Seasonal, Interannual, and Decadal variability of Great Lakes ice cover: Research and Prediction

Jia Wang

NOAA GLERL and CIGLR, Ann Arbor, MI

In collaboration with

James Kessler, Anne Clites, Haoguo Hu, Brent Lofgren, George Leshkevish, Philip Chu, John Bratton

Great Lakes Conference, MSU, March 6, 2018

Acknowledgements: GLRI for Climate Informatio for Decision Making

GLERL Great Lakes Environmental Research Laboratory

CILER Cooperative Institute for Limnology and Ecosystems Research University of Michigan

Outline

I. Introduction

II. Research

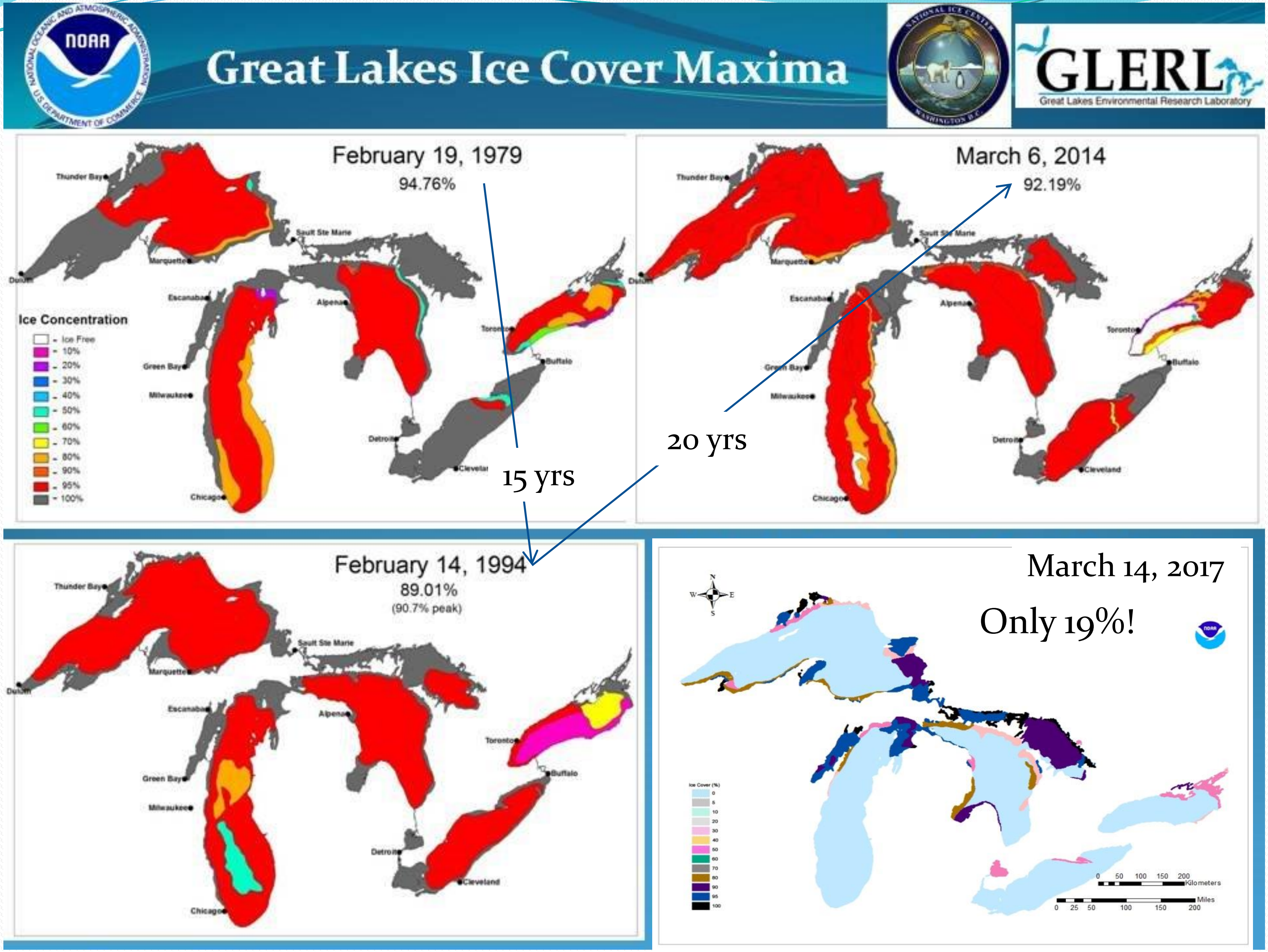
1. Seasonal Variations
2. Interannual (year-to-year) Variability: El Nino and Southern Oscillation (ENSO) and North Atalantic Oscillation (NAO)
3. Decadal teleconnection patters: Atlantic Multidecadal Oscillation (AMO) and Pacific Decadal Oscillation (PDO) and their Impacts on Lake ice and LST

III. Prediction: Transition of Research to Application (R2A) and Operation (R2O)

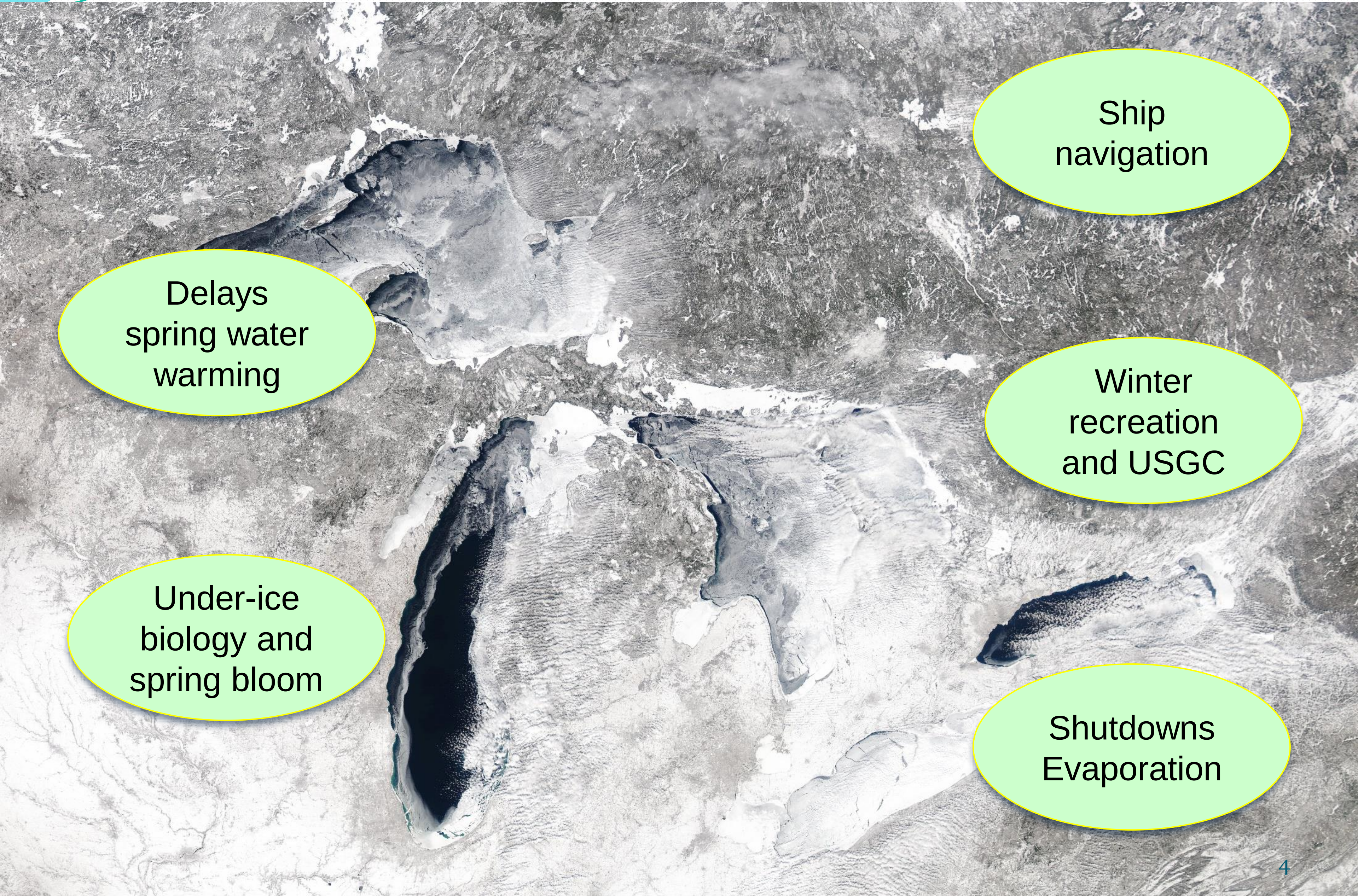
1. Coupled Great Lake Ice-lake Model (GLIM)
2. Statistical, multi-variable models
3. 2018 Projection

IV. Summary

I. Introduction (Decadal Time Scales)



In the Great Lakes …



In the Great Lakes …

Michigan

By the numbers: Icebreaking on the Great Lakes last winter

[http://connect.mlive.com/staff/gellison/index.html] By Garret Elliso
Follow on Twitter [http://twitter.com/garretellison]
on October 22, 2015 at 5:05 PM, updated October 22, 2015 at 6:21 PM

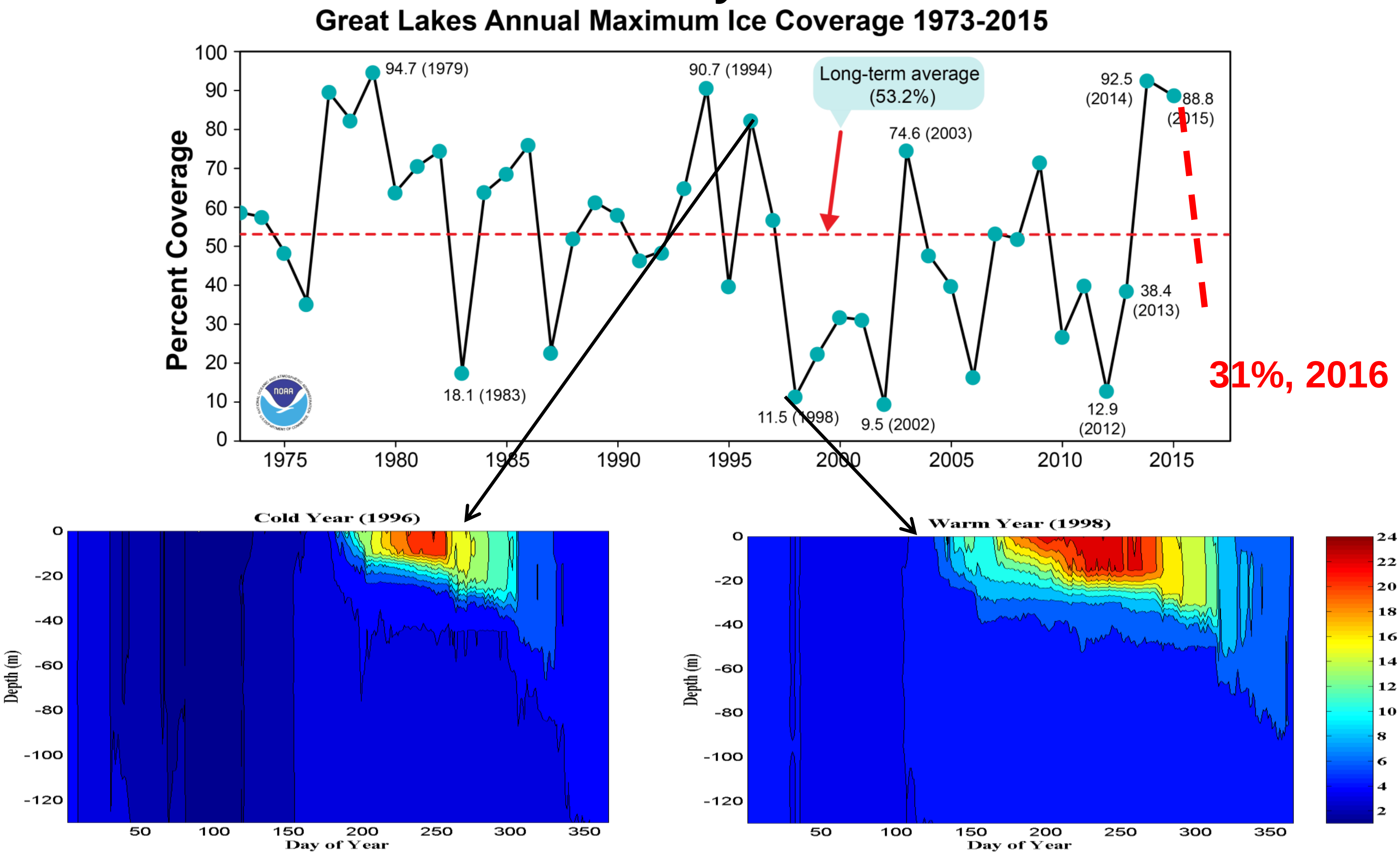
CLEVELAND, OH — Another icebreaking season is around the co
hoping it's not as brutal as the past two.

This week in Cleveland, members of the U.S. & Canadian Coast (
icebreaking operations for the upcoming winter season after tw
ice cover on the Great Lakes.

Ice cover peaked in 2015 at 89 percent. In 2014, total ice cover p
surpassing all-time records set in 1994 and 1979.

Back-to-back winters of historic ice caused shipping delays, ind
and prompted calls from vessel owners and politicians for anoth
icebreaker, **but the region faces competition [http://www.mli**

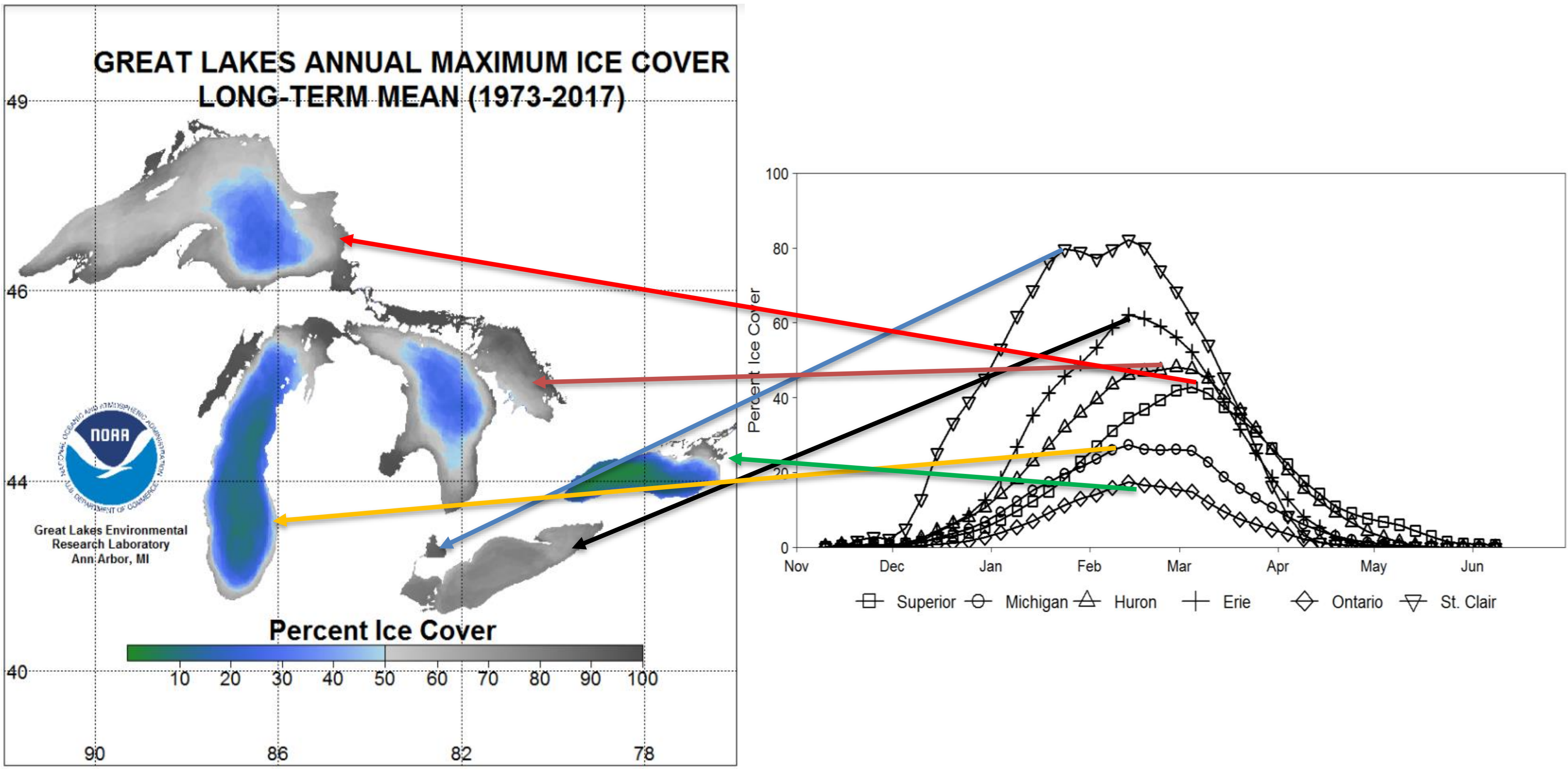
Large interannual variability in ice cover ➔ lake thermodynamics ➔ heat fluxes ➔ T stratification ➔ ecosystem

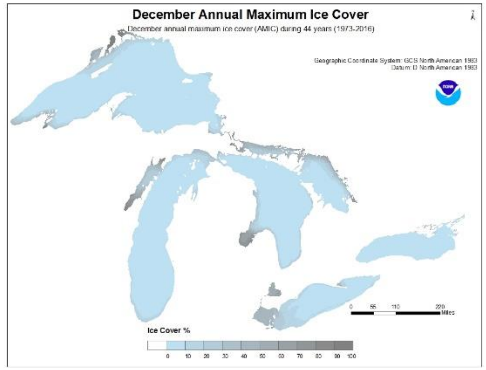


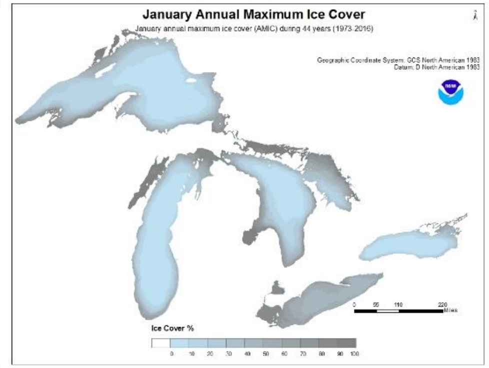
II. Great Lakes Ice and Climate Research

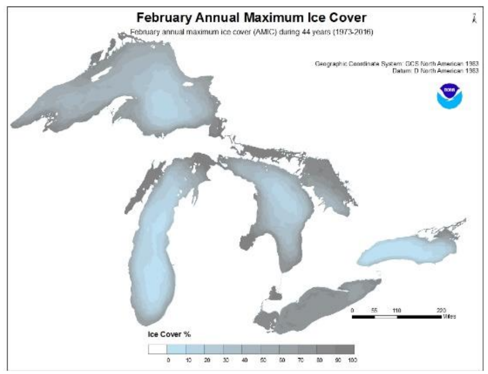
1. Seasonal Variations
2. Interannual (year-to-year) Variability: El Nino and Southern Oscillation (ENSO) and North Atalantic Oscillation (NAO)
3. Decadal teleconnection patters: Atlantic Multidecadal Oscillation (AMO) and Pacific Decadal Oscillation (PDO) and their Impacts on Lake ice and LST

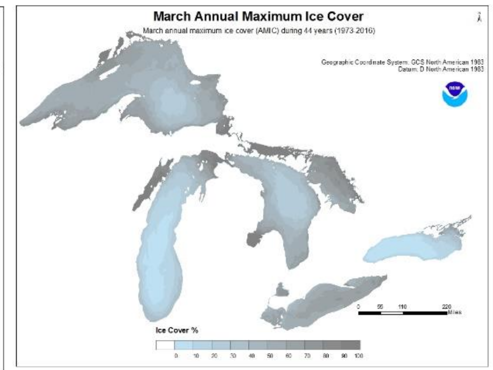
1. Seasonal Variation

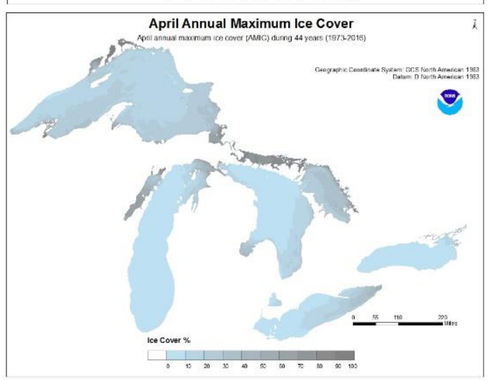












Climatological maps for monthly AMIC (annual maximum ice cover) in all five Great Lakes for December, January, February, March, and April for the period 1973-2017.

