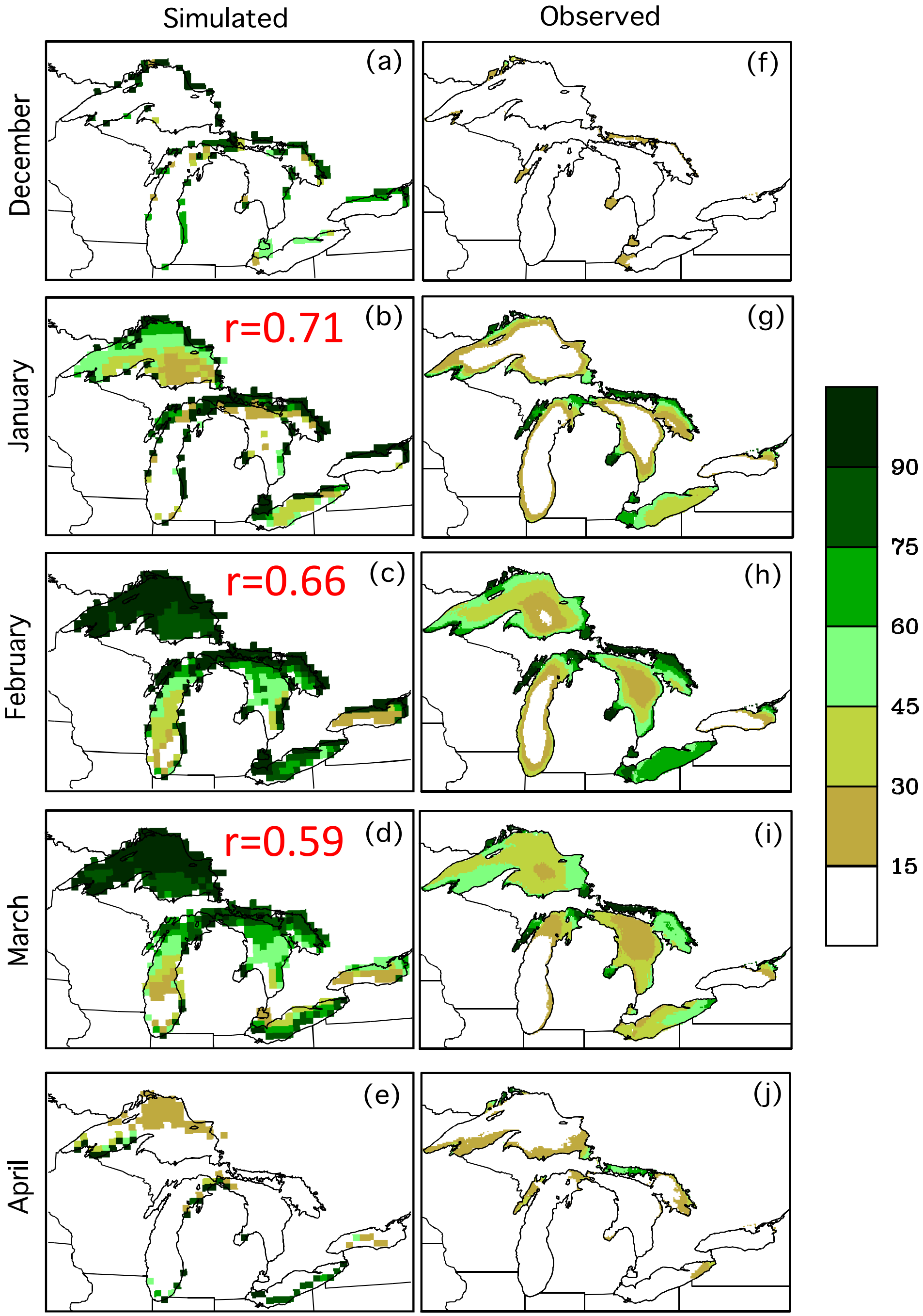
Mean simulated and observed % ice cover across Great Lakes for DJFMA 1977-2002

Model: RegCM4

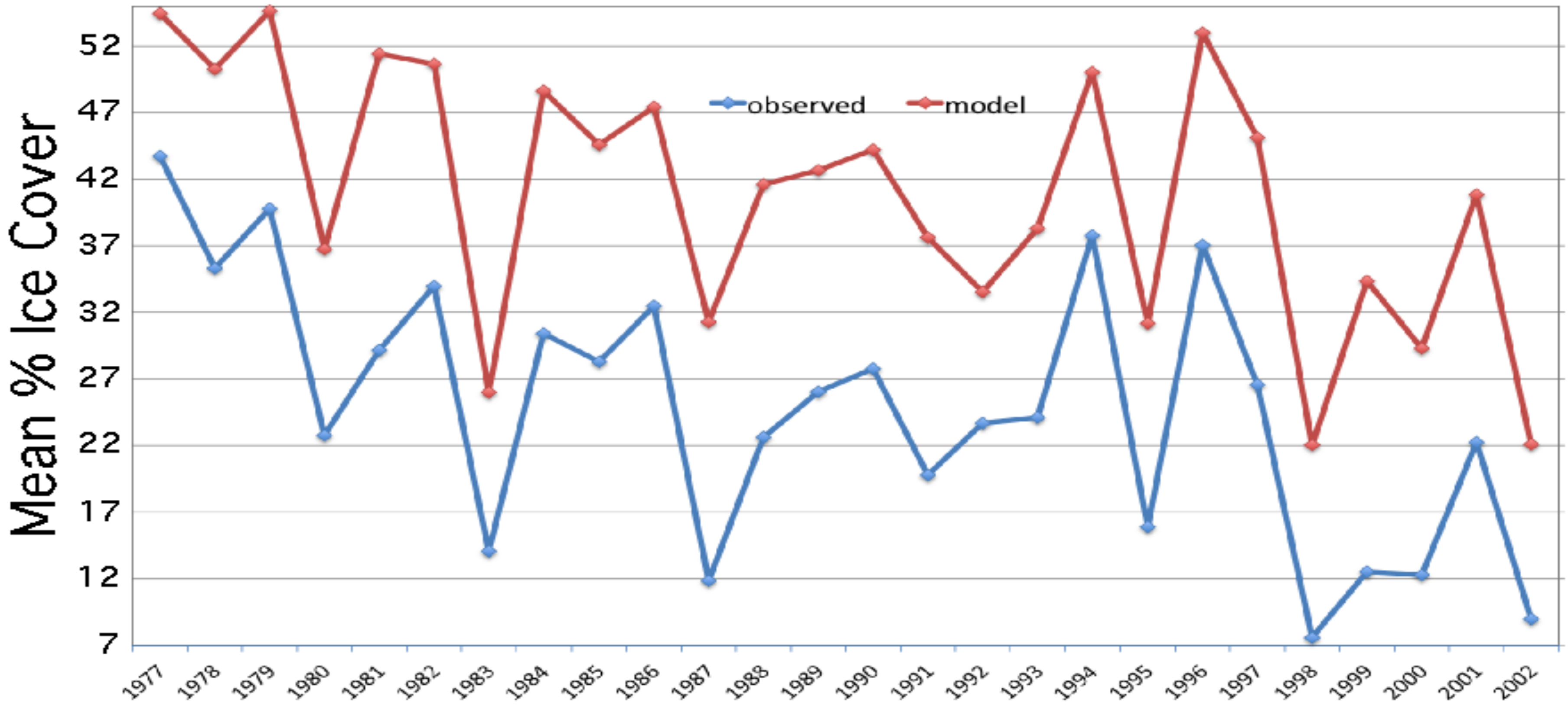
Obs: NOAA Great Lakes Ice Atlas

RegCM4 produces a fair representation of spatial distribution and seasonal evolution of Great Lakes ice cover (Notaro et al. 2013).

The absence of horizontal mixing and ice movement in the lake model causes an excessive and overly-persistent ice cover, with ice developing too early.



Dec-May Percent Ice Cover



Blue = Observed
(NOAA Great Lakes Ice Atlas)

Red = RegCM4

r = 0.95

Observed trend = -0.75%/year
Simulated trend = -0.70%/year

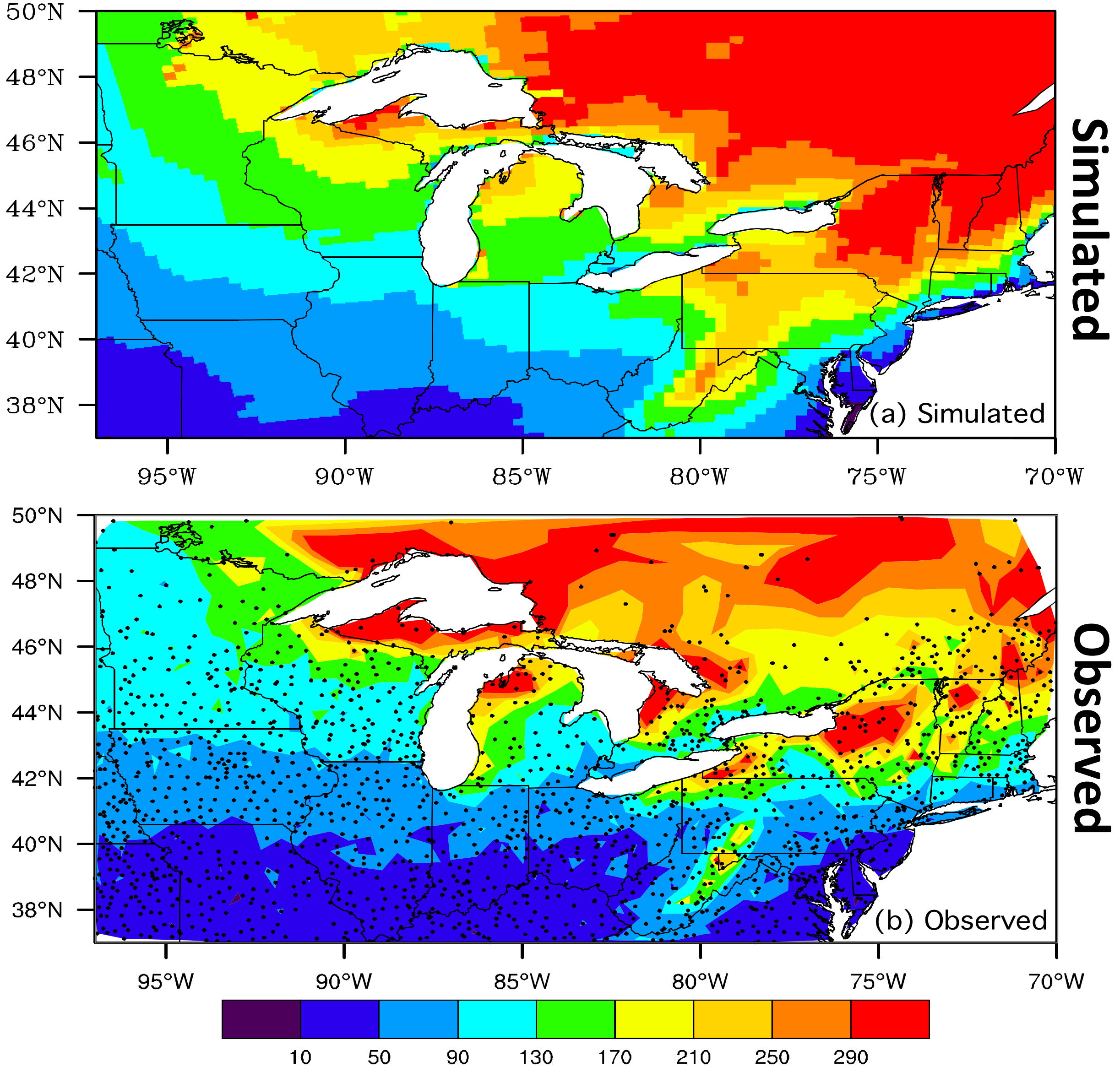
Despite its excess ice cover bias, RegCM4 accurately captures year-to-year fluctuations in Great Lakes' % ice cover.

Mean Annual Snowfall (cm) for 1976-2002

Spatial r = 0.81
(n=2880 stations)

Model bias = +26%

All of the major lake-effect snow regions, in excess of 250 cm, are captured by the model.

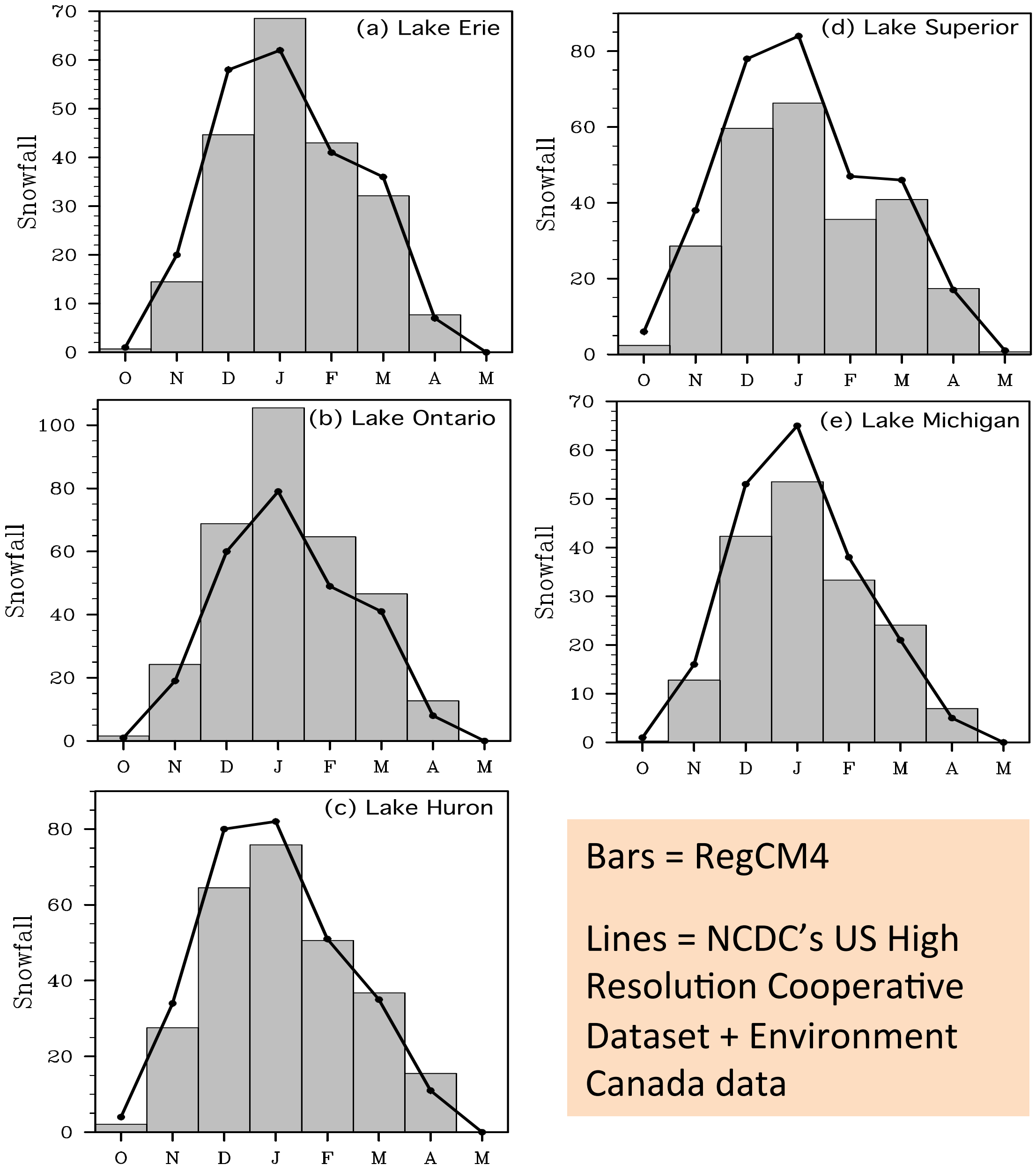


Obs: US High Resolution Cooperative Dataset from NCDC
+ data from Environment Canada

Seasonal Cycle of Monthly Mean Snowfall (cm) Downstream of Each Lake During 1976-2002

Observed and simulated snowfall downstream of the Great Lakes is greatest during early winter (Jan). By Feb, ice cover is most extensive, thereby reducing lake-effect snowfall.

Biases in simulated seasonal snowfall downwind of lakes ranges from -21% for Superior to +27% for Ontario.