2. Interannual (year-to-year) Variability

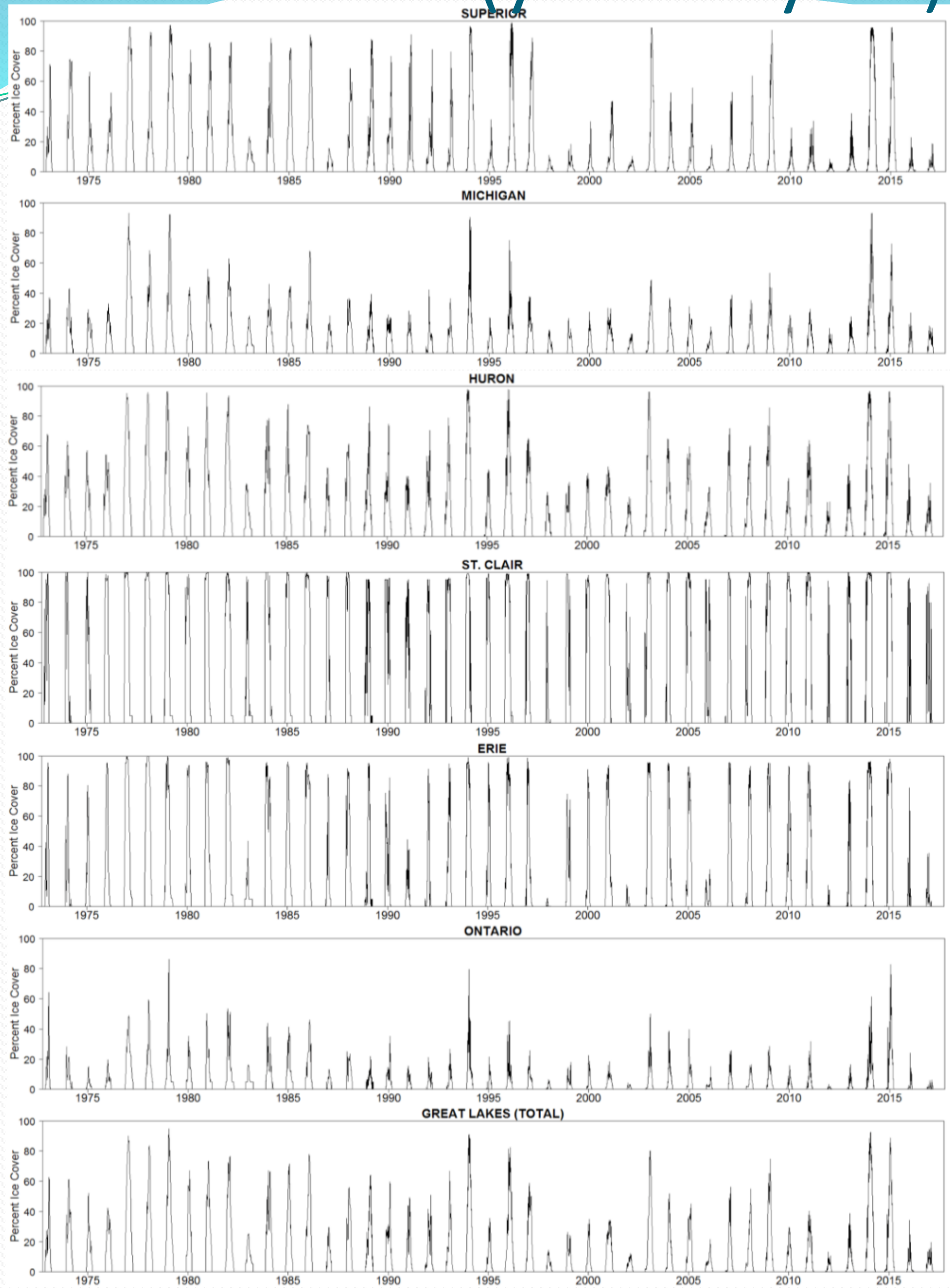


Figure 5. Time Series of Ice Cover in the Great Lakes, 1973-2017

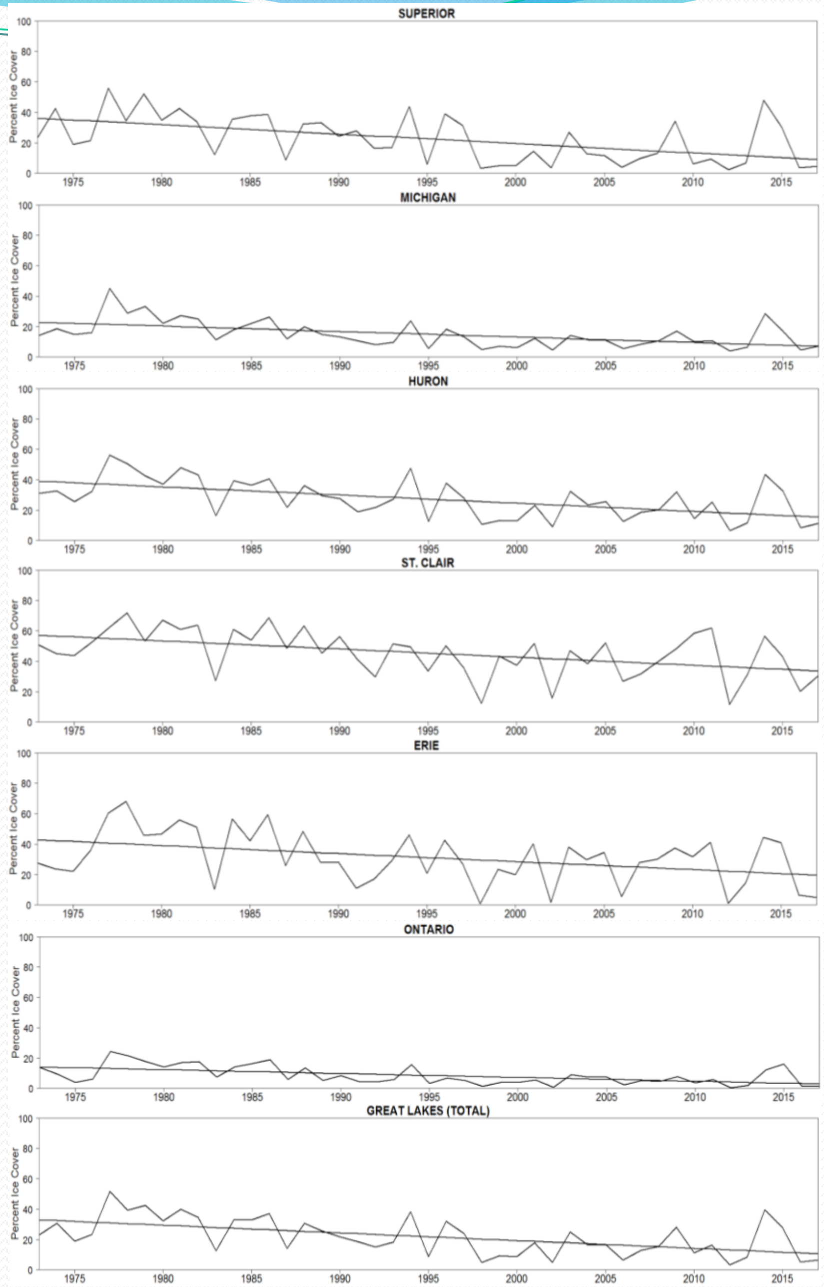


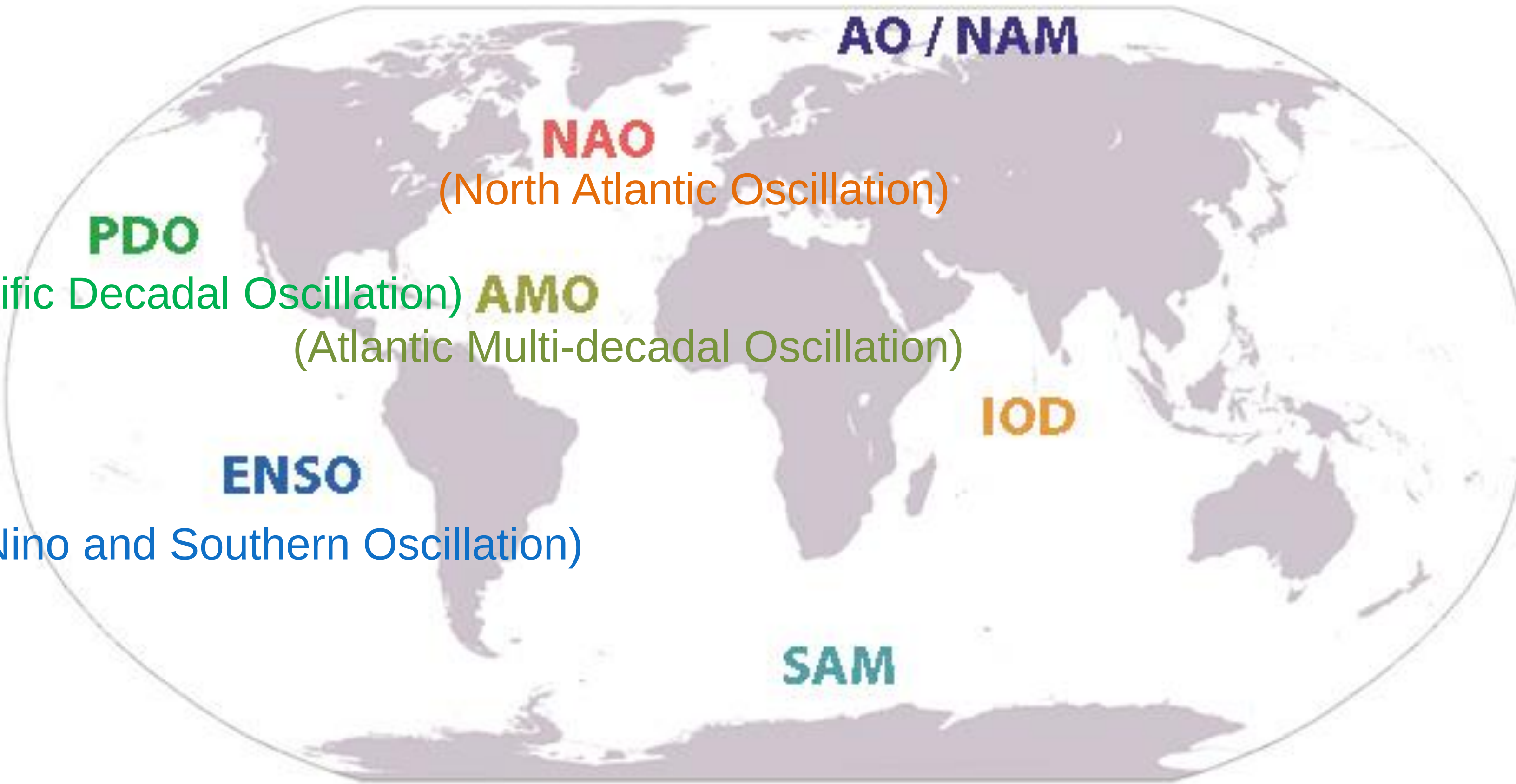
Figure 6. Annual Mean Ice Cover (AAIC) and Trend in the Great Lakes, 1973-2017.

Why Year-to-Year Change?

- Global atmospheric teleconnection patterns?

- They are too far from us. How can they influences Great Lakes?

Major global-scale atmospheric teleconnection patterns



(North Atlantic Oscillation)

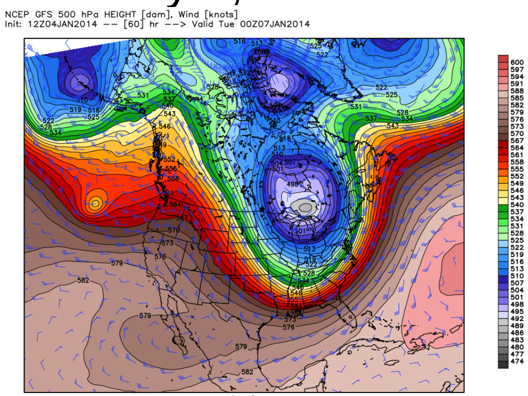
(Pacific Decadal Oscillation)

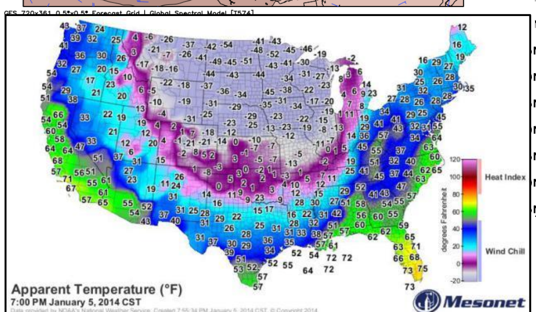
(Atlantic Multi-decadal Oscillation)

(El Nino and Southern Oscillation)

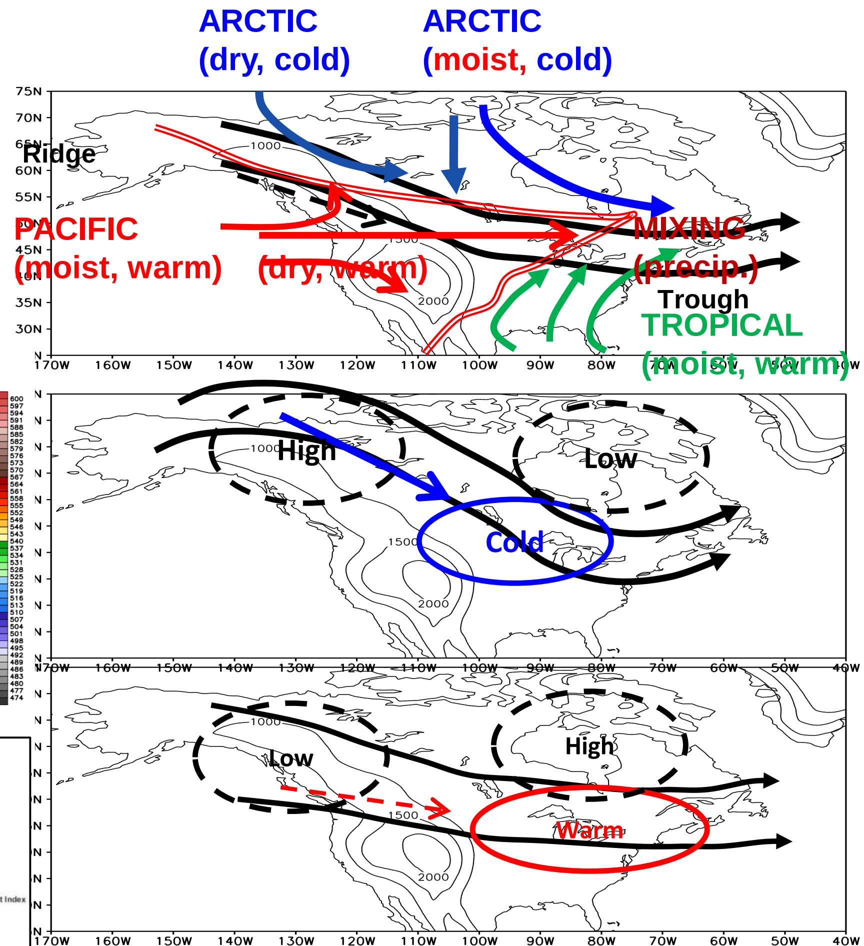
Climate Teleconnection and Lake Ice

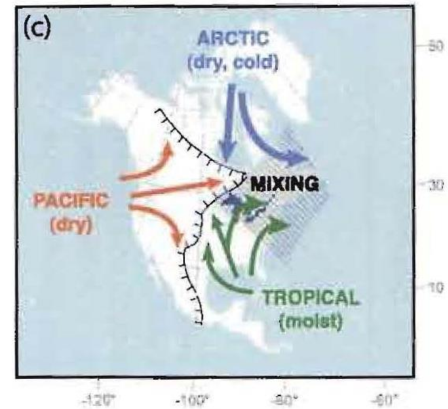
Polar vortex on January 5, 2014





Before Present



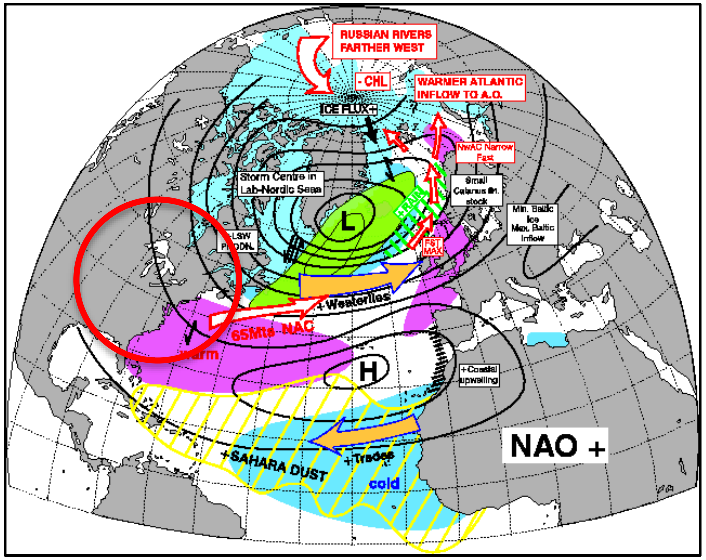


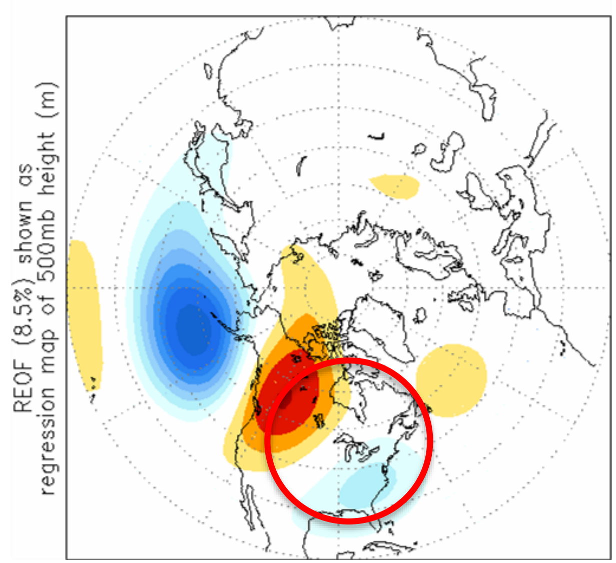
Lewis et al. 2008, EOS

Conceptual diagram for the development of teleconnection patterns associated with severe and least ice cover, through the Westerly Jet ridge-trough system's intensification and weakening (Bai and Wang, 2012)

Relationship between Lake ice and NAO/AO and ENSO

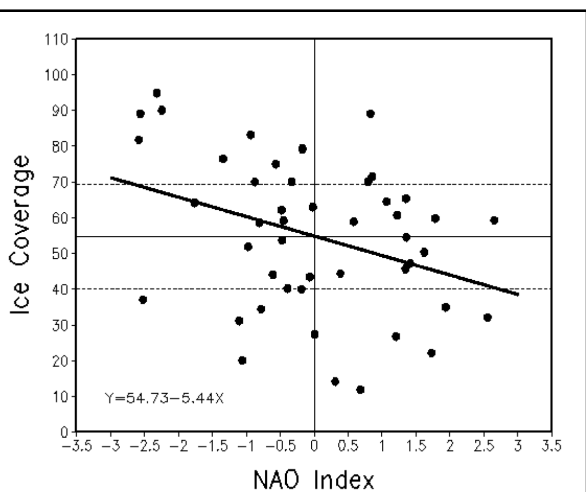
(Bai et al. 2012, JGR)





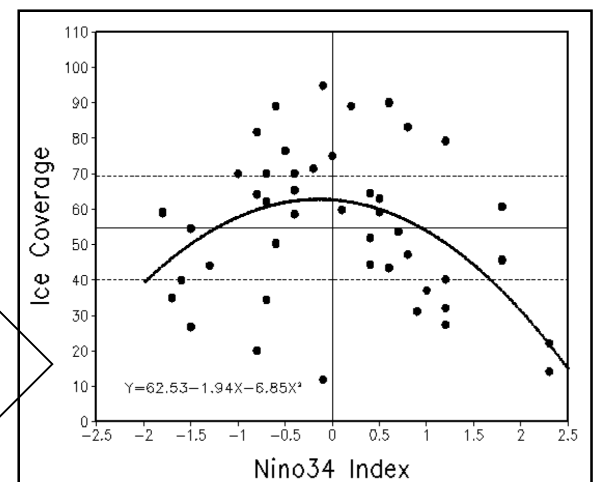
- **North Atlantic Oscillation (NAO) (Arctic Oscillation)**

Pacific North America Pattern (El Nino/La Nina, ENSO)

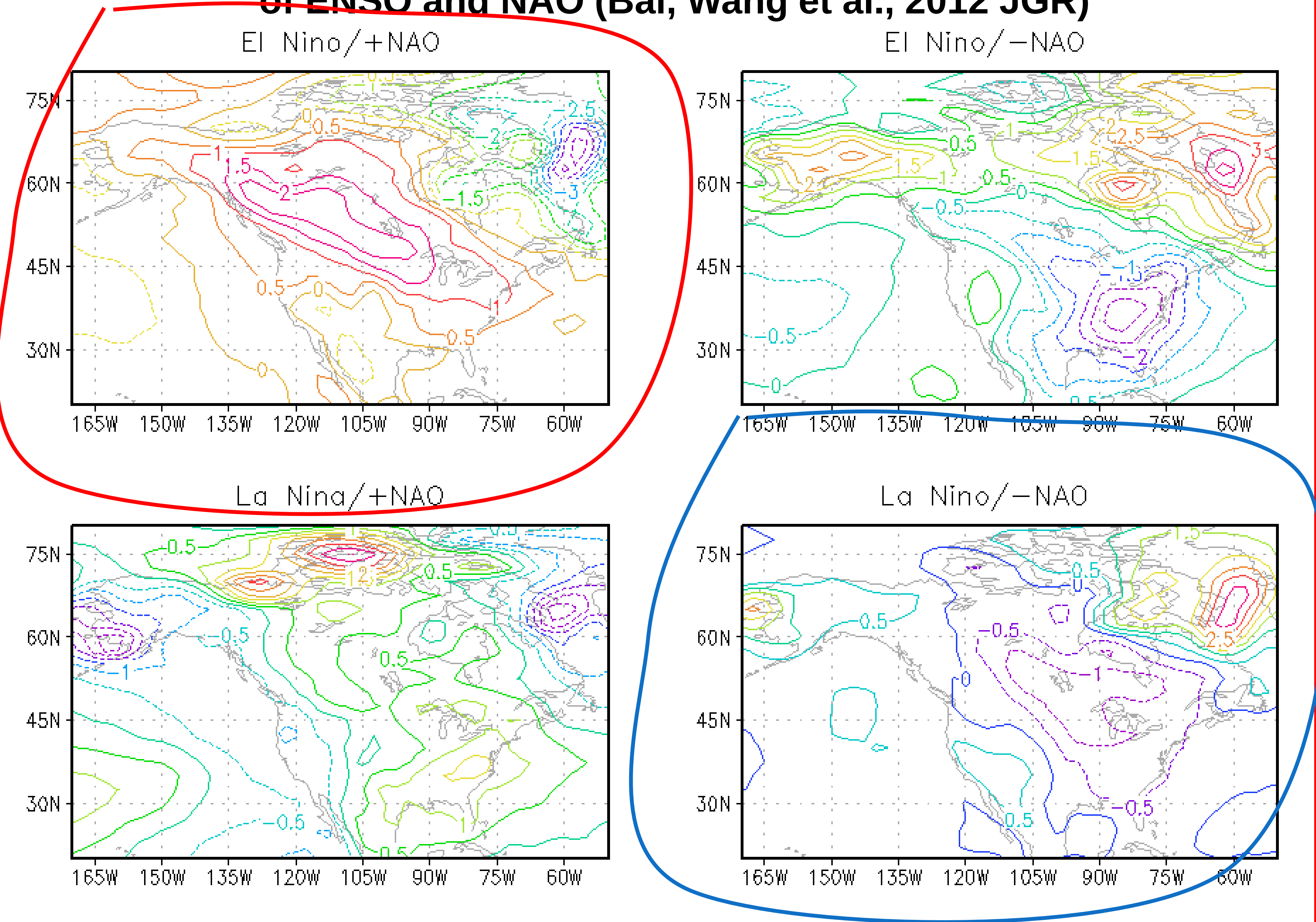


Ice and NAO:
Linear relationship

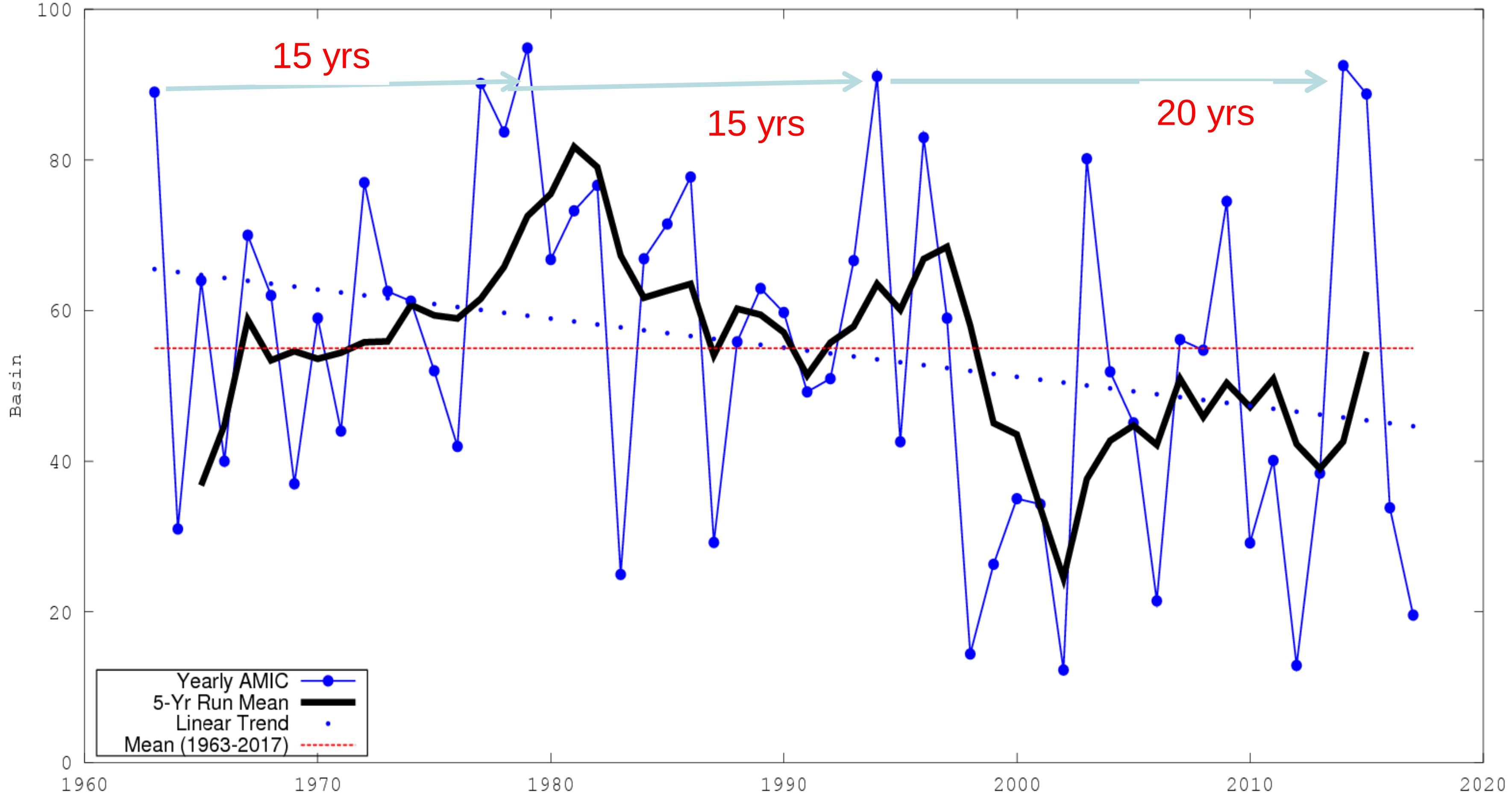
Ice and ENSO:
Nonlinear and asymmetric relationship



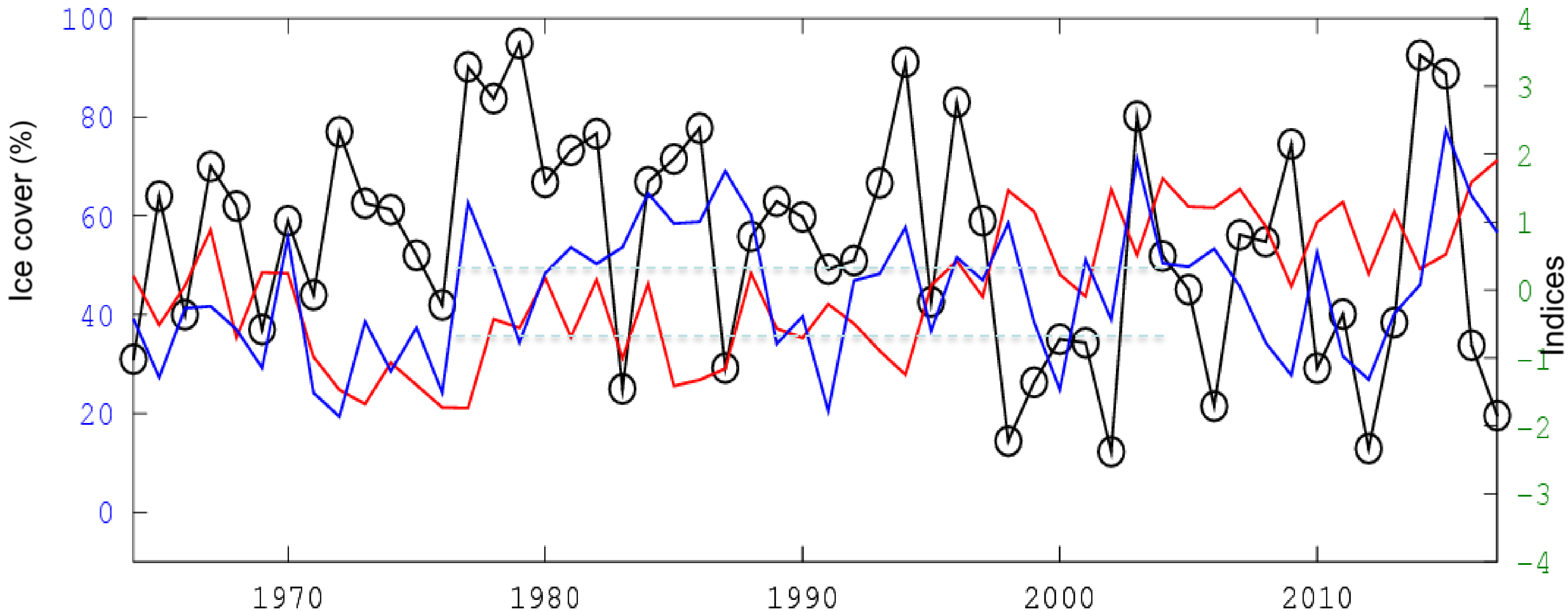
Surface air temperature anomalies induced by combined effect of ENSO and NAO (Bai, Wang et al., 2012 JGR)



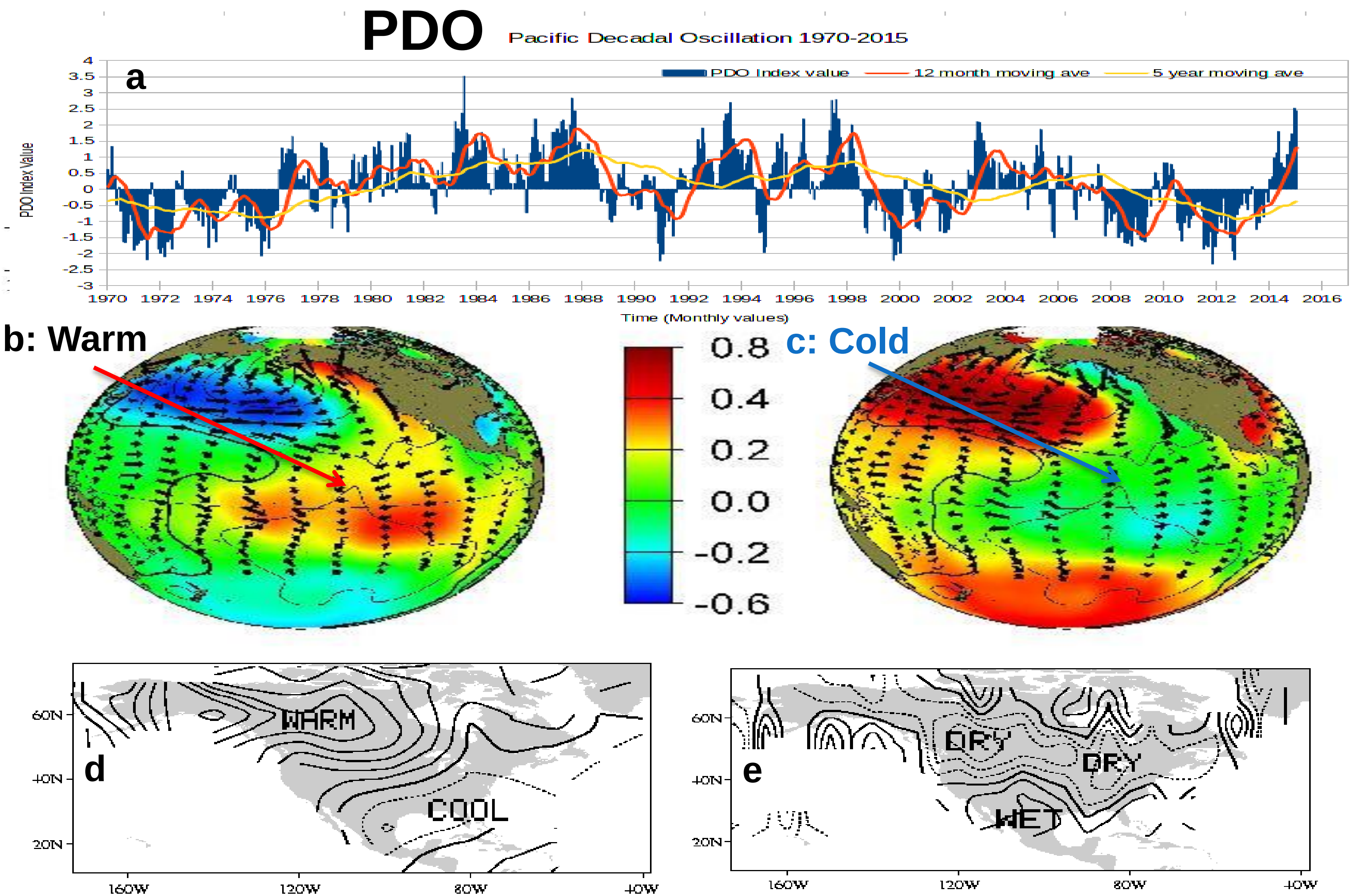
3. Decadal Variability



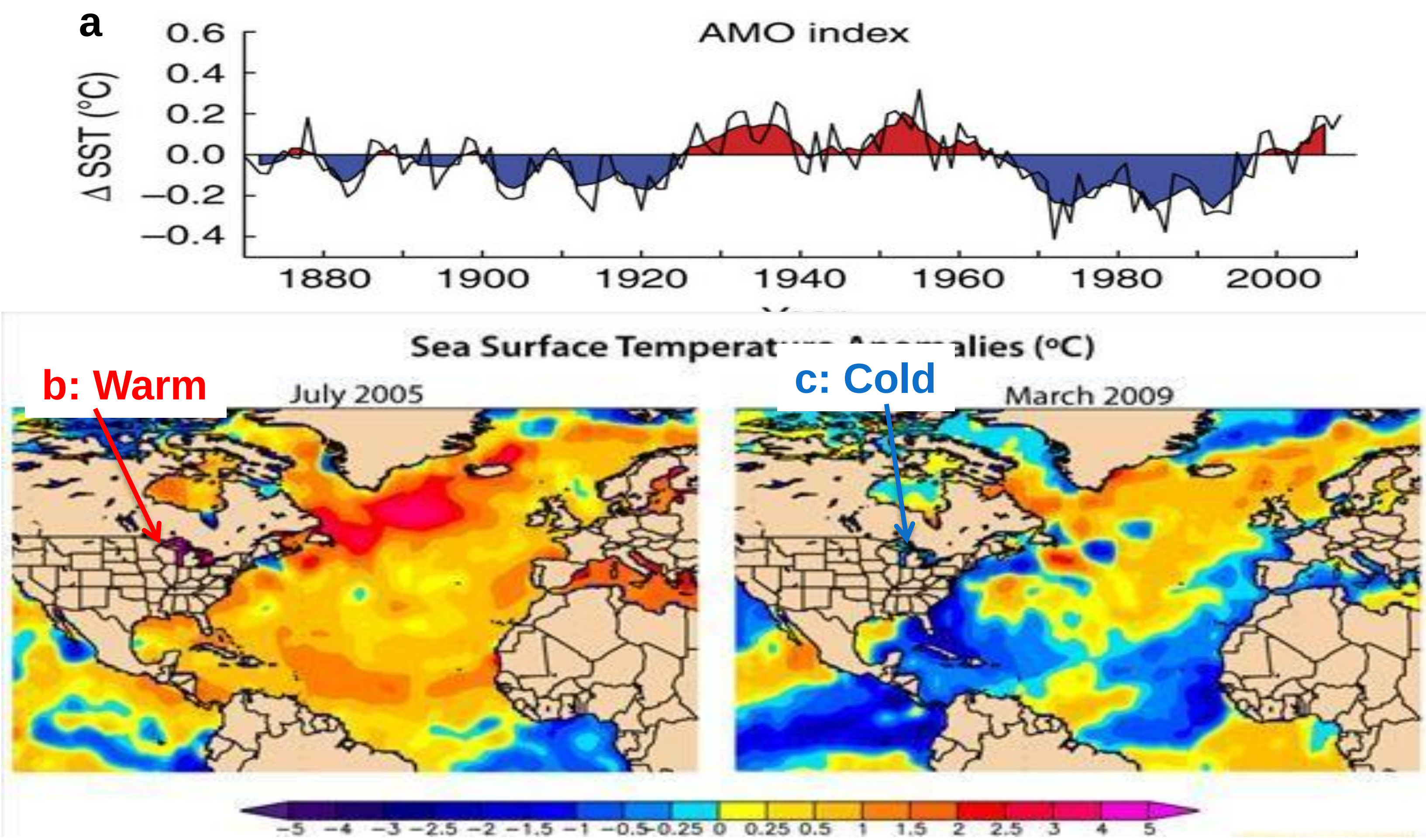
Decadal Time Scales in Annual Max Ice Cover (AMIC)