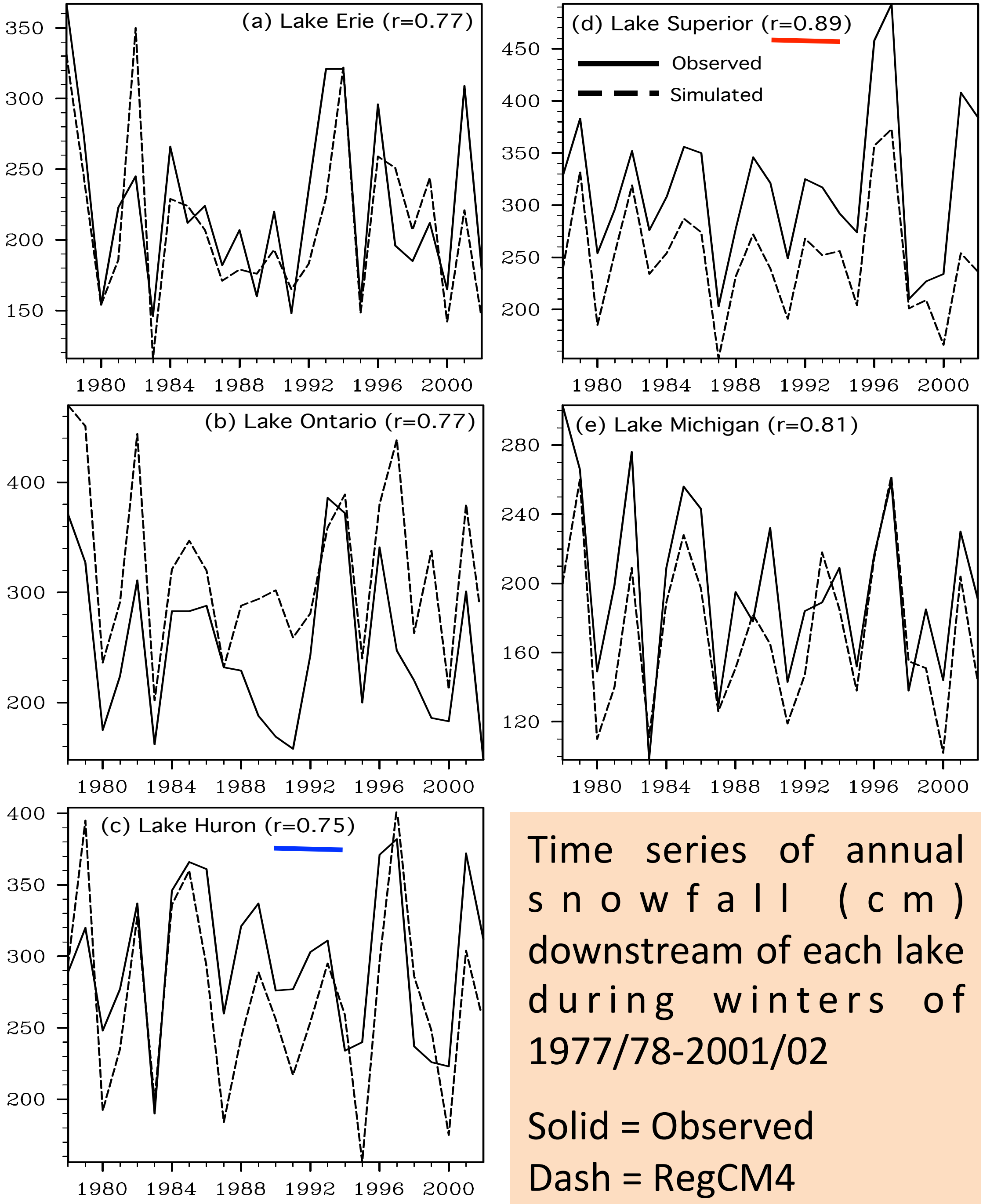


Bars = RegCM4

Lines = NCDC's US High Resolution Cooperative Dataset + Environment Canada data

RegCM4 reproduces much of the interannual variability in annual snowfall downwind of the Great Lakes.

Temporal correlations range from 0.75 for Huron to 0.89 for Superior.



Time series of annual snowfall (cm) downstream of each lake during winters of 1977/78-2001/02

Solid = Observed

Dash = RegCM4

CRITERIA FOR SIMULATED HEAVY LAKE-EFFECT SNOWSTORMS IN RCM

LOCATION
Grid cell must be located over land and within 100-km of one of the Great Lakes' shorelines. (Dewey 1979; Eichenlaub 1979)

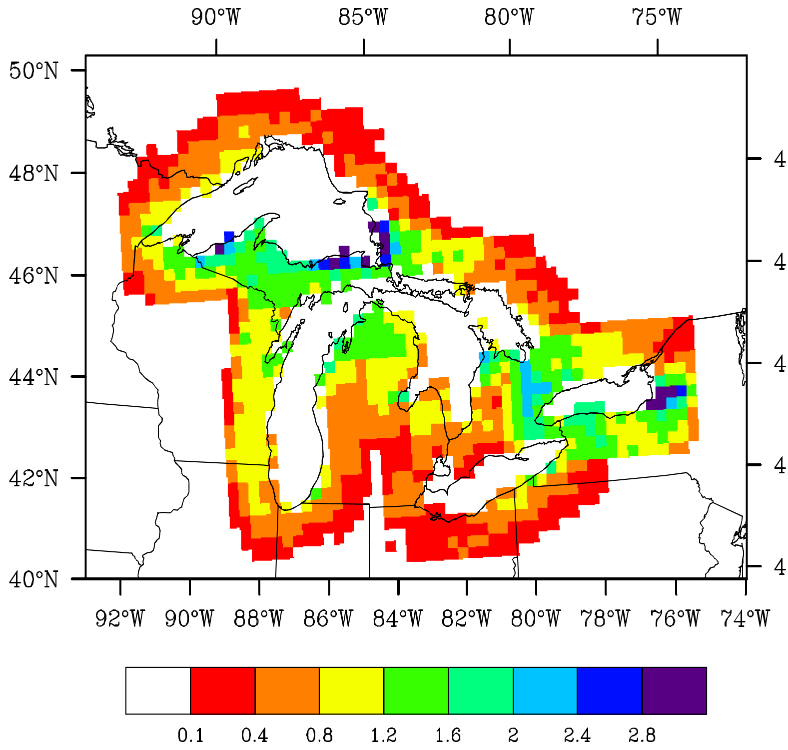
WIND
For at least 6 hours, the mean 10-m wind direction must be off one of the lakes, allowing for sufficient fetch (Kunkel et al. 2002)

ICE
The ice cover fraction on the lake, off which the wind is flowing, must be less than 70% (Gerbush et al. 2008)

AMOUNT
Local daily snowfall must be at least 10 cm (Liu and Moore 2004)

ENHANCEMENT
Local, near-lake daily snowfall must exceed the mean non-local/continental snowfall, far from the lake, by at least 4 cm (Kunkel et al. 2002)

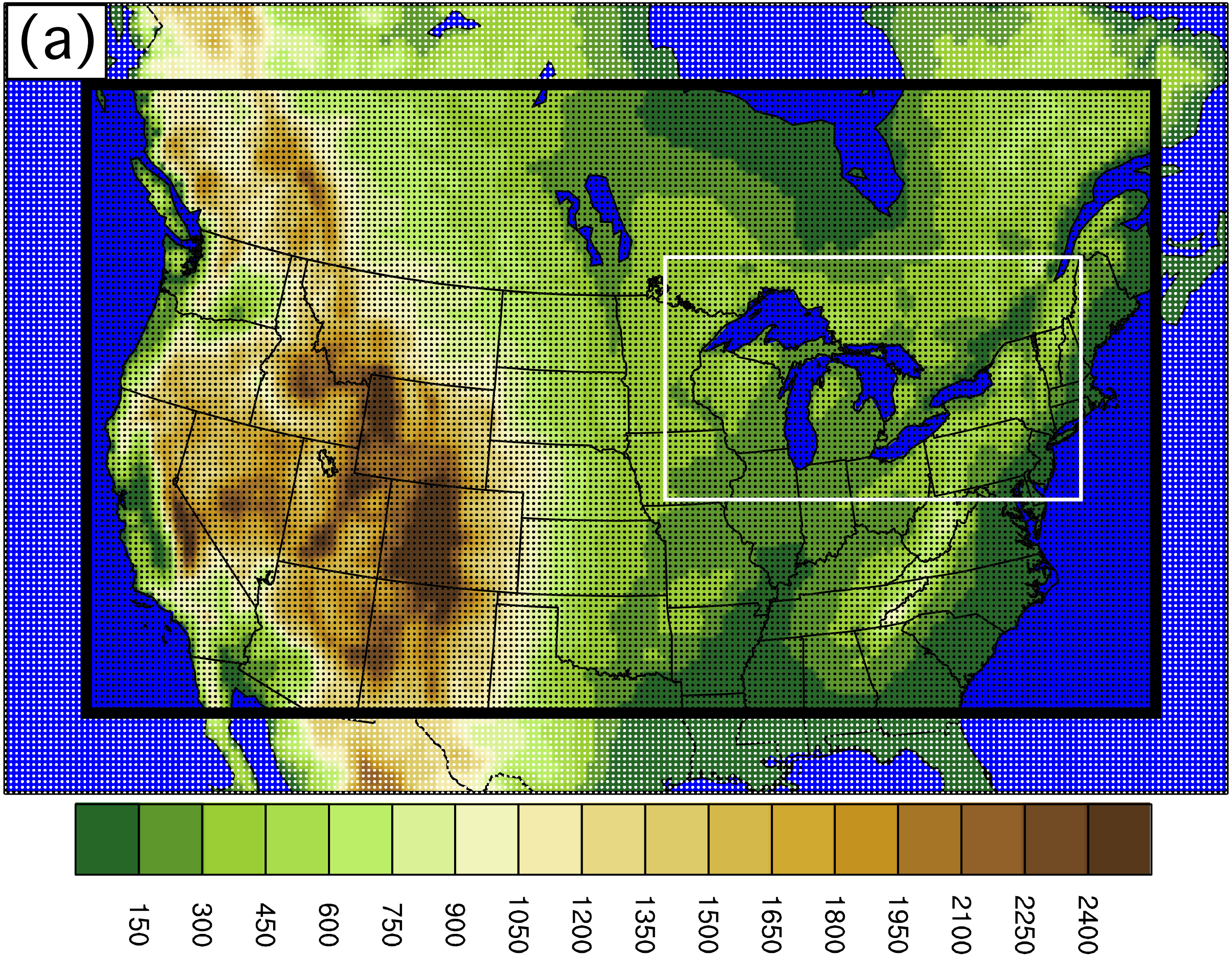
Mean # of Simulated Heavy Lake-Effect Snowfall Days Per Year During 1976-2002



This definition of heavy-lake effect snowstorms was applied to the 1976-2002 simulation across the Great Lakes Basin to estimate the mean annual frequency of heavy lake-effect snowstorms.

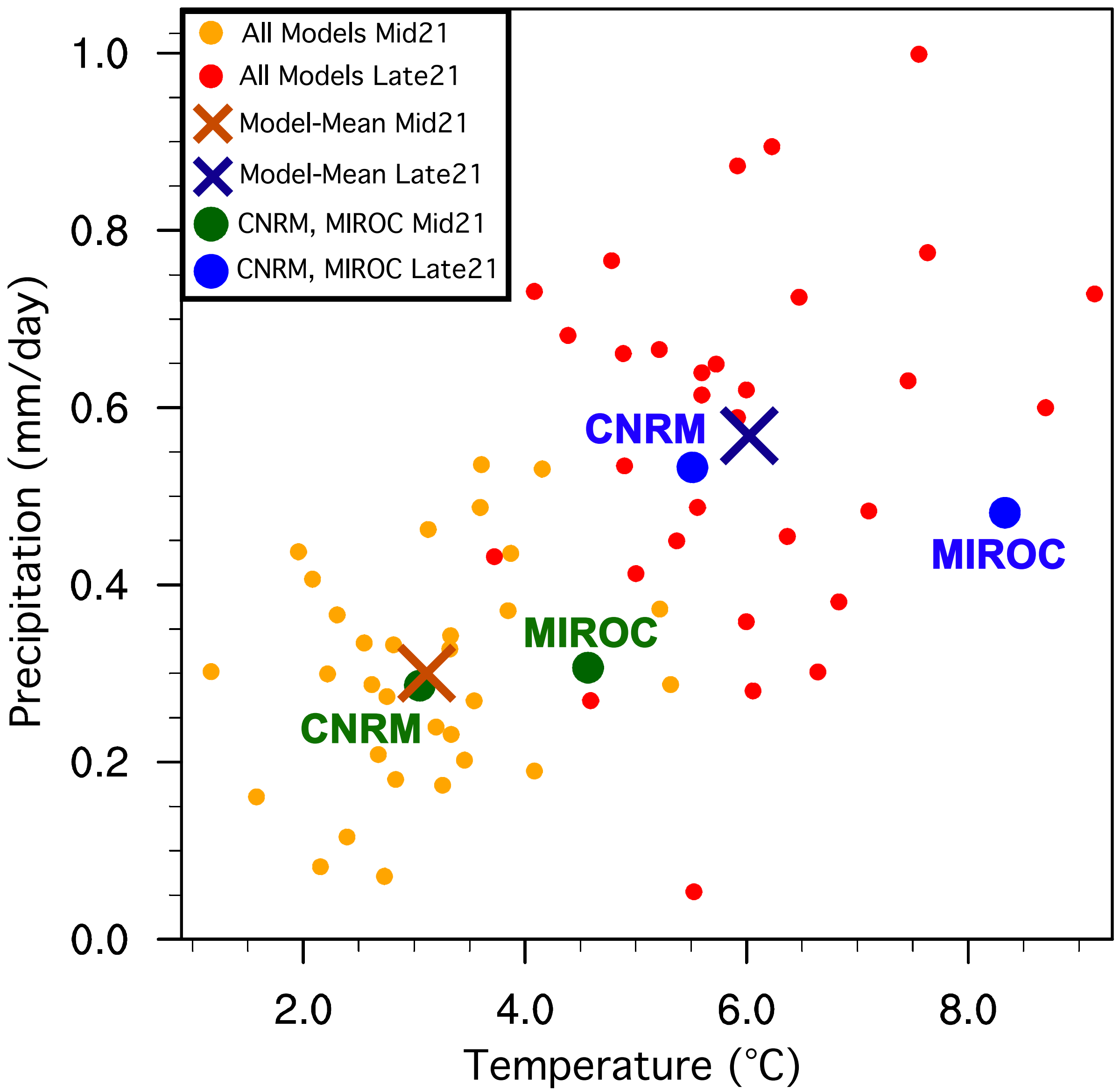
Future CMIP5-Forced Simulations

DOMAIN WITH ELEVATION (m)



Expanded domain
25-km grid spacing, 15 grid cell buffer zone, linear relaxation scheme

Projected Change in Dec-May 2-m Air Temperature (°C) and Precipitation (mm/day) Across Great Lakes Region over Land from CMIP5 GCMs



Projections by mid-21st century

T Mean: +3.1°C

T Range: +1.2°C to +5.3°C

P Mean: +0.30 mm/d

P Range: +0.07 to +0.54 mm/d

CNRM: +3.1°C, +0.29 mm/d

MIROC5: +4.6°C, +0.31 mm/d

Projections by late 21st century

T Mean: +6.0°C

T Range: +3.7°C to +9.1°C

P Mean: +0.57 mm/d

P Range: +0.05 to +1.00 mm/d

CNRM: +5.5°C, +0.53 mm/d

MIROC5: +8.3°C, +0.48 mm/d

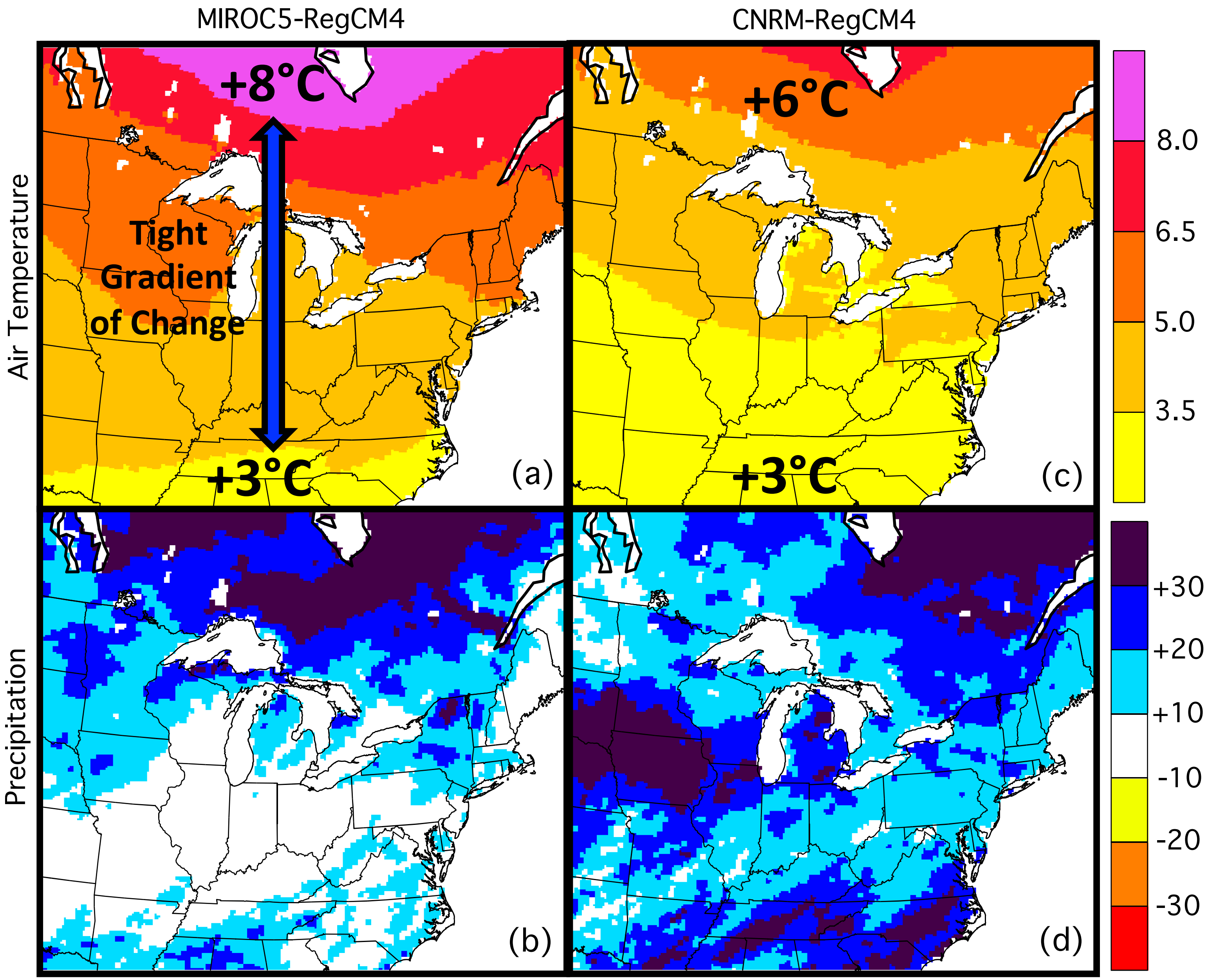
Projected Change in NDJFM Air Temperature (°C) and Precipitation (%) (Late 21st-Late 20th)

MIROC5-RegCM4: Great Lakes Basin is projected to warm by 4-7°C, from south to north

CNRM-RegCM4: Great Lakes Basin is projected to warm about 4°C

The entire domain is projected to become wetter in both models, including downwind of the lakes.