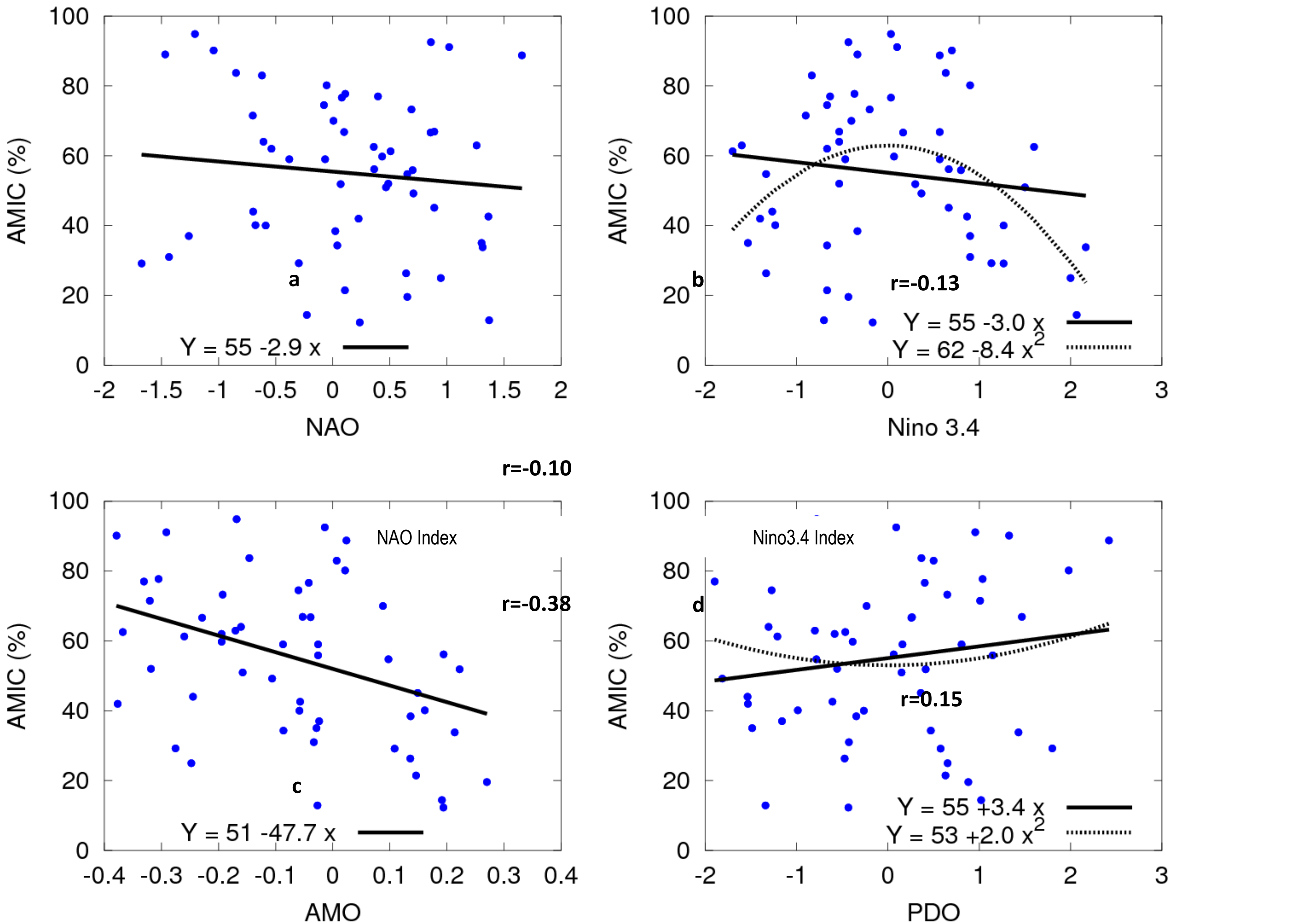
The annual time series of AMIC (black), AMO index (red), and PDO index (blue). The linear correlation coefficients are calculated: r(AMIC, AMO)=-0.38, and r(AMIC, PDO)=0.15. The dashed lines denotes the indices >1 and <-1.



a) The Pacific Decadal Oscillation (PDO) Index is defined as the leading principal component of North Pacific monthly sea surface temperature variability (poleward of 20N). b) warm phase and c) cold phase of PDO, and corresponding October-March surface air temperature (d) and precipitation (e) anomaly during the warm phase in North America for the 1900-1993 period. http://takvera.blogspot.com/2015/03/taking-earths-temperature-and-influence.html (John Englart). Data sources: http://research.jisao.washington.edu/pdo/PDO.latest



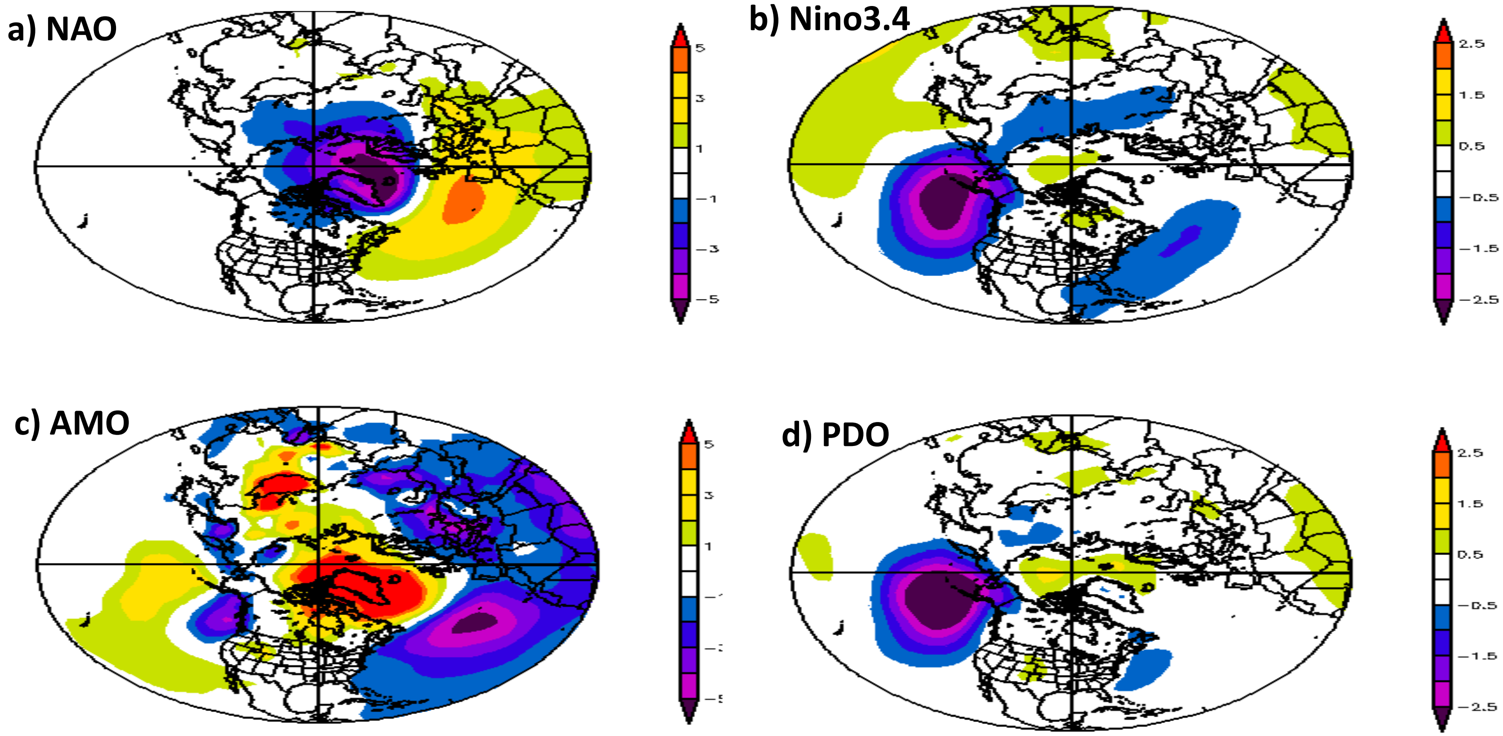
a) The AMO Index is defined as the North Atlantic Ocean SST anomaly with the linear trend removed. Spatial pattern of SST anomaly for warm phase (b) and cold phase (c) of AMO.



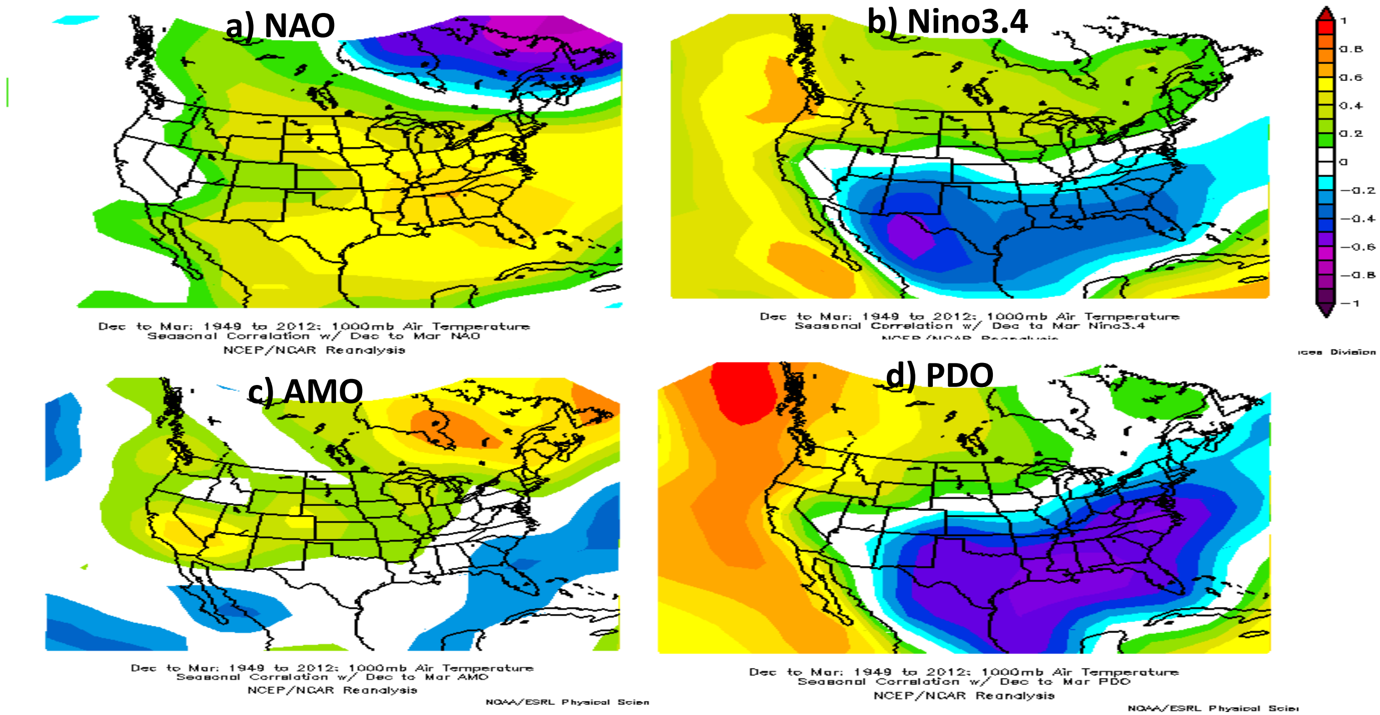
Scatter plots of AMIC vs. NAO index (a), Niño3.4 index (b), AMO index (c), and PDO index (d). The linear regression lines are given. The quadratic curves are also given for Niño3.4 and PDO. *r* indicates the linear correlation coefficients between the time series of AMIC and the individual indices for the period of 1963-2017.

Table 1. Correlations and p-values of AMIC with teleconnection patterns. The significance levels are calculated using Monte Carlo simulation (Livezey and Chen 1983; Wang et al. 1994).

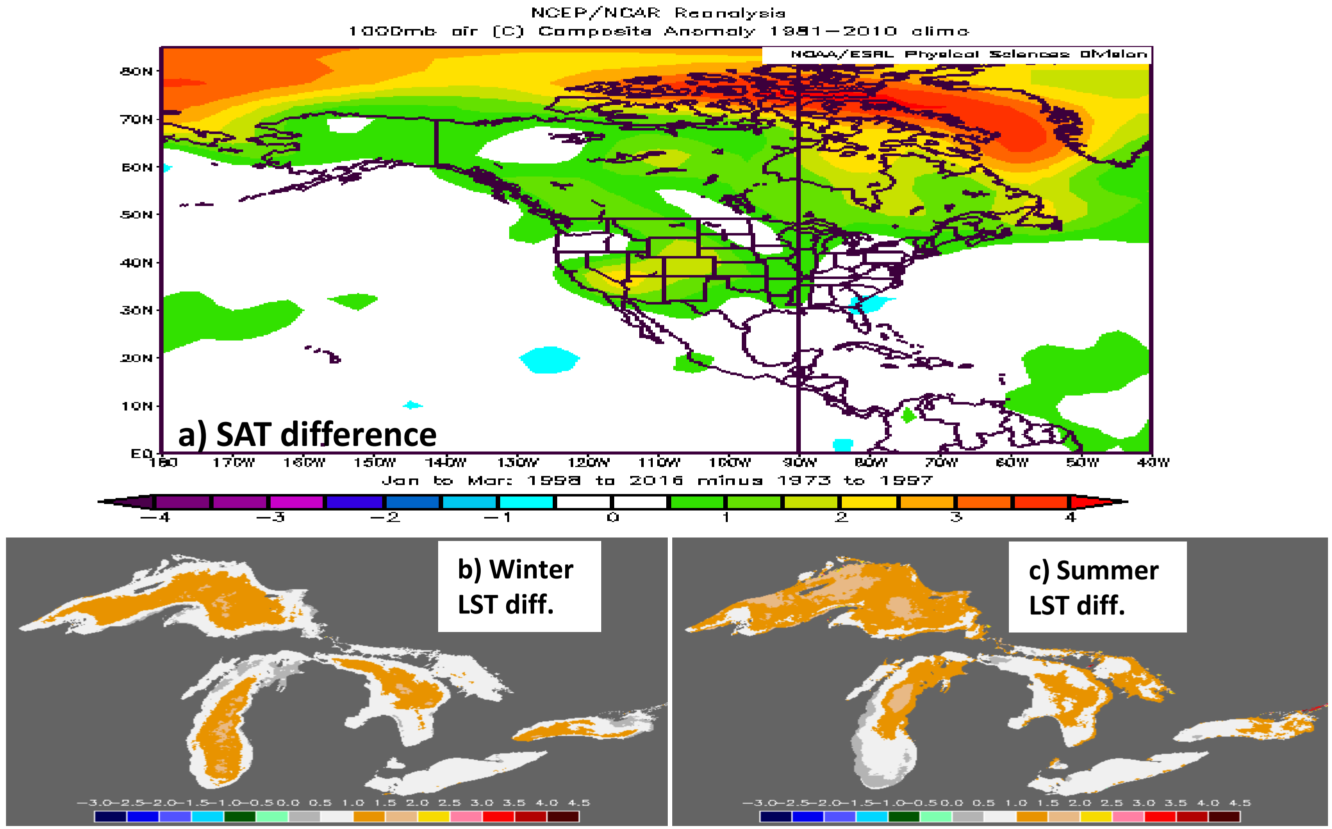
Index	***r***	***p-value***	***Significance* (%)**
Nino3.4	-0.131	0.340	*66*
$Nino3.4^2$	-0.415	0.002	**99.8**
NAO	-0.102	0.458	*54.2*
NAO^2	-0.004	0.979	1
AMO	-0.377	0.005	**99.5**
AMO^2	-0.096	0.484	*51.6*
PDO	0.151	0.271	*62.9*
PDO^2	0.109	0.429	*57.1*



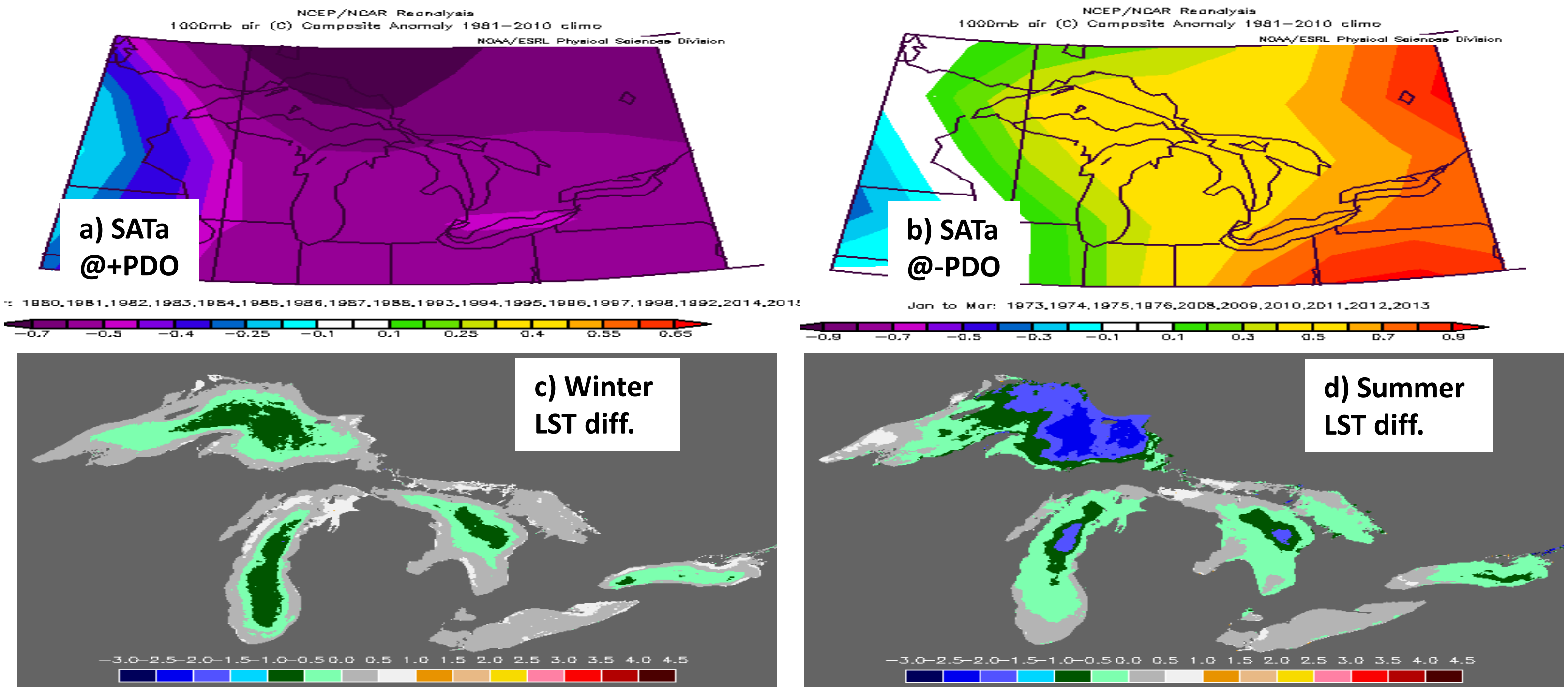
Spatial regression map between the sea-level pressure (SLP) and DJFM indices of 1) NAO, b) Nino3.4, c) AMO, and d) PDO during 1949-2016. The color bars are in dynamic height, hPa.