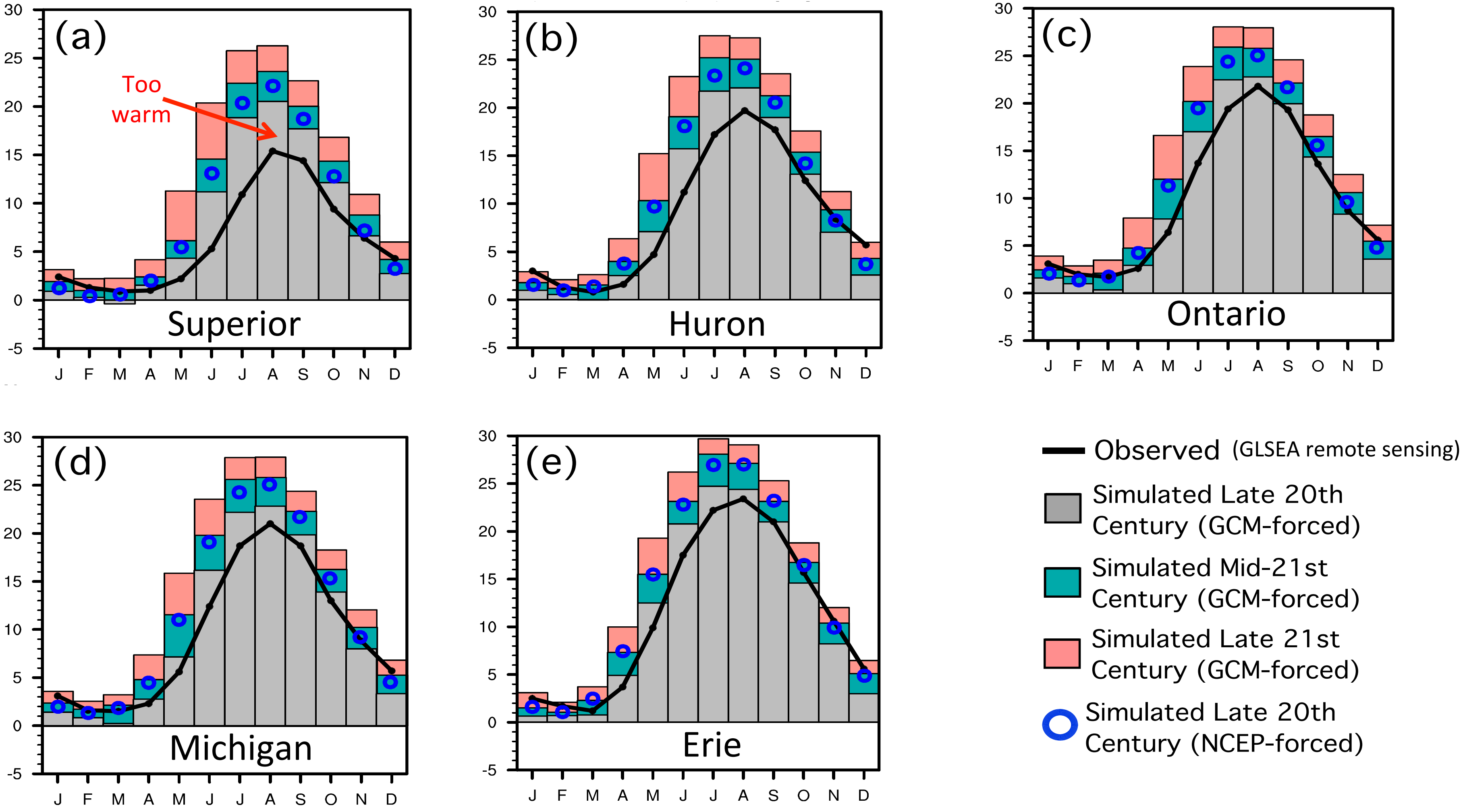
Greater lake-effect precipitation due to increased lake evaporation and fetch (dynamical).



Feb: 10-30% increases downwind of lakes

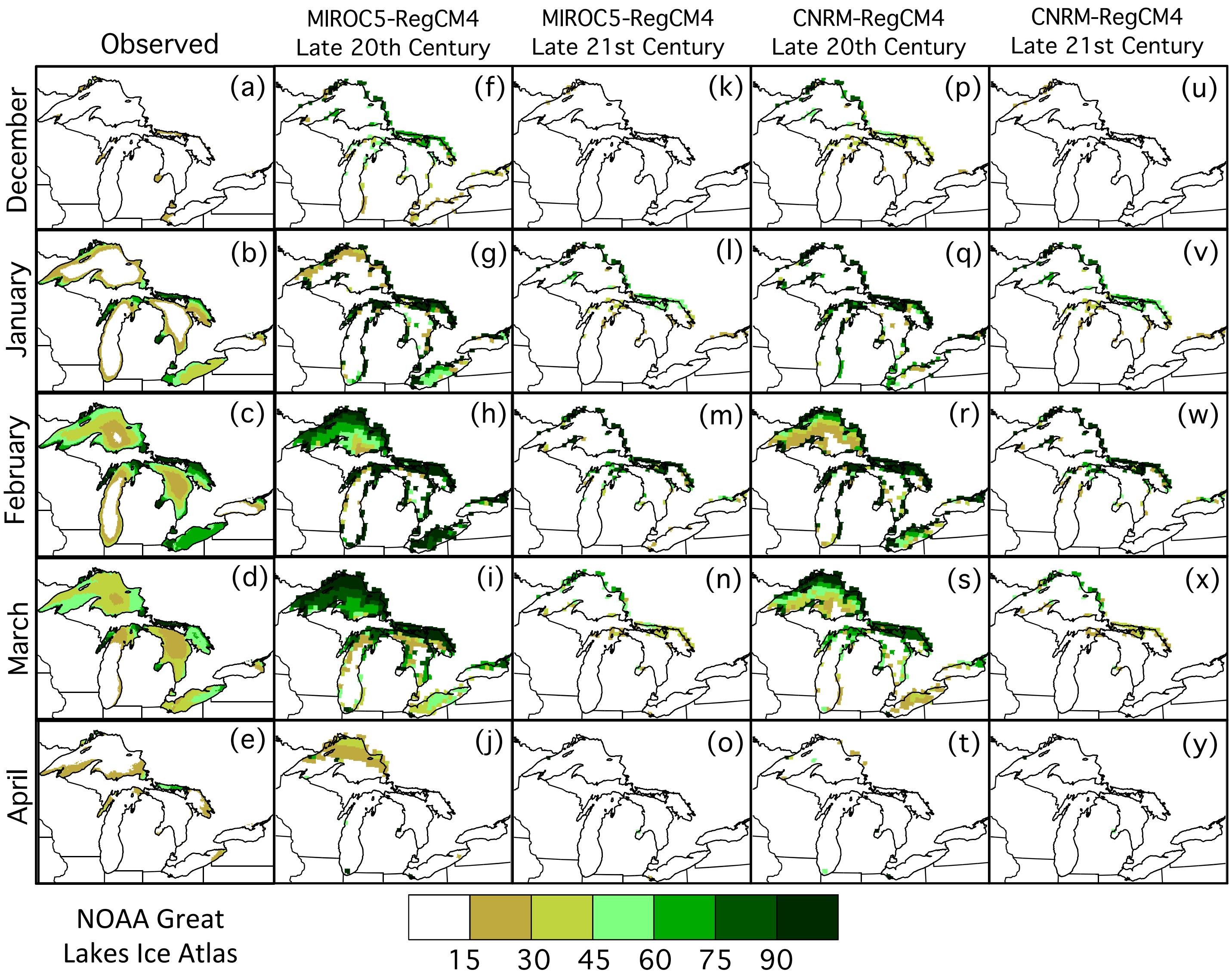
Dec, Mar: 10-30% increases downwind of lakes

Seasonal Cycle of Lake Surface Temperatures (LSTs): MIROC5-RegCM4



Annual projected increases in LST:
By mid-21st century = +2.0°C for Superior to +2.4°C for Michigan
By late 21st century = +4.1°C for Erie to +4.6°C for Michigan
Large late spring-early summer increase in LST = earlier stratification

Mean Percent Ice Cover

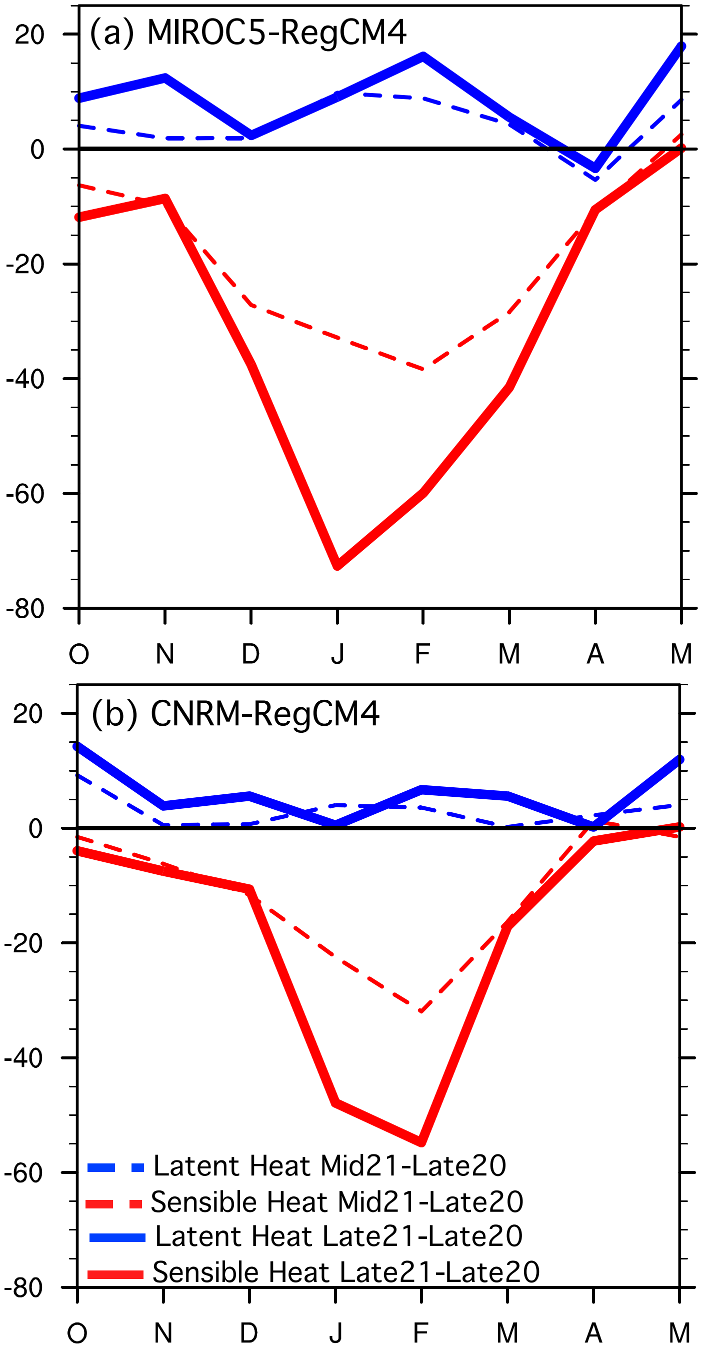


NOAA Great Lakes Ice Atlas

During late 20th century, in both model & observations, ice develops along shallow shores in Dec and becomes most extensive in Feb-Mar, with the greatest ice cover over Superior (coldest area) and Erie (shallowest).