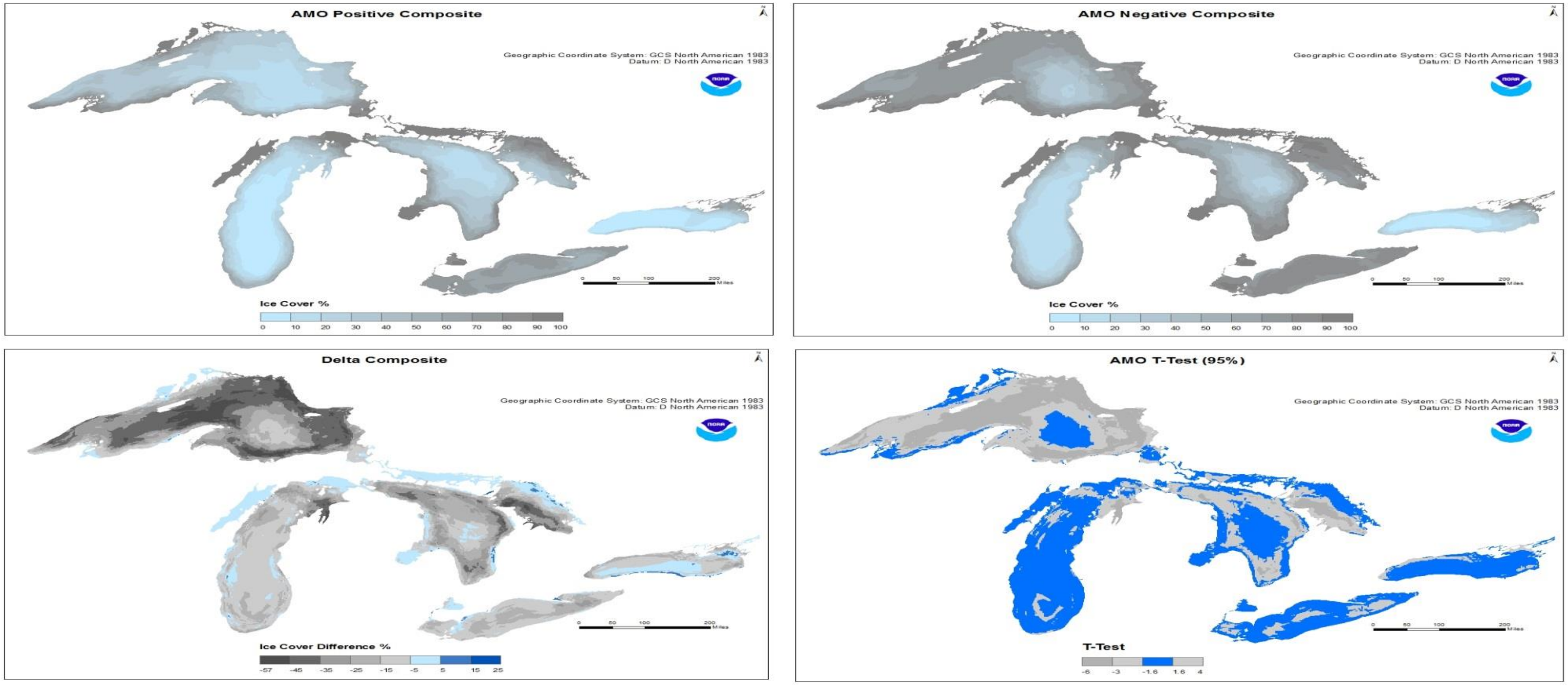
Spatial correlation map between the surface air temperature (SAT) and DJFM indices of 1) NAO, b) Nino3.4, c) AMO, and d) PDO during 1949-2016.



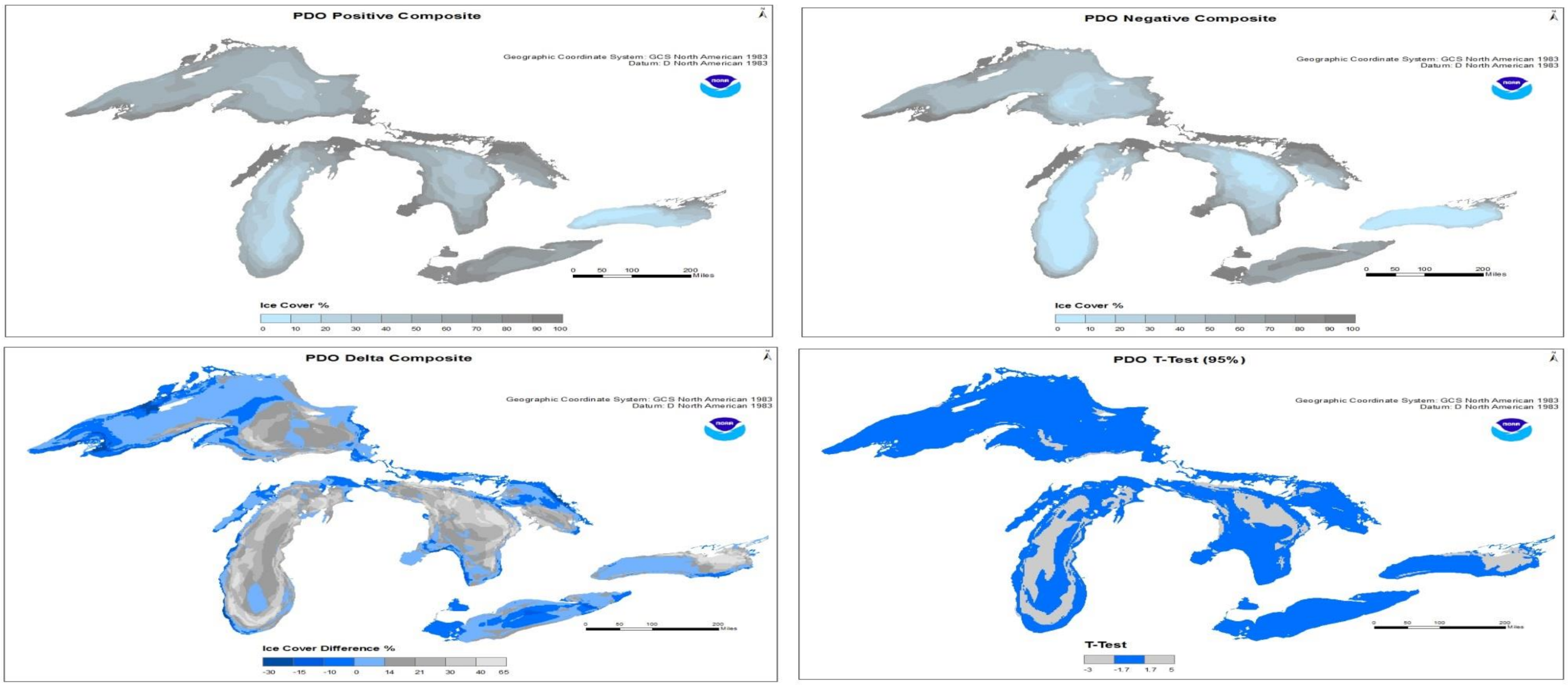
Spatial difference (or anomaly) map between the positive phase (years) of AMO (1998-2017) and the negative phase (years) of AMO (1973-1997) for a) SAT, and winter (b) and summer (c) LST difference between the +AMO and -AMO. Units are in ^{o}C.



Spatial composite DJFM SAT anomaly map referred to the climatology/mean of 1949-2016 for a) the positive phase (years) of PDO, b) the negative phase (years) of PDO, and winter (c) and summer (d) LST difference between +PDO and -PDO. Units are in ^{o}C.



Spatial composite AMIC during +AMO years (upper left), -AMO years (upper right), LST difference between +AMO and –AMO years (lower left), and Student T-test areas for over 95% significance level (lower right).



Spatial composite AMIC during +PDO years (upper left), -PDO years (upper right), LST difference between +PDO and –PDO years (lower left), and Student T-test areas for over 95% significance level (lower right).

III. Prediction of Great Lakes Ice Cover

1. Coupled Great Lake Ice-lake Model (GLIM)
2. Statistical, multi-variable models
3. 2018 Projection

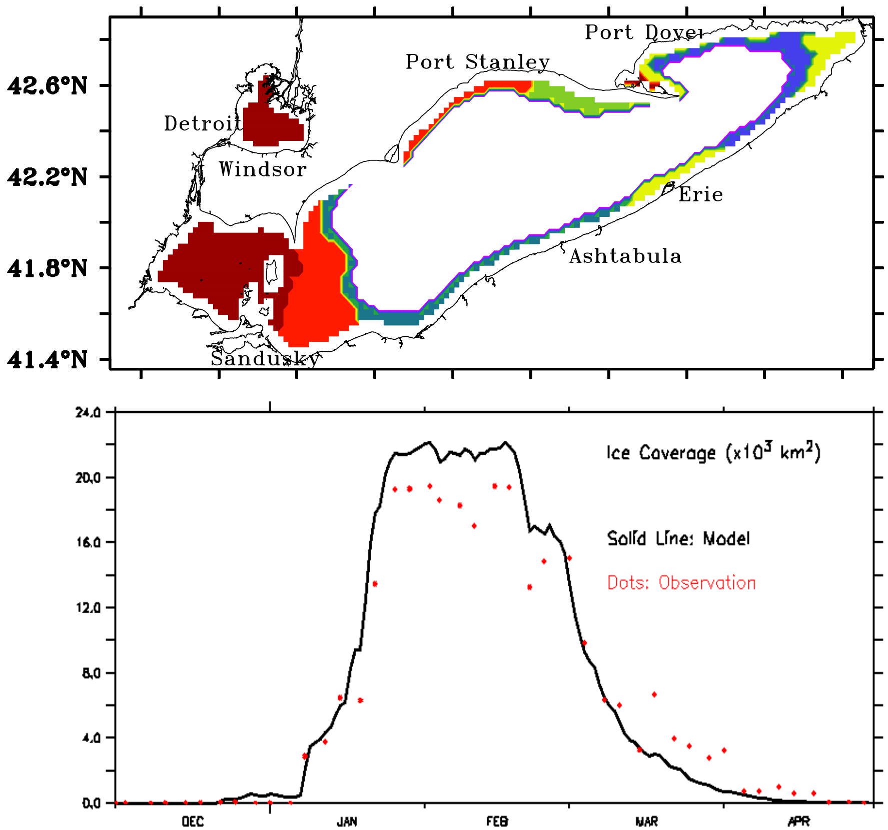
1. Computer Modeling:
Resolution for the Great Lakes Ice-lake Model (GLIM)

2011-2012 ice season

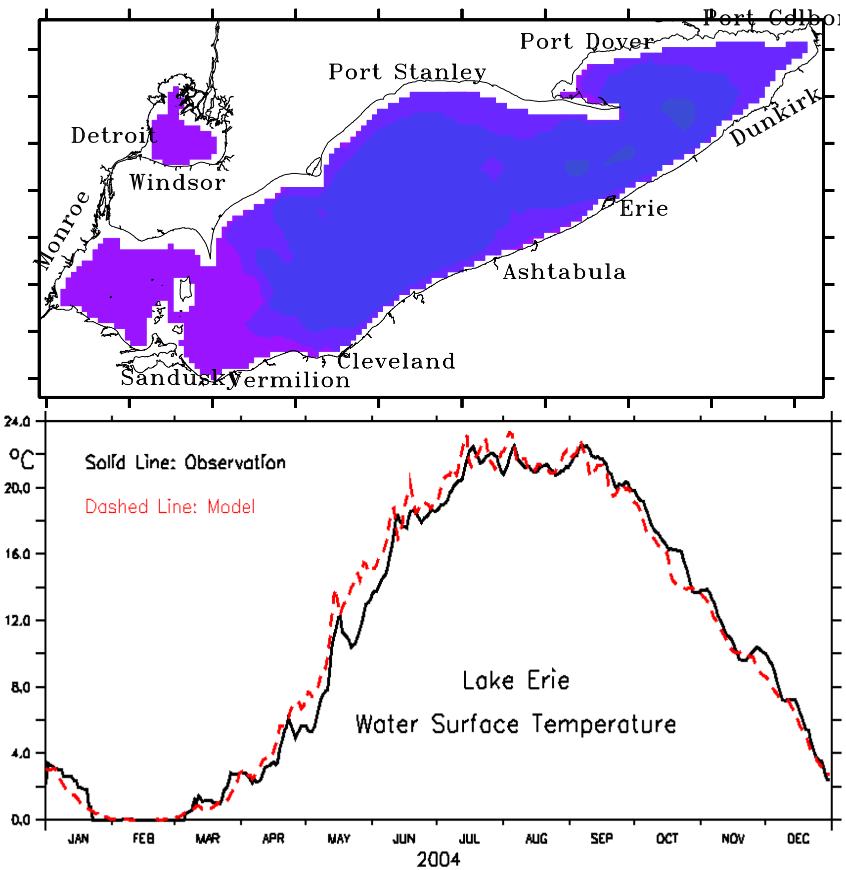
Validation of GLIM

Wang et al. (2010, JGLR)

SSM/I, MODIS-Ice C.



AVHRR-SST

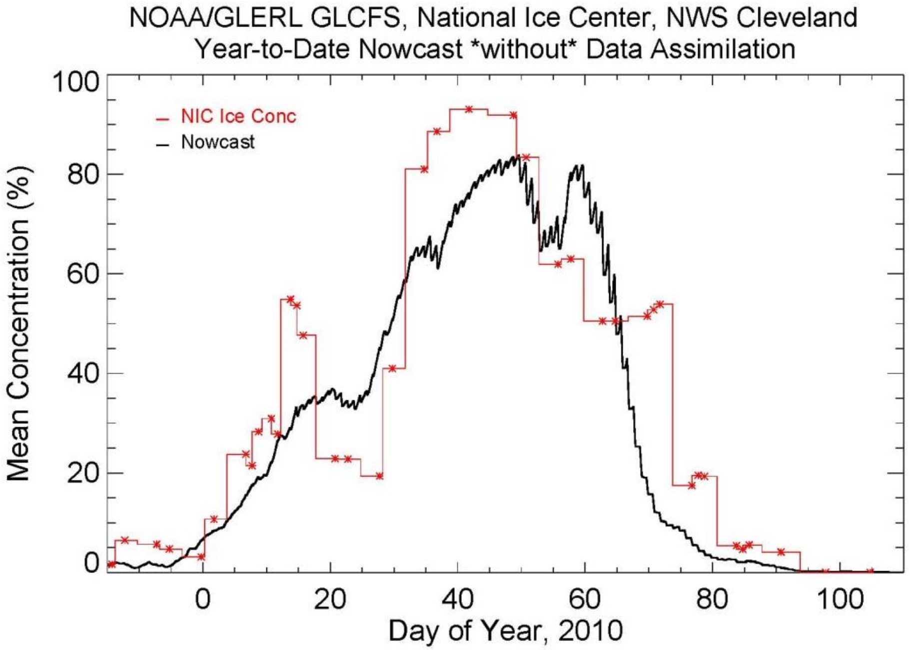


GLIM was implemented into the Great Lakes Coastal Forecasting System (GLCFS) beginning in winter 2009/10 (by Philip Chu, Dave Schwab and Greg Lang):

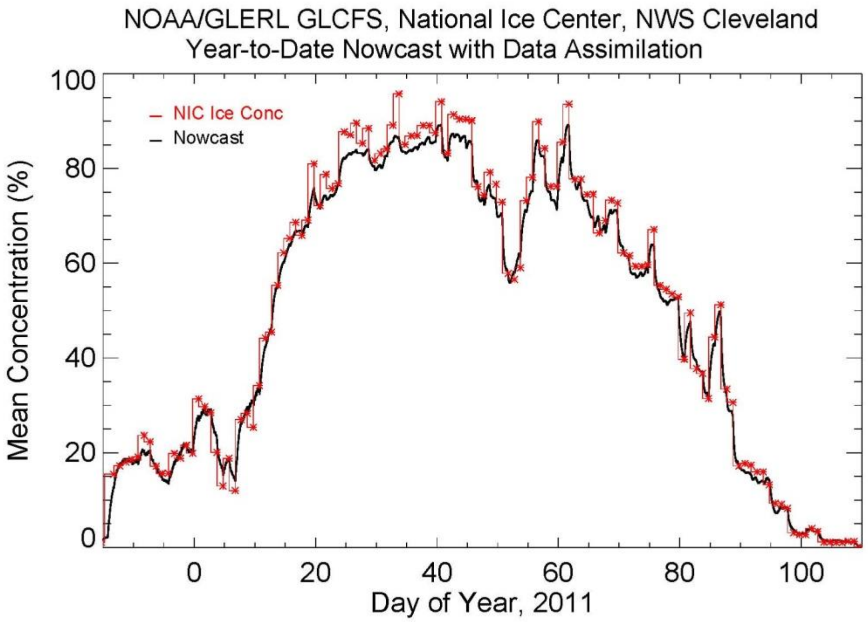
http://www.glerl.noaa.gov/res/glcfs/erie-ice.php?lake=e&type=F&hr=01

R2O: GLCFS-Ice Forecasts

2009-2010 (no assim.)



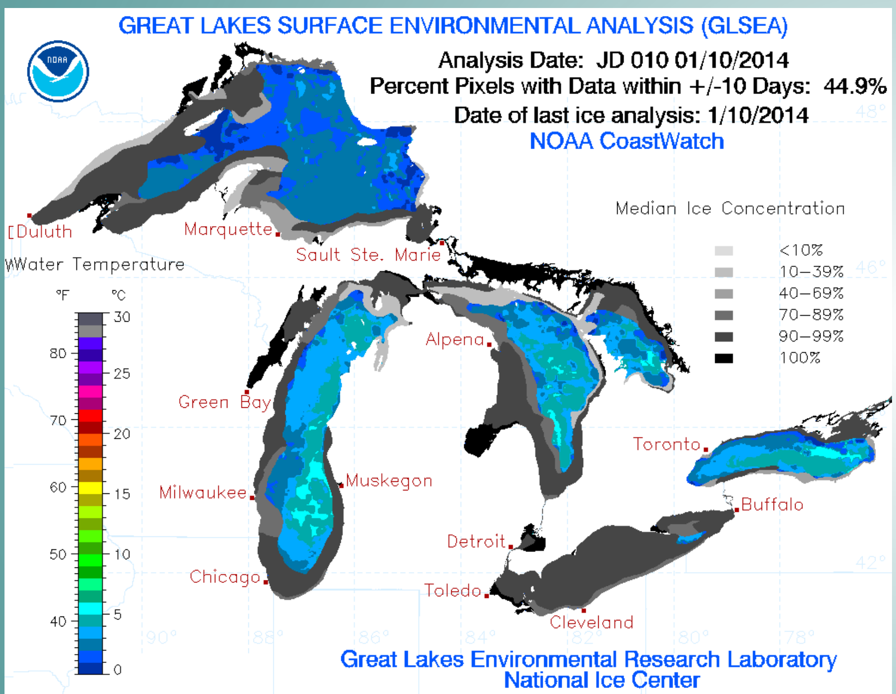
2010-2011 (assim.)



Ice forecast with "data assim." has been implemented into the Great Lakes Coastal Forecasting System (collaborated with Dave Schwab and Greg Lang):

http://www.glerl.noaa.gov/res/glcfs/erie-ice.php?lake=e&type=F&hr=01

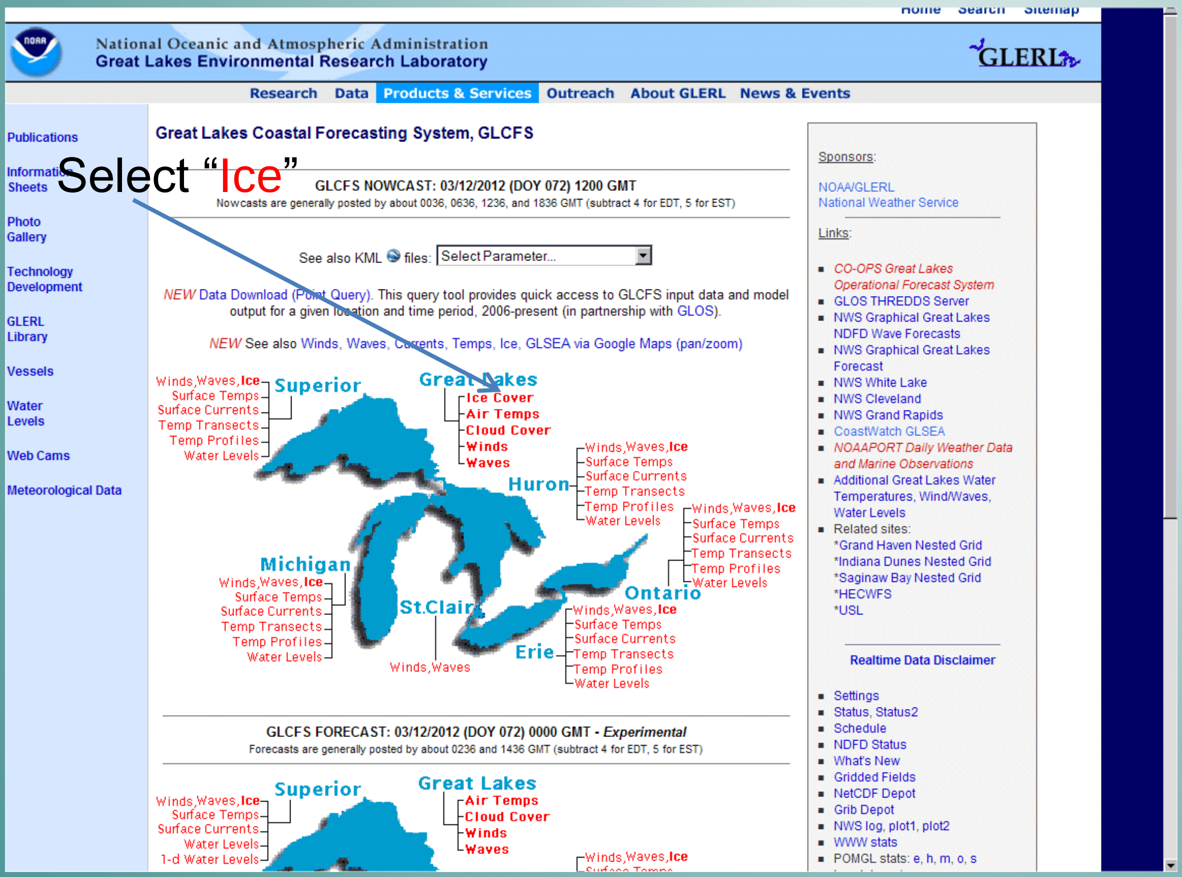
GLIM 5-day Prediction during 2013-14 ice season (heavy ice season)



R2O: GLERL Ice Forecast (GLIM) has been in the GLCFS (Great Lakes Coastal Forecasting System) since 2010

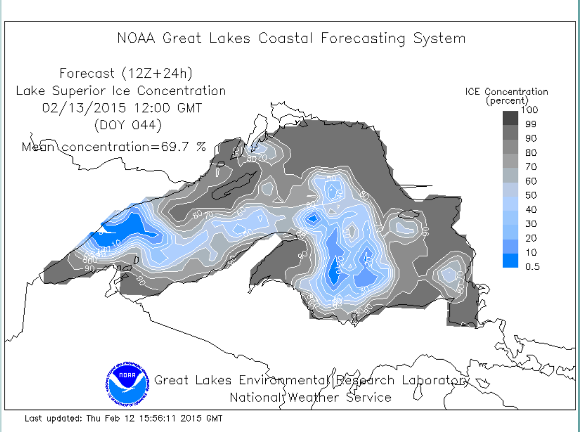
(Wang et al. 2010, JGLR; Fujisaki et al 2012 JGLR, 2013 JGR)

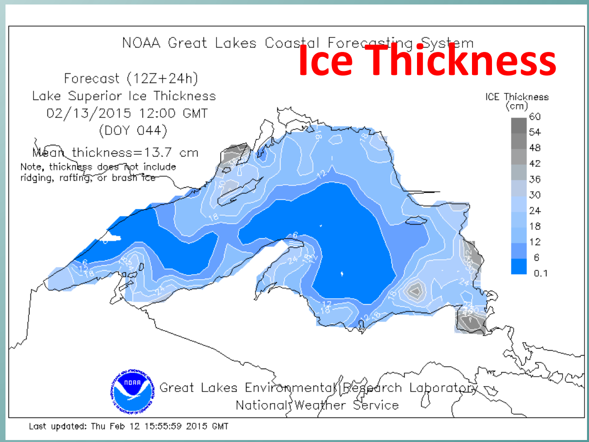
http://www.glerl.noaa.gov/res/glcfs/



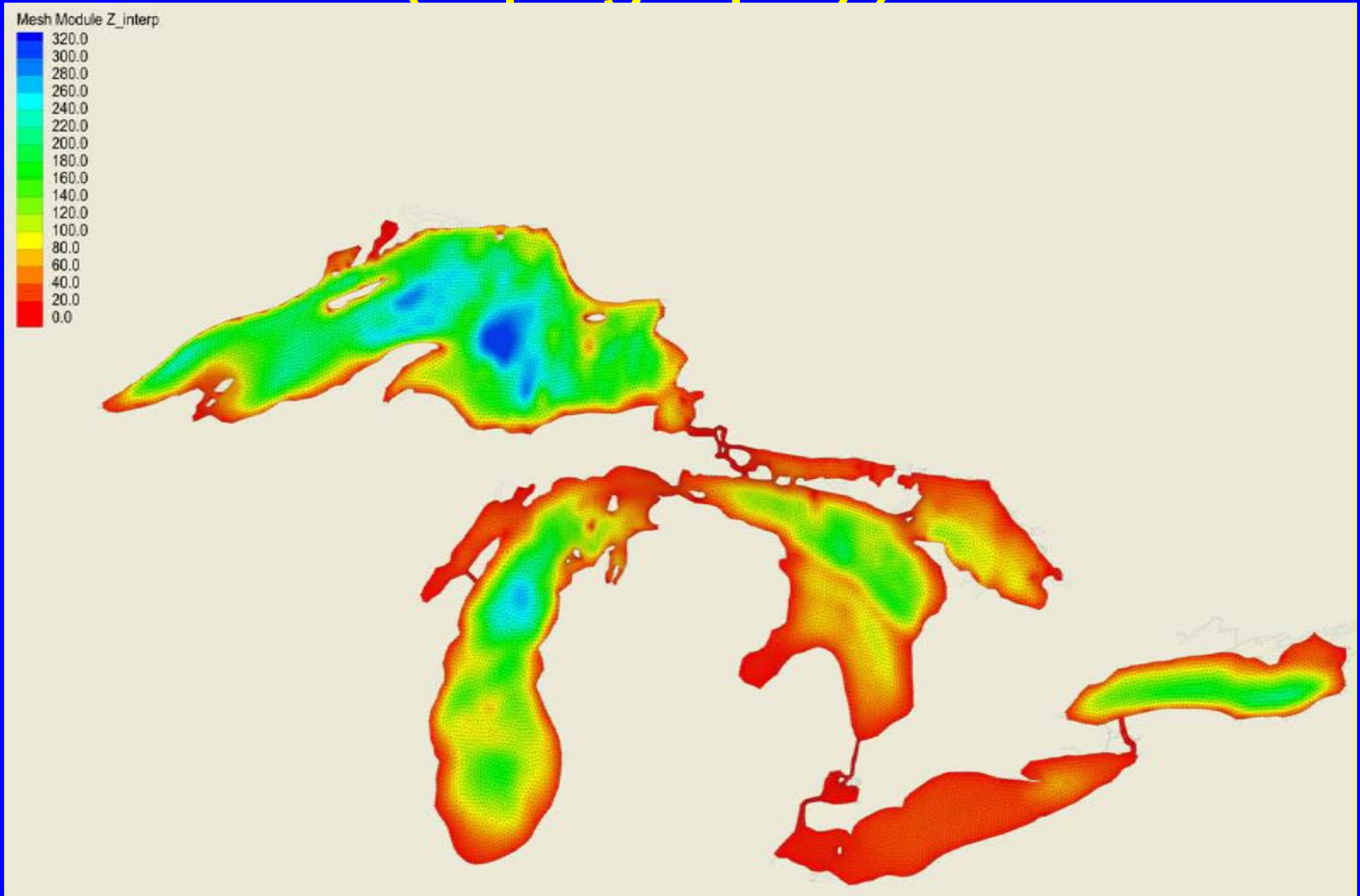
up to 5-day Forecast

Ice Concentration

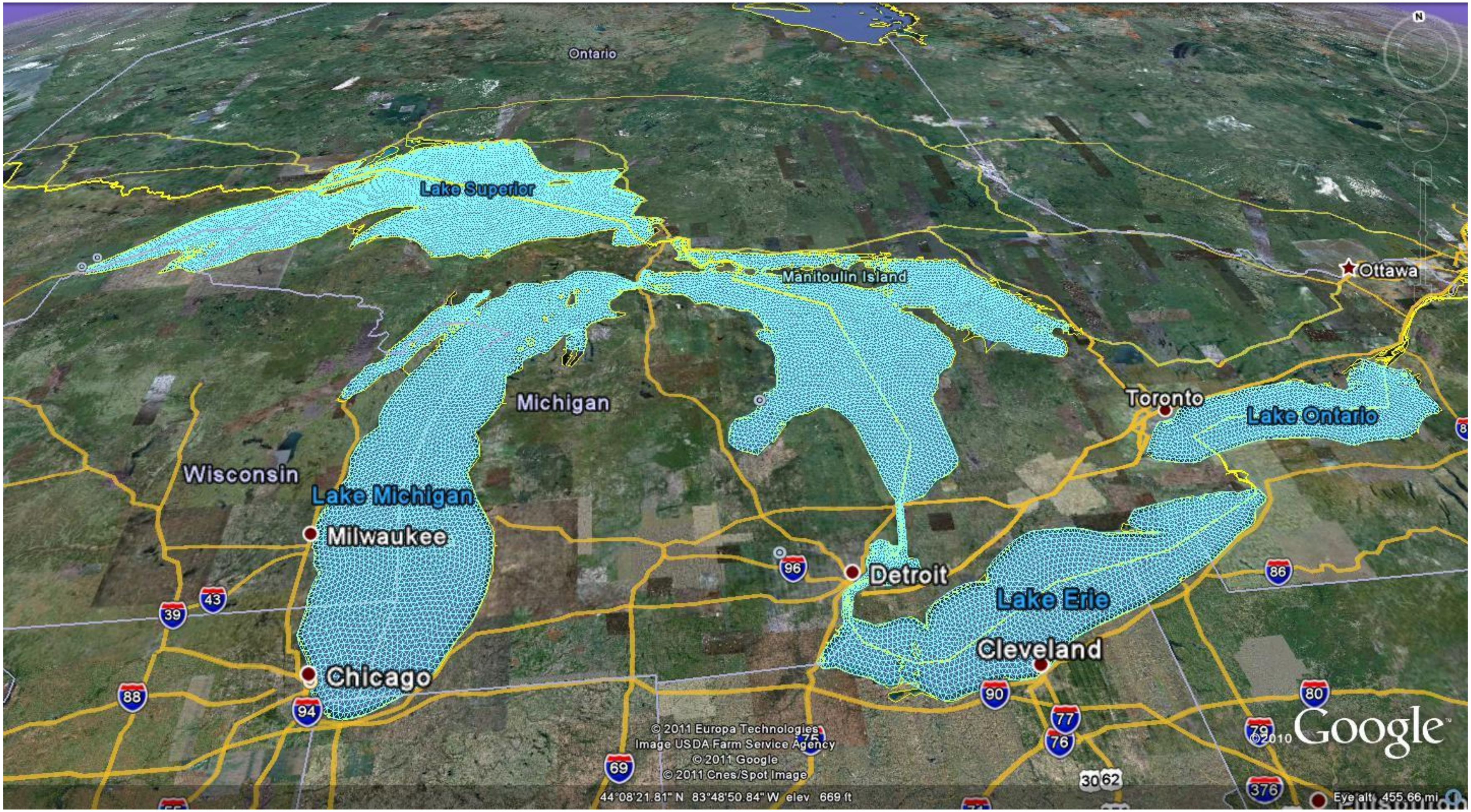




New model: Unstructured-grid FVCOM (finite volume coastal ocean model) (topography)



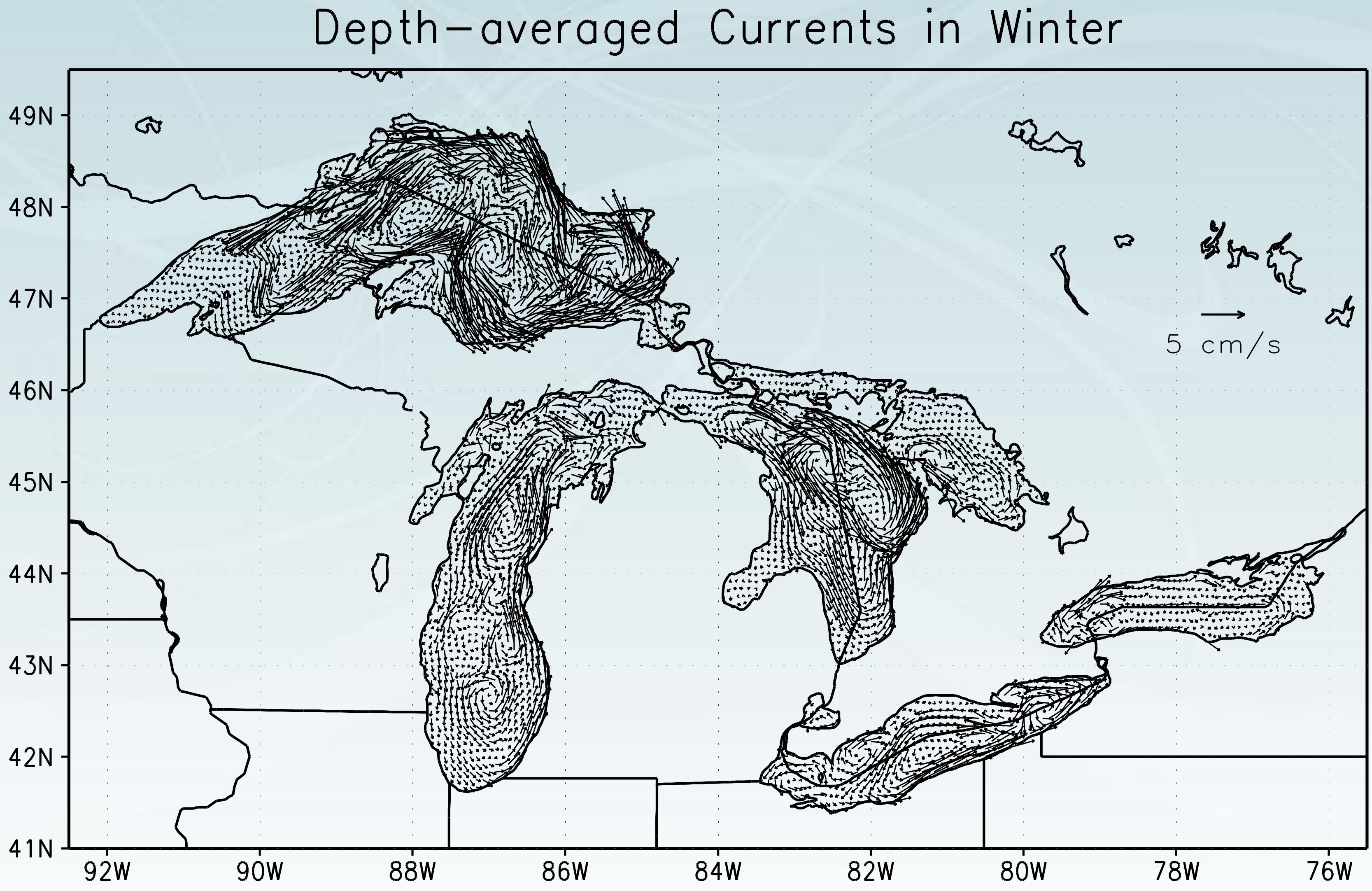
Unstructured grids
(new generation)