By late 21st century, ice becomes primarily restricted to northern shores, leaving most of the lakes as open water even in mid-winter, with ice only typically developing during Jan-Mar.

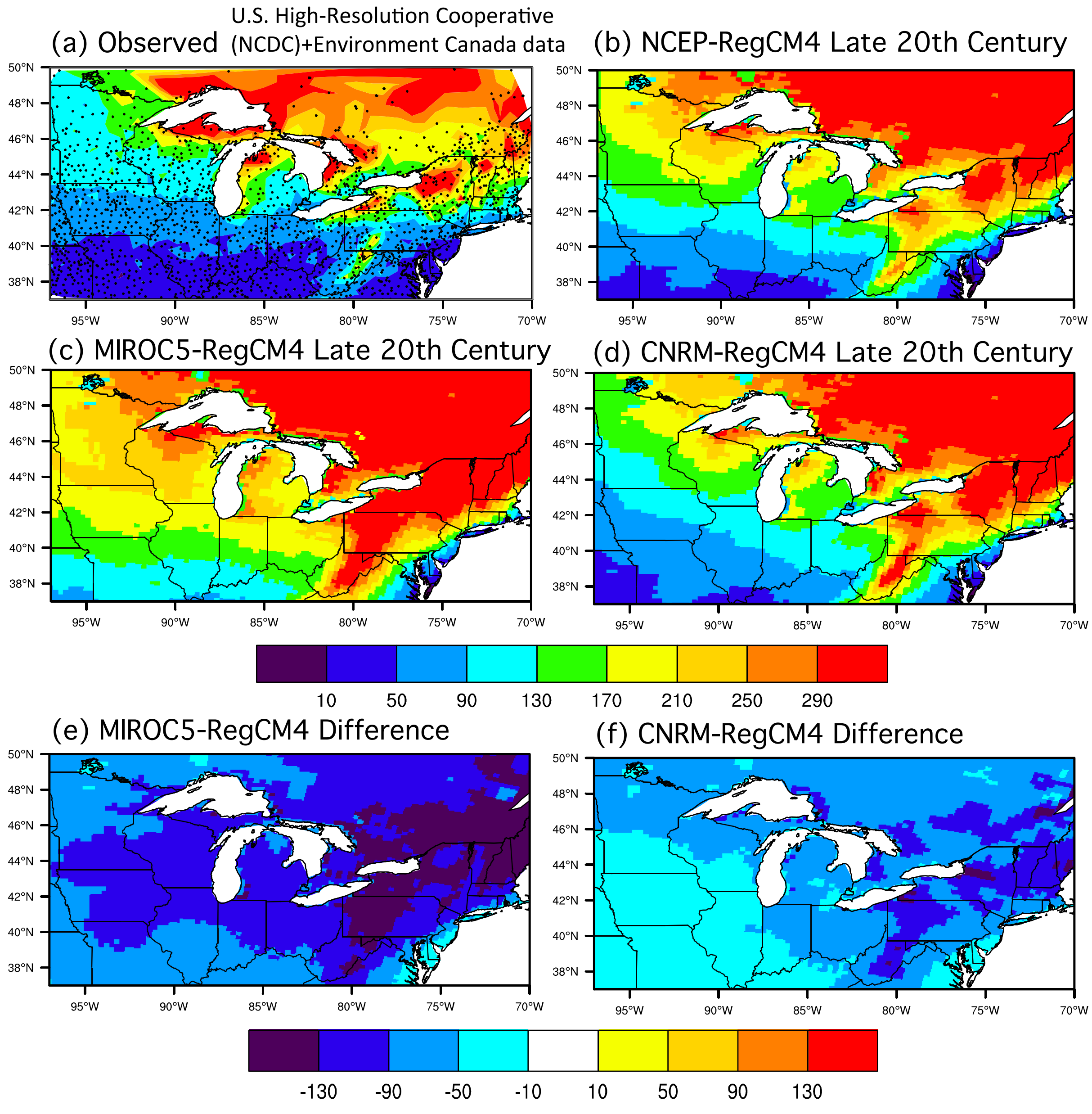
Seasonal Cycle of Projected Change in Mean Over-Lake Sensible and Latent Heat Fluxes (W/m²) for Great Lakes



In response to declining ice cover and enhanced wind speed, lake evaporation increases during 21st century during Oct-May, which supports greater total lake-effect precipitation. LH fluxes during Oct-May increase by 5-6 W m^{-2} in CNRM-RegCM4 and 8-10 W m^{-2} in MIROC5-RegCM4.

Given that lower tropospheric air temperature increases more than LST by late 21st century during cold season, SH fluxes greatly diminish, particularly during Jan-Feb and over Superior. Projected reductions in SH flux during Oct-May range from -14 W m^{-2} for Erie to -27 W m^{-2} for Superior in CNRM-RegCM4 and from -22 W m^{-2} for Michigan to -37 W m^{-2} for Superior in MIROC5-RegCM4.

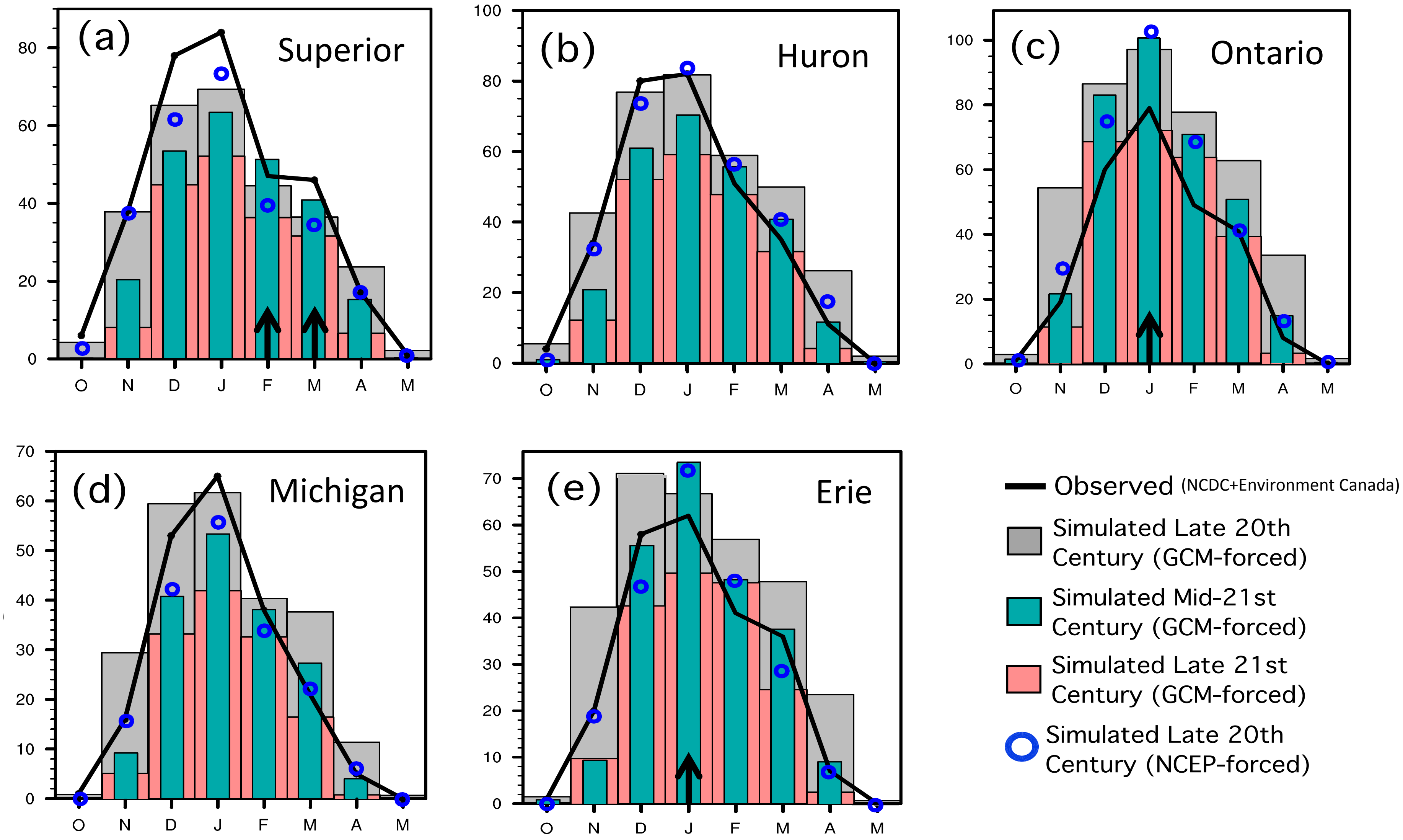
Mean Annual Snowfall (cm)



Annual snowfall is projected to decline across Great Lakes Basin, Midwest, and Northeast U.S. by both mid- and late 21st century, with largest declines by late 21st century across Northeast, exceeding 130 cm in MIROC5-RegCM4 and 90 cm in CNRM-RegCM4.