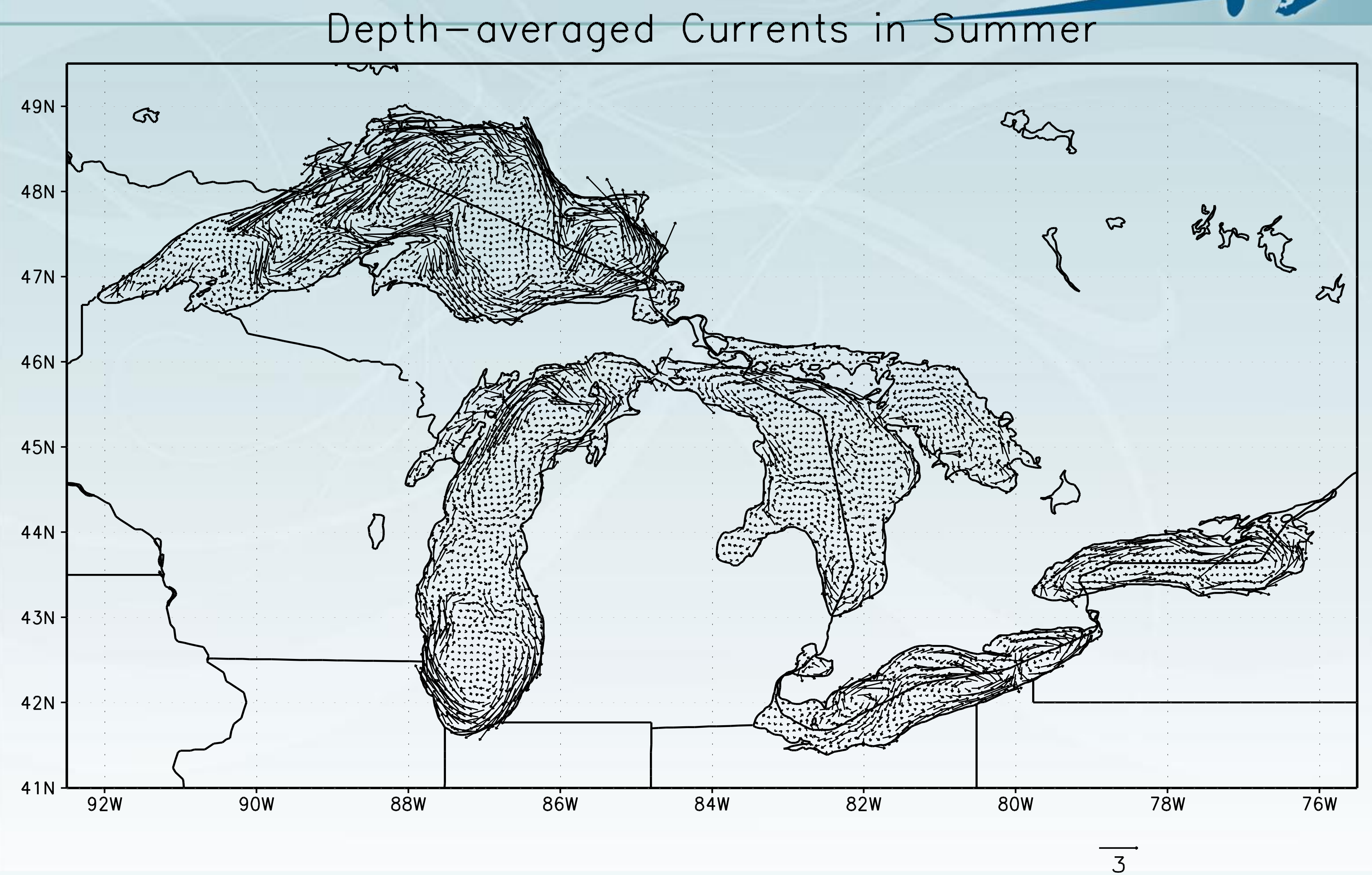
Model Validation

- Satellite Surface temperature (GLSEA2)
- Thermistor chain measurement

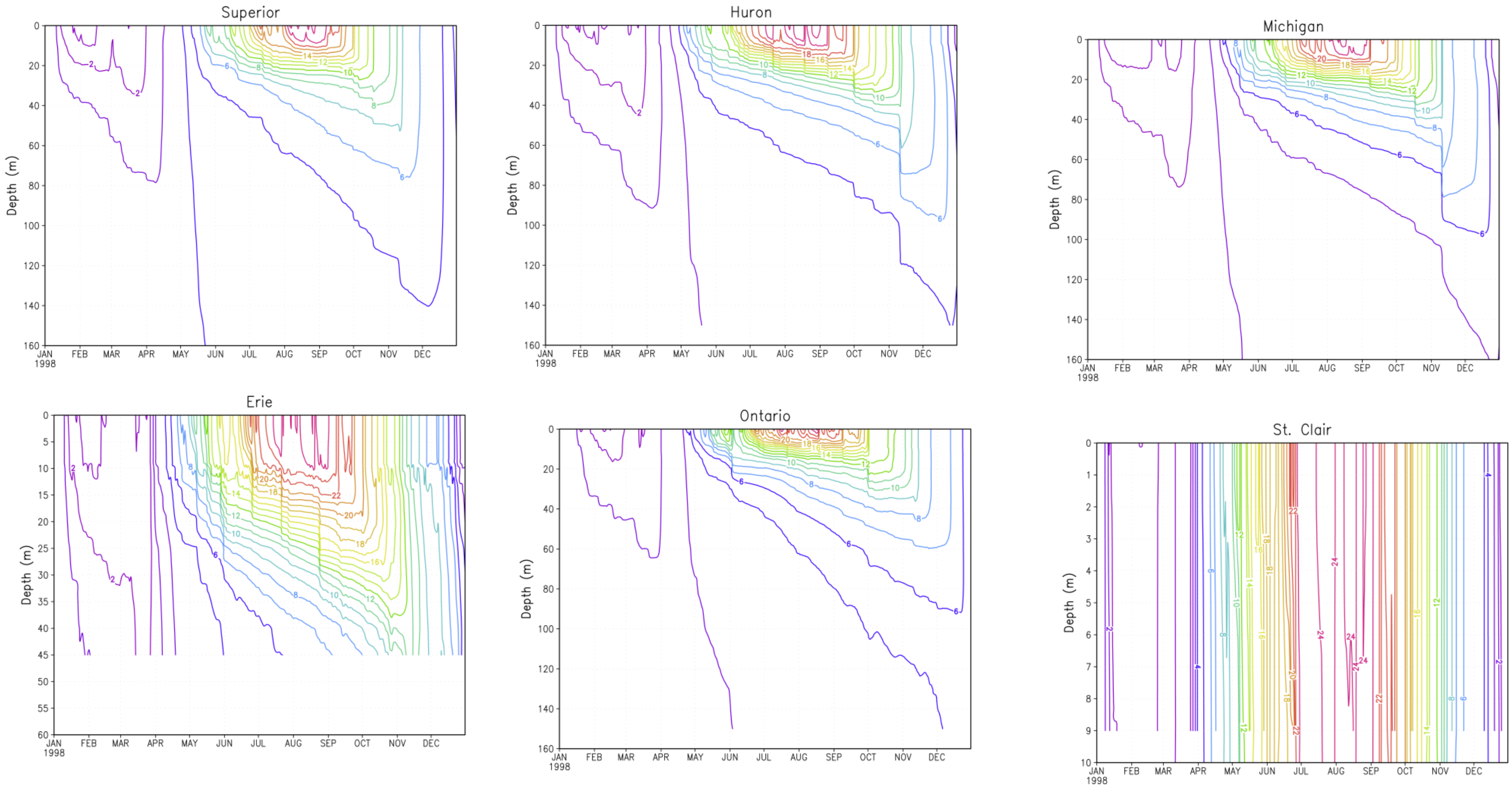
Model Results： Long-term 1993-2008 mean circulation



Model Results： Long-term 1993-2008 mean circulation



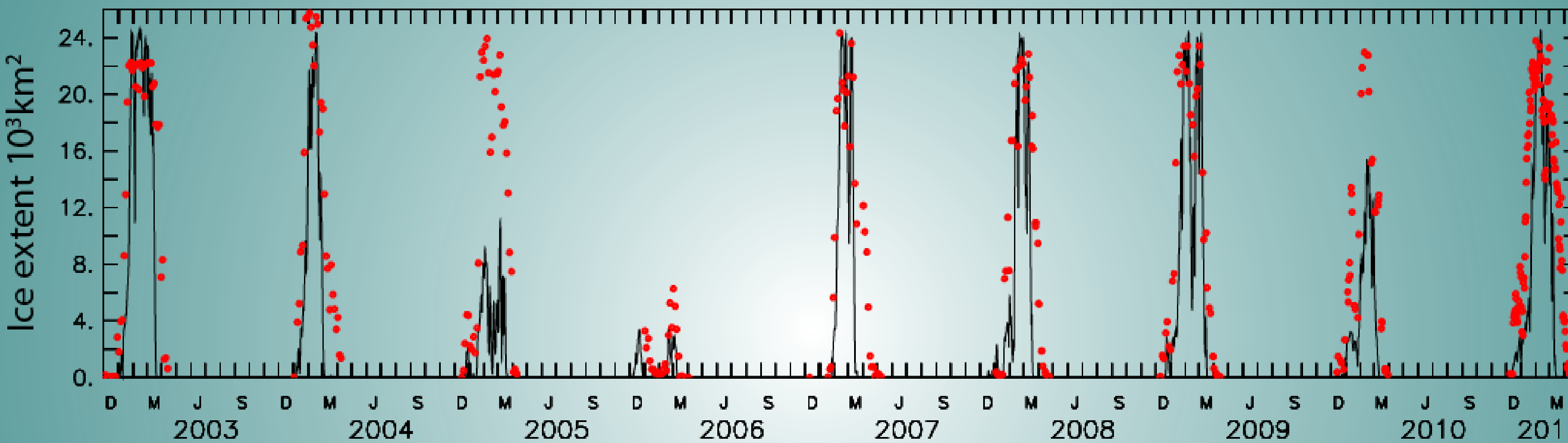
Seasonal Cycle of Lake Averaged Water Temperature

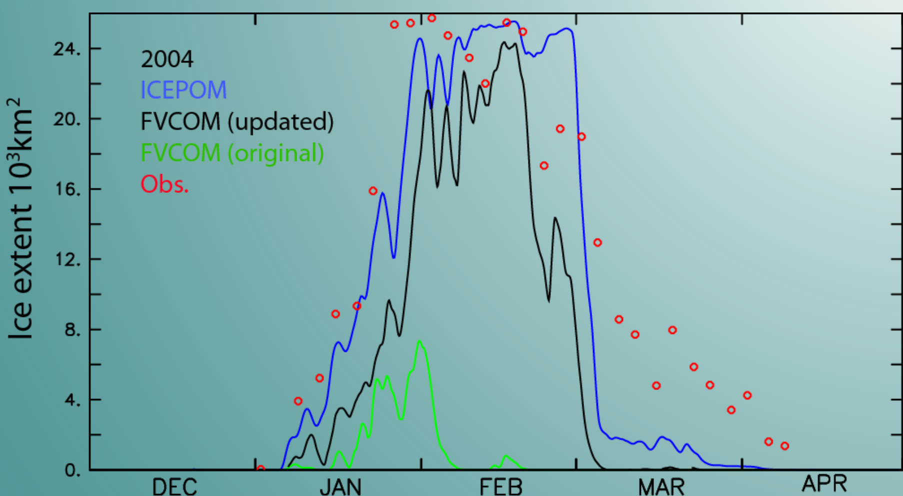


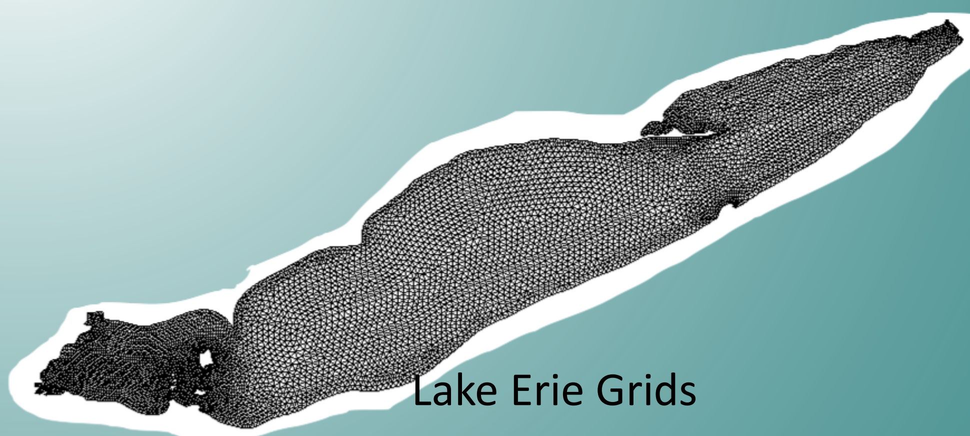
R&D: Modification and Implementation of FVCOM-Ice model

Changed Euler forward scheme and 4th-order Runge-Kutta scheme that are inertially unstable (Wang and Ikeda 1997, MWR) to centered differencing scheme of neutral stability for inertial motion.

Observed(red) and Simulated(black) Ice Extent in Lake Erie from 2003-2011





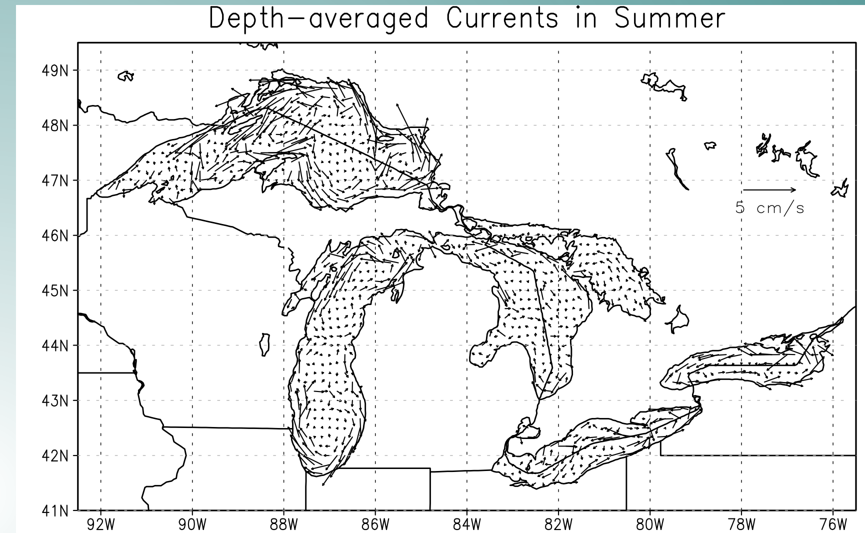


(Fujisaki-Manome and Wang 2015, in Prep.)

R&D: Development of 5-lake unstructured-grid FVCOM with ice (CICE4)

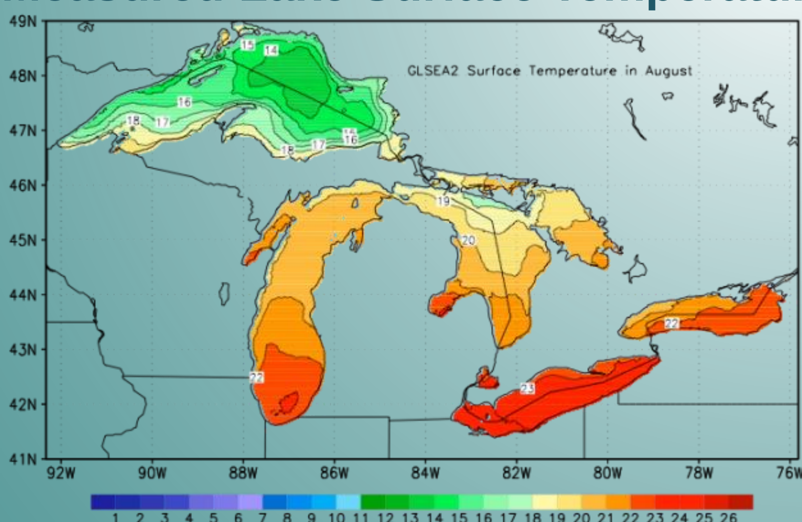
Grids

Modeled summer circulation

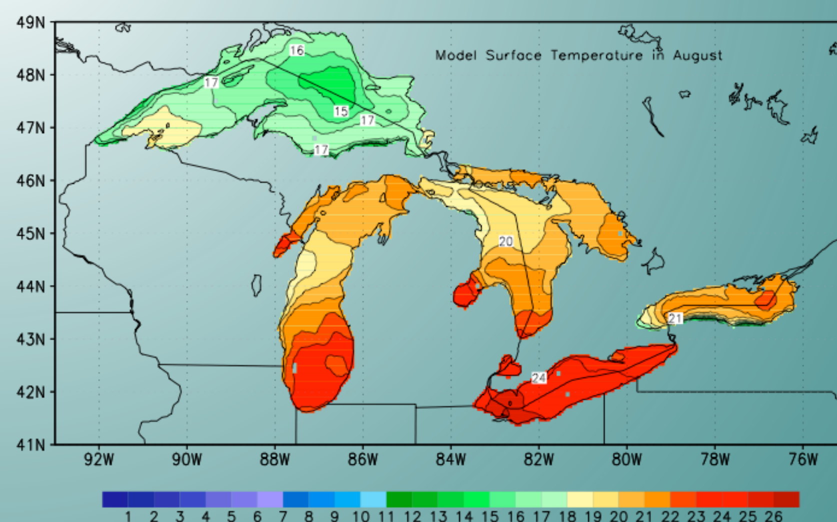


Measured Lake Surface Temperature

Aug

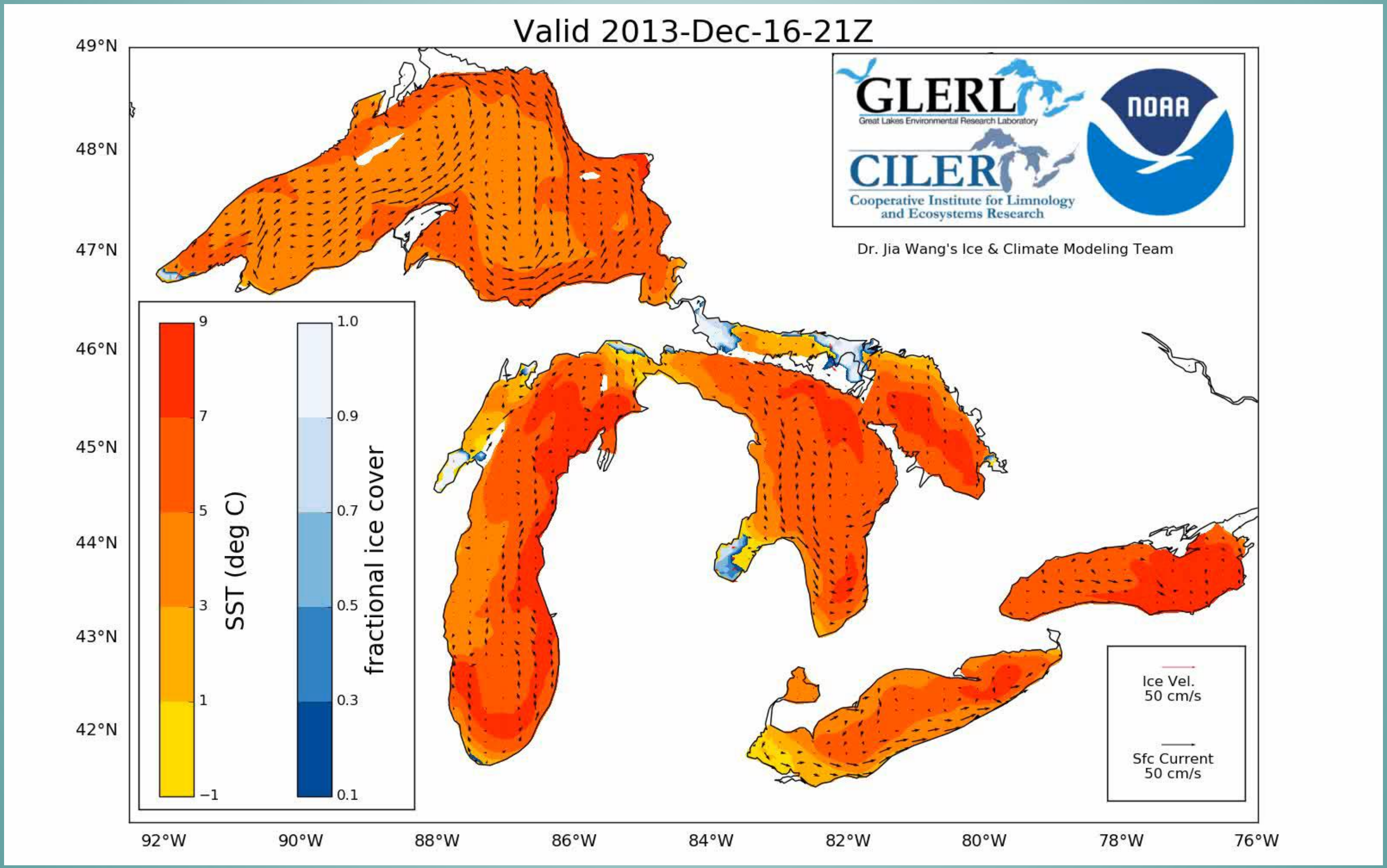


Modeled Lake Surface Temperature



(Bai et al. 2013, Ocean Modelling)

Model-simulated ice cover (blue scales) and ice flow (red arrows), and water temperature (red scales) and velocity (black)



2. Develop multiple variables regression models

Orig: (Bai et al. 2012, JGR) (1963-2017)