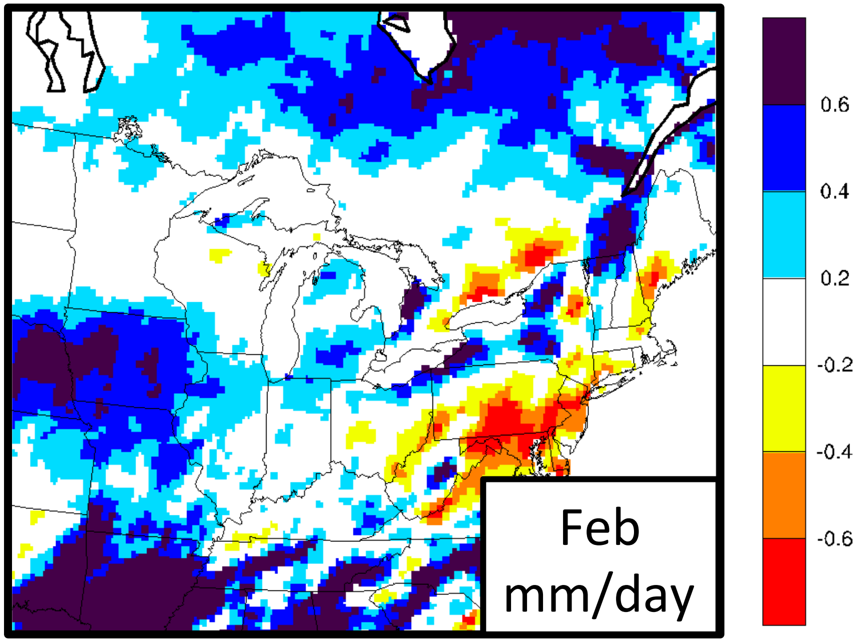
The former model produces greater warming, thereby converting more precipitation into the form of rain.

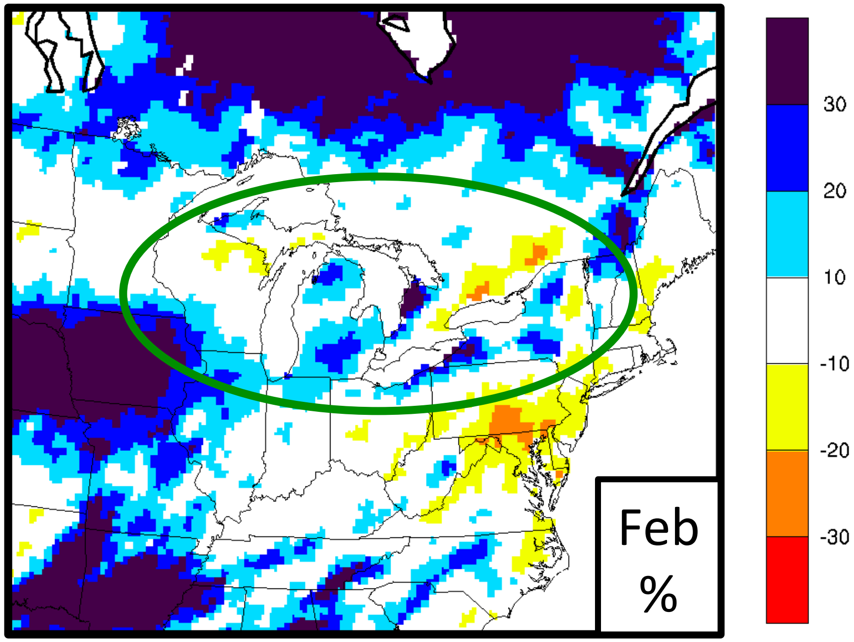
Mean Seasonal Cycle of Monthly Snowfall (cm) Downstream of Each Lake: MIROC5-RegCM4



MIROC-RegCM4 simulates reductions in mean annual snowfall by late 21st century that range from -34% downwind of Superior to -46% downwind of Michigan, with largest reductions in Nov for all lakes. Mid-21st century projections include increased mid-late winter snowfall downwind of Superior in Feb-Mar and Ontario and Erie in Jan by MIROC5-RegCM4, in addition to large snowfall reductions during late autumn-early winter (compressed snow season).

Projected Change in Precipitation (Late 21st-Late 20th): MIROC5-RegCM4



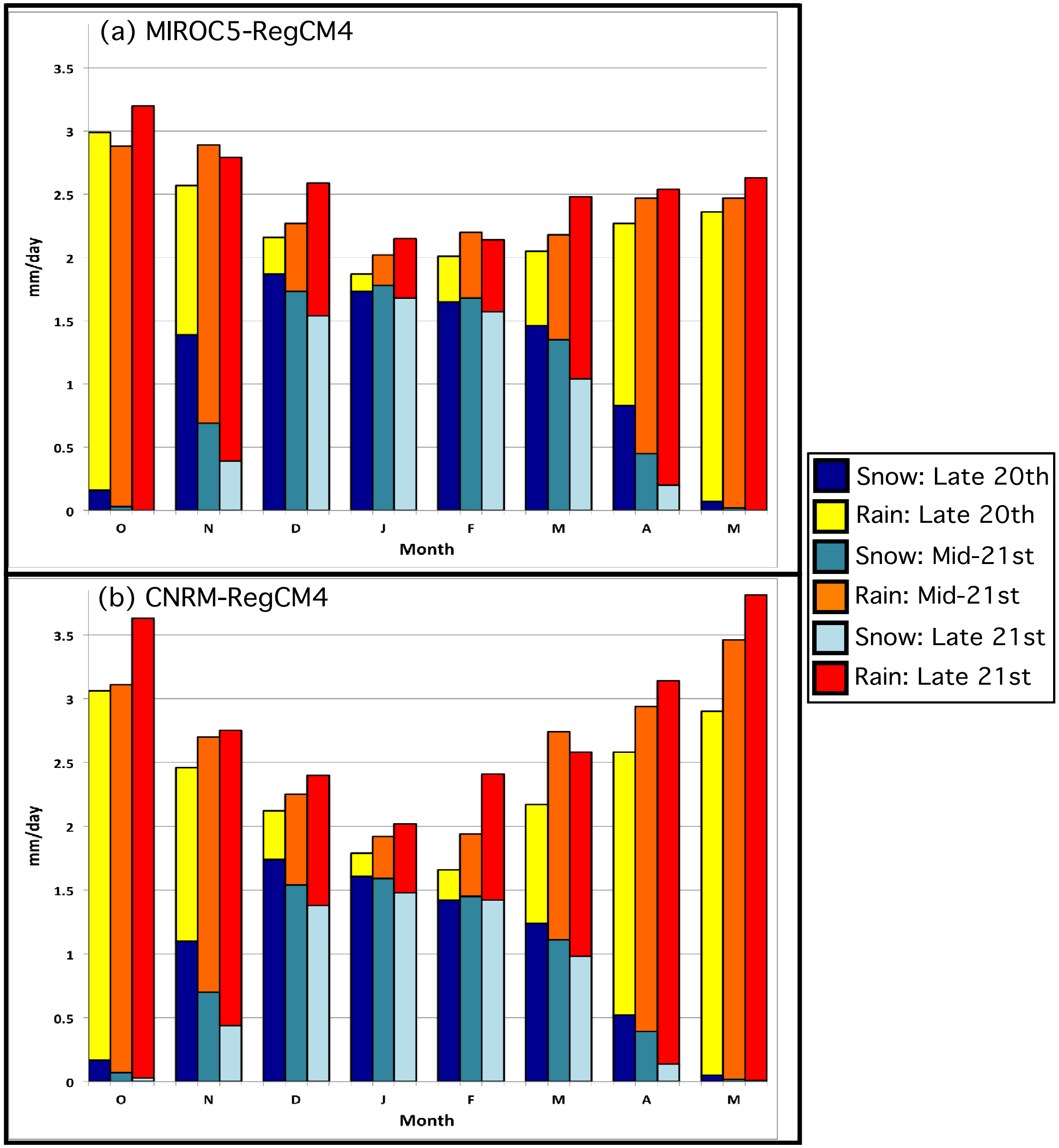


Less ice cover -> Greater evaporation for lake-effect precipitation

Lower pressure over S. Canada -> Stronger NW winds over lakes -> Greater fetch and evaporation for lake-effect precipitation

As a result, total lake-effect precipitation is likely to increase (not necessarily snow though).

Seasonal Cycle of Distribution of Total Precipitation (mm/day) as Rain or Snow in Great Lakes Basin (Land-Only)

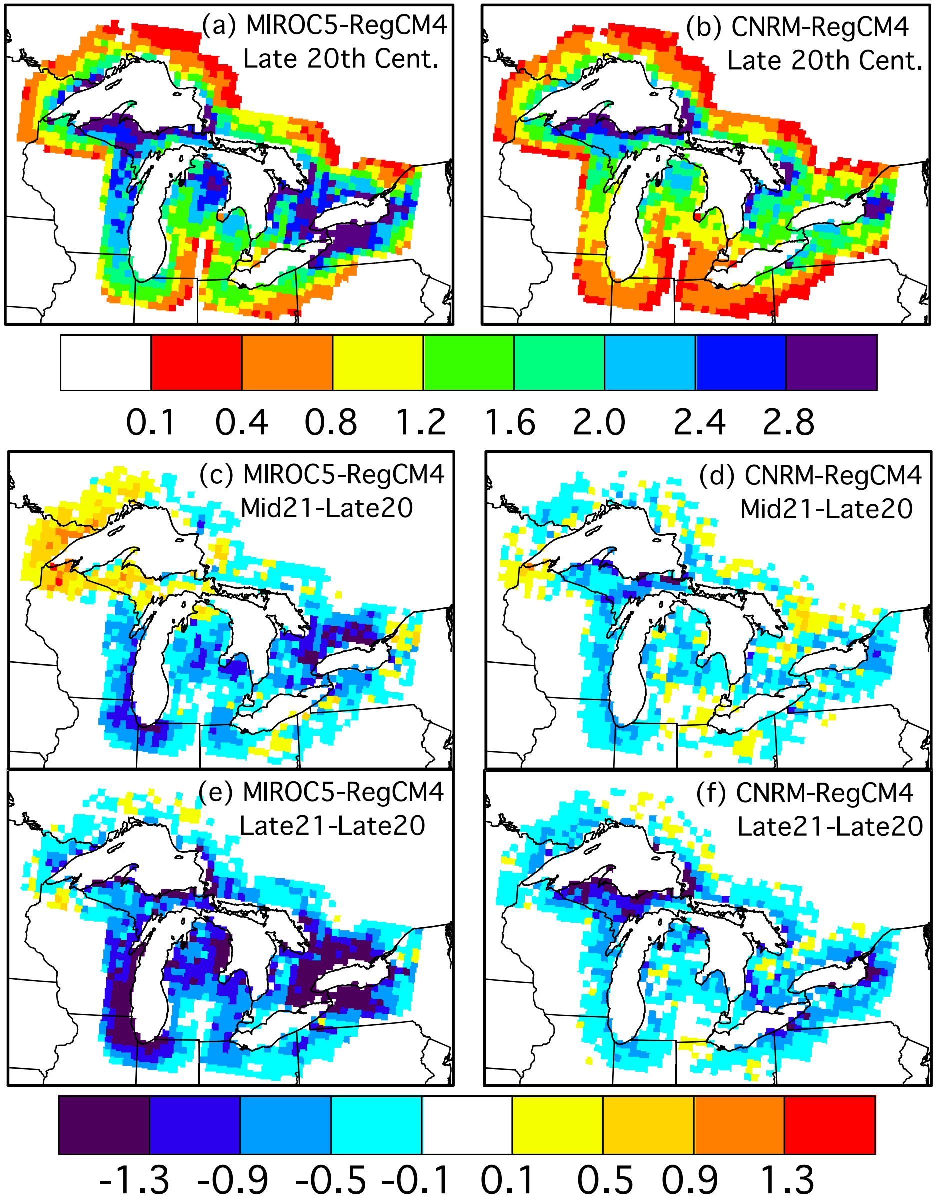


The snow season in Great Lakes Basin is likely to become substantially compressed during 21st century in response to warming.

Annual precipitation is projected by late 21st century to increase by +10% in MIROC5-RegCM4 and +15% in CNRM-RegCM4, with dramatic increases in annual rainfall (+26% in MIROC5-RegCM4, +28% in CNRM-RegCM4) and decreases in annual snowfall (-29% in MIROC5-RegCM4, -25% in CNRM-RegCM4).

By late 21st century, largest percentage declines in probability of falling precipitation occurring as snow are simulated in Nov.

Mean Number of Simulated Heavy Lake-Effect Snowfall Days Per Year



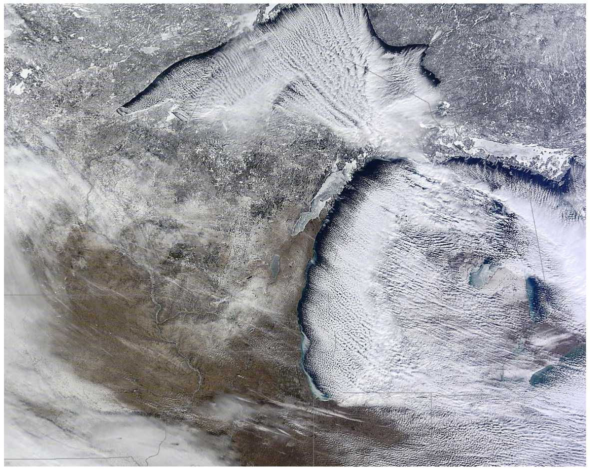
Frequency of heavy lake-effect snow days across Great Lakes Basin is projected to decline by late 21st century by -46% in MIROC5-RegCM4 and -35% in CNRM-RegCM4.

Projections by mid-21st century are less certain around Superior, with MIROC5-RegCM4 simulating an increased frequency of heavy lake-effect snowstorms, where mean snowfall also increases during Feb-Mar, and CNRM-RegCM4 simulating mostly weak reductions in frequency.

Air temperatures are climatologically lowest around Superior, allowing lake-effect precipitation events to continue to fall as snow in mid-winter despite large projected warming.

Declining ice cover, enhanced evaporation, and enhanced fetch support an increase in total lake-effect precipitation, but primarily with a large increase in rainfall and decrease in snowfall.

CONCLUSIONS



In order to assess projected changes in lake-effect snowfall across the Laurentian Great Lakes Basin for the mid- and late 21st century, two CMIP5 global climate models are dynamically downscaled using 25-km RegCM4, interactively coupled to a 1D lake model.

Projected cold-season changes for the basin include:

(1) warming and increased precipitation
(2) rapid loss of Great Lakes' ice cover, with ice becoming confined to the northern shallow lakeshores during mid-late winter
(3) increased evaporation due to reduced ice cover and greater wind fetch
(4) enhanced total lake-effect precipitation, with increased rainfall at expense of snowfall
(5) declining annual snowfall with a compressed snow season
(6) general reduction in the frequency of heavy lake-effect snowstorms, except around Superior by mid-21st century where a greater occurrence is possible.

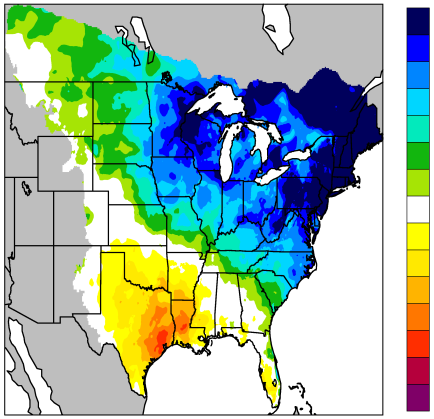
The dynamically downscaled data is also being applied, in conjunction with the NOAA GLERL channel model, to project future changes in Great Lakes' water levels.

Notaro, M., A. Zarrin, S. Vavrus, and Val Bennington, 2013: Simulation of heavy lake-effect snowstorms across the Great Lakes Basin by RegCM4: Synoptic climatology and variability. Monthly Weather Review, 141, 1990-2014.
Notaro, M., V. Bennington, and S. Vavrus, 2014: Dynamically downscaled projections of lake-effect snow in the Great Lakes Basin. J. Climate, in review.

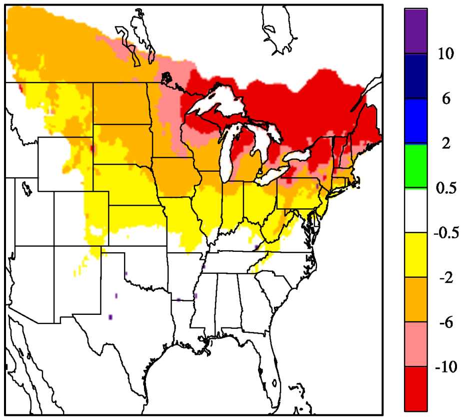
Statistically Downscaled Climate Projections from UW-Madison Center for Climatic Research

A subset of the CMIP3 models have been statistically downscaled to 0.1 degree resolution for the central-eastern North American Landscape Conservation Cooperatives for daily maximum temperature, minimum temperature, and precipitation. This data has also been used to force a snow model to develop projections of daily snowfall, snow depth, and winter severity, with applied studies of the response of regional wildlife (white-tailed deer, dabbling ducks) to changing winter conditions.

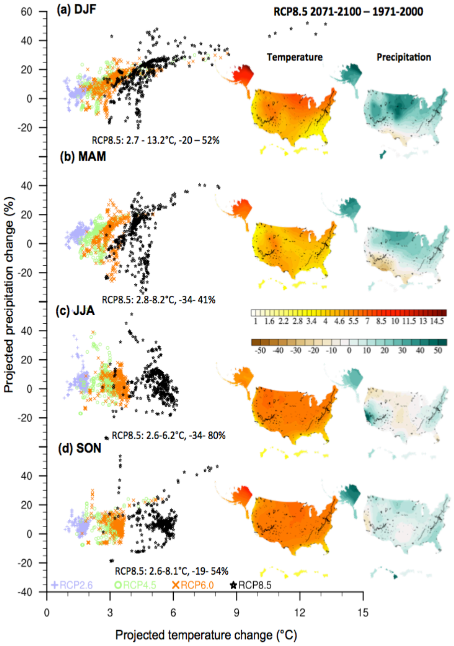
Projected change in
Frequency of 1”+ Precipitation
Days (A2, Late21-Late20)



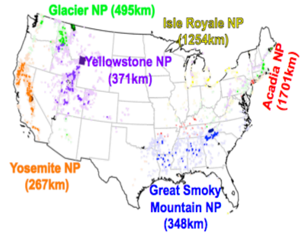
Projected change in Nov-April
snow depth (cm)
(A2, Late21-Late20)



For the purpose of assessing future climate change for the entire set of U.S. national parks, we have applied Bias Correction and Spatial Disaggregation to the full set of CMIP5 GCMs. The statistically downscaled climate projections include monthly-mean maximum and minimum temperature and precipitation across the U.S. fifty states at 800-m spatial resolution. Using this product, we have performed climate velocity and climate dissimilarity analysis for the national parks.



CLIMATE ANALOG



Consistent with our findings regarding climate velocities, the analog distance for parks within mountains regions is shorter than for parks at low elevations.

Collaborators: Jack Williams, Fuyao Wang, Patrick Gonzalez, Dan Vimont