Y=0.46 -0.01Niño3.4 -0.53(Niño3.4)2 -0.33NAO+ 0.30NAO•(Niño3.4)2

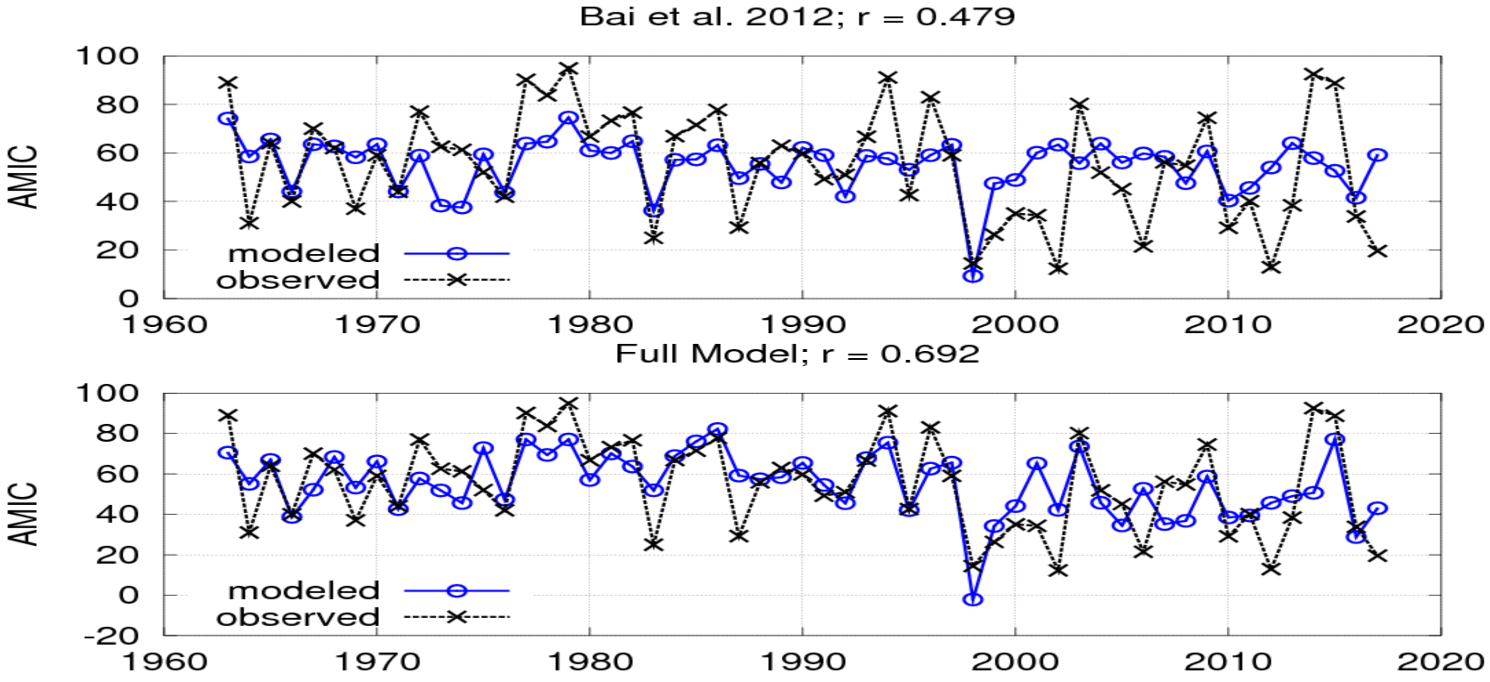
Full model

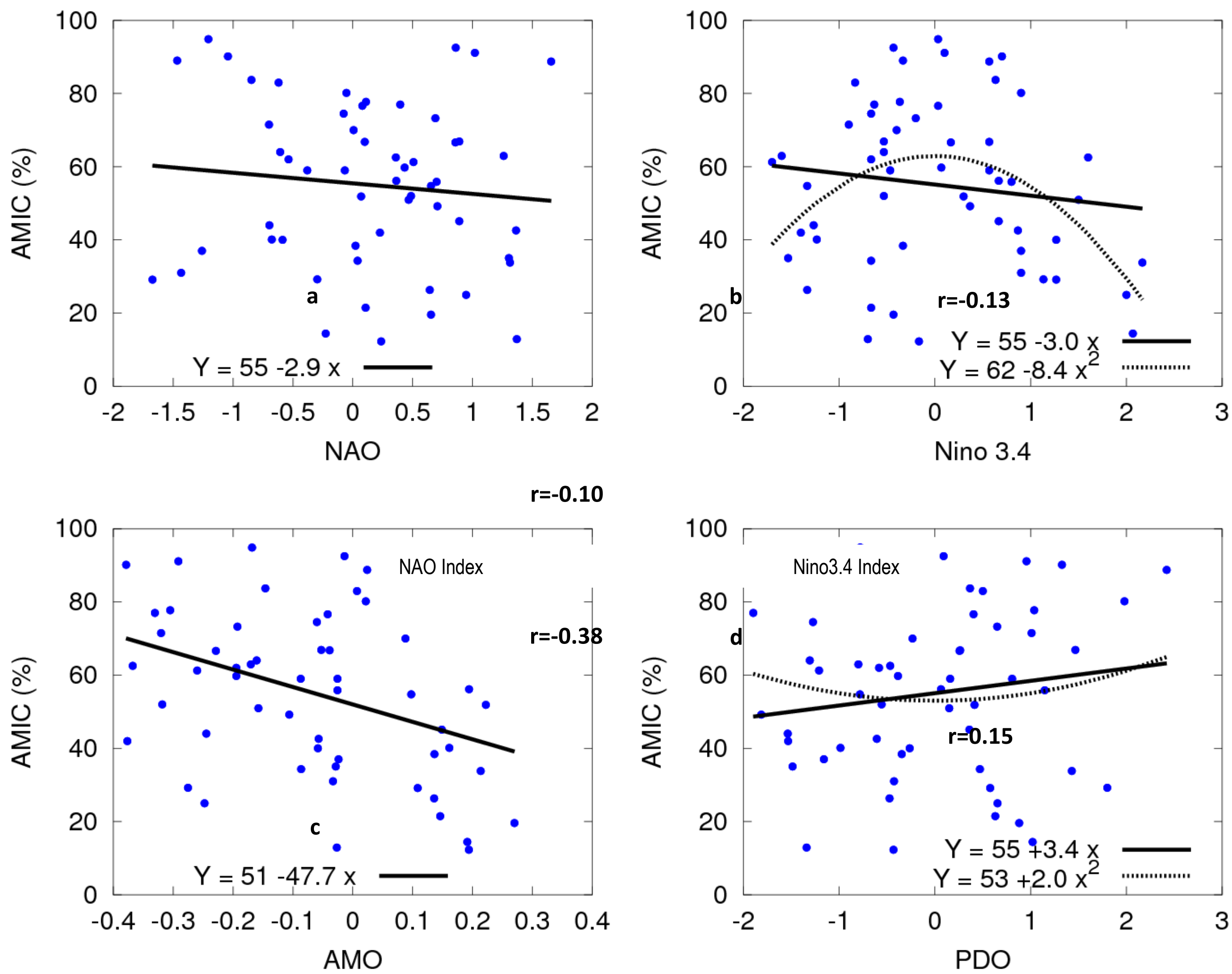
Y=0.18 -0.16Niño3.4 -0.47(Niño3.4)^2 -0.57NAO+ 0.38NAO•(Niño3.4)^2

-2.8AMO+0.25PDO+0.22PDO^2

-1.00AMO•NAO-0.07PDO2•(Niño3.4)^2

+0.98AMO•PDO^2





Scatter plots of AMIC vs. NAO index (a), Niño3.4 index (b), AMO index (c), and PDO index (d). The linear regression lines are given. The quadratic curves are also given for Niño3.4 and PDO. *r* indicates the linear correlation coefficients between the time series of AMIC and the individual indices for the period of 1963-2017.

Develop multiple variables regression models

Full model without LST (1982-2017)

$Y=0.26 -0.15Niño3.4 -0.41(Niño3.4)^2 -0.25NAO+ 0.13NAO•(Niño3.4)^2$

$-3.86AMO+0.25PDO+0.15PDO^2$

$-0.64AMO•NAO-0.001PDO^2•(Niño3.4)^2$

$+2.32AMO•PDO^2$

Full model with LST (1982-2017)

$Y=0.21 -0.18Niño3.4 -0.32(Niño3.4)^2 -0.12NAO+ 0.04NAO•(Niño3.4)^2$

$-3.62AMO+0.22PDO+0.12PDO^2$

$-0.01AMO•NAO+0.001PDO^2•(Niño3.4)^2$

$+2.28AMO•PDO^2$ $-0.26LST$

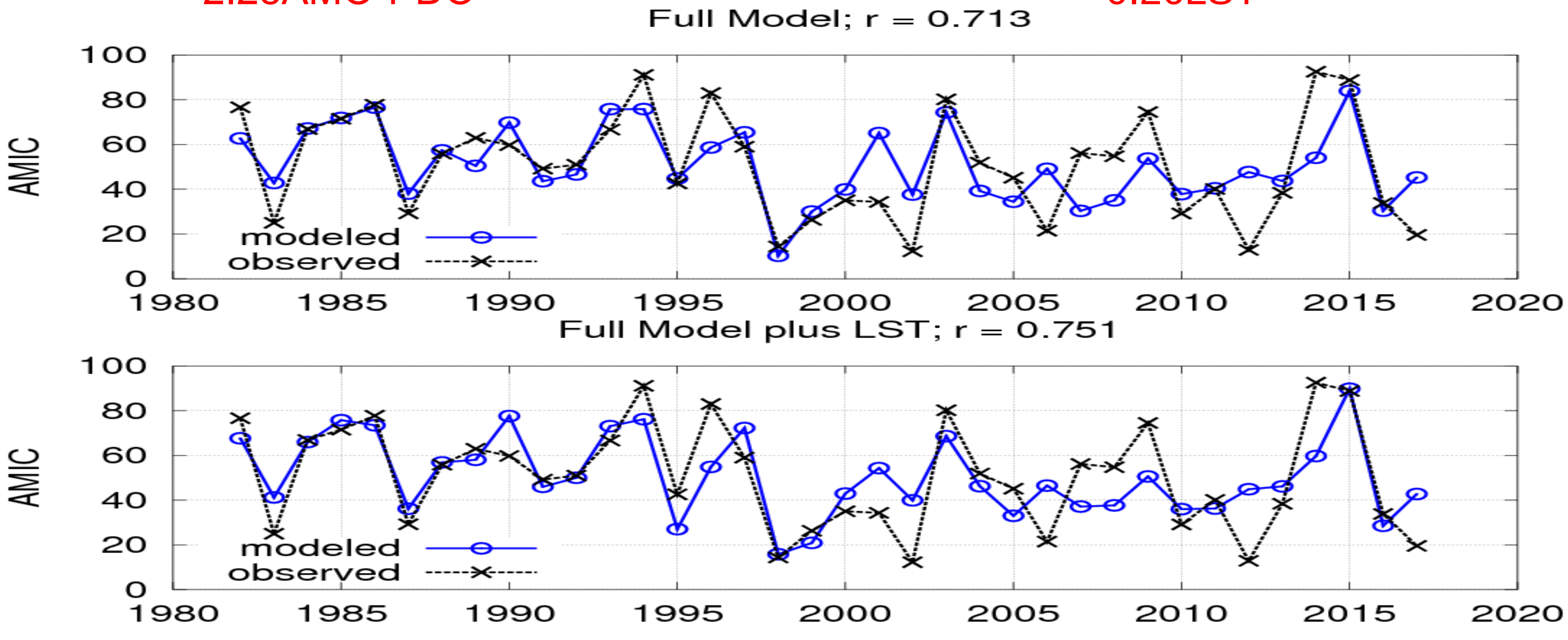
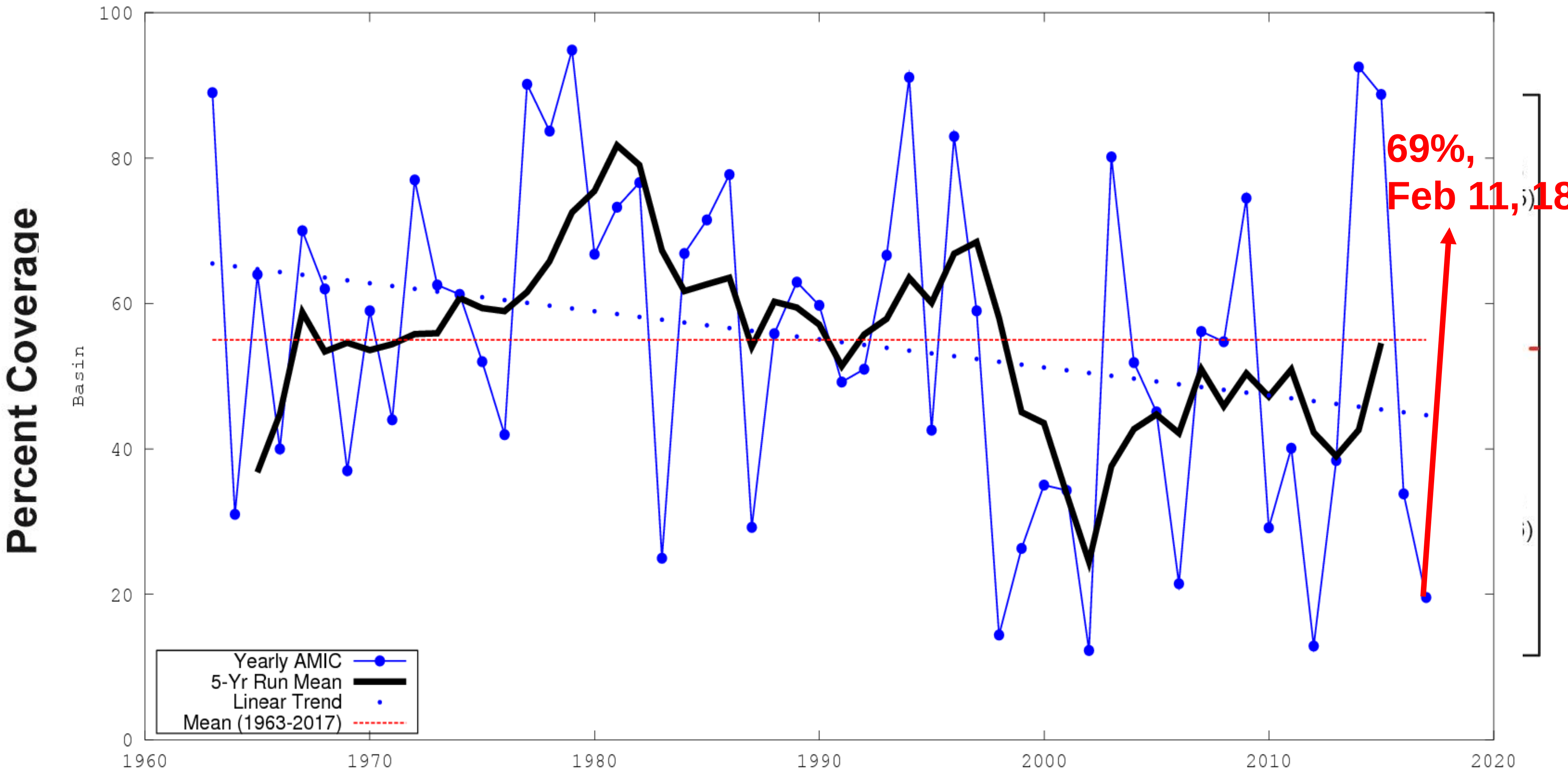


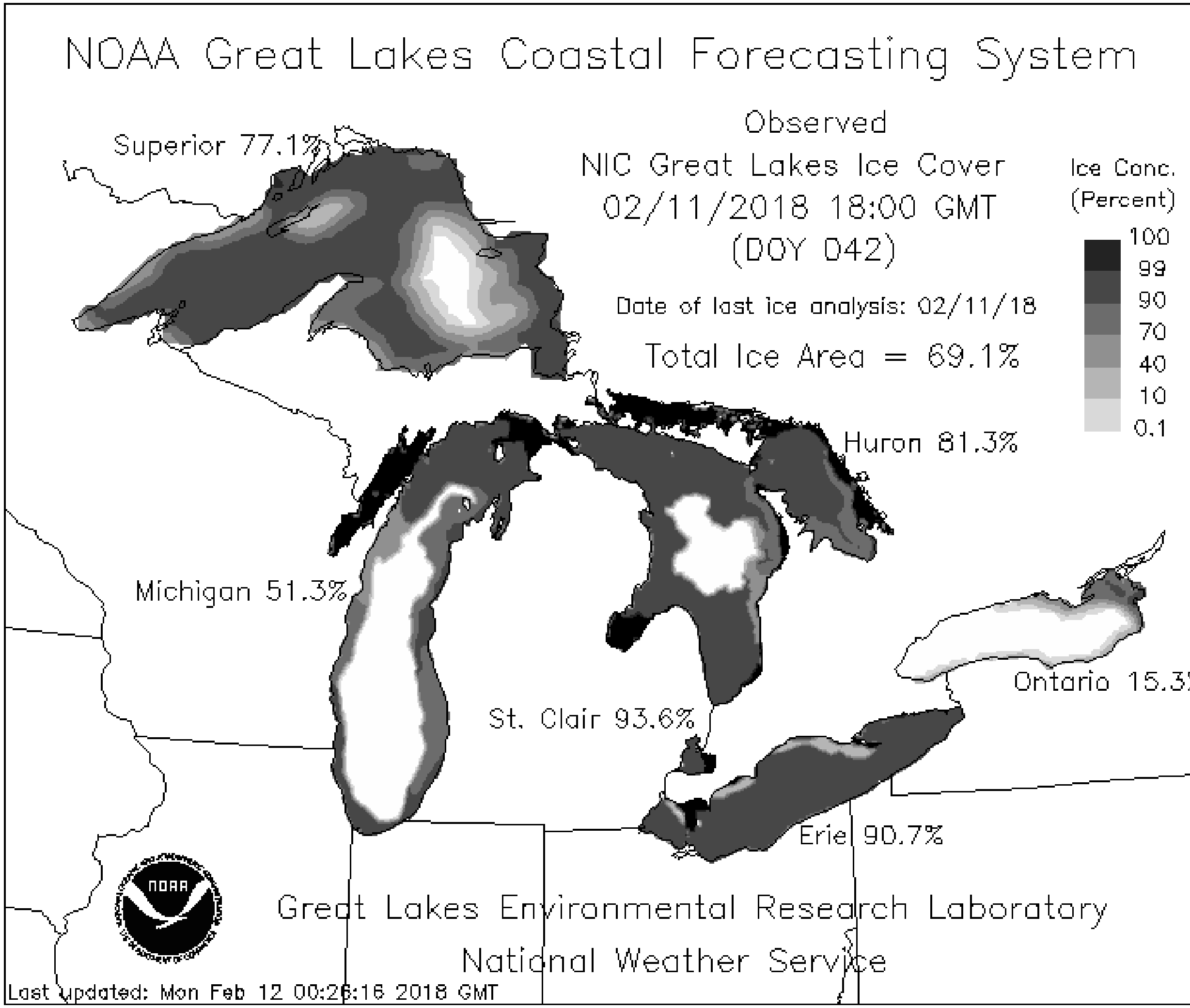
Table 2: Statistics for model compared to observed ice cover. RMSE is root mean square error, correlation is Pearson's correlation coefficient (r), p-value is the significance of correlation based on students T-test, adjusted-R^2 is r-squared value adjusted to penalize for multiple predictor variables, w/in 20% is the percentage of years that model predicted ice cover within 20% of observations (less than 20% absolute error), and w/in 10% is percentage of years with less than 10% absolute error

	Data used	**RMSE**	**Correl.**	**p-value**	**r^2**	**adj-r^2**	**w/in20%**	**w/in10%**
Bai et al.	(1963-2017)	20.47	0.48	0.00022	0.23	0.17	65%	38%
Full model	(1963-2017)	17.91	0.69	4.9×10^{-9}	0.48	0.36	78%	47%
Full model	(1981-2017)	19.17	0.71	1.1×10^{-6}	0.51	0.31	75%	53%
Full w/LST	(1981-2017)	18.41	0.75	1.3×10^{-8}	0.56	0.36	78%	53%

3. Application: 2018 projection

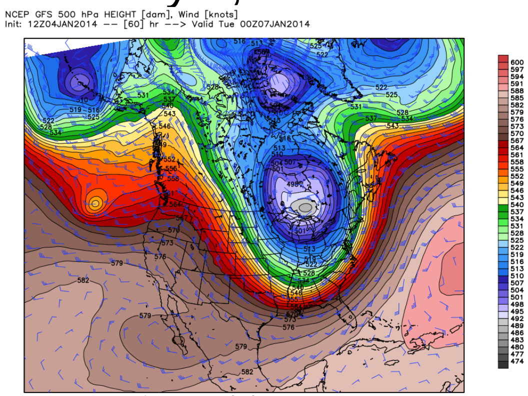


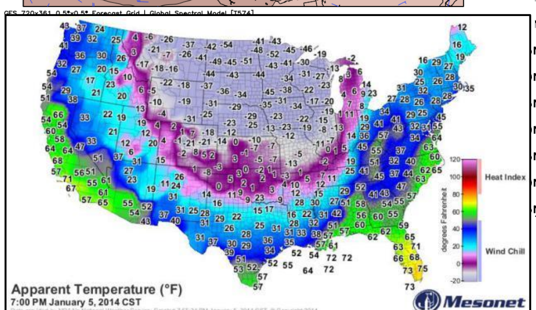
Max Ice Cover, Feb 11, 2018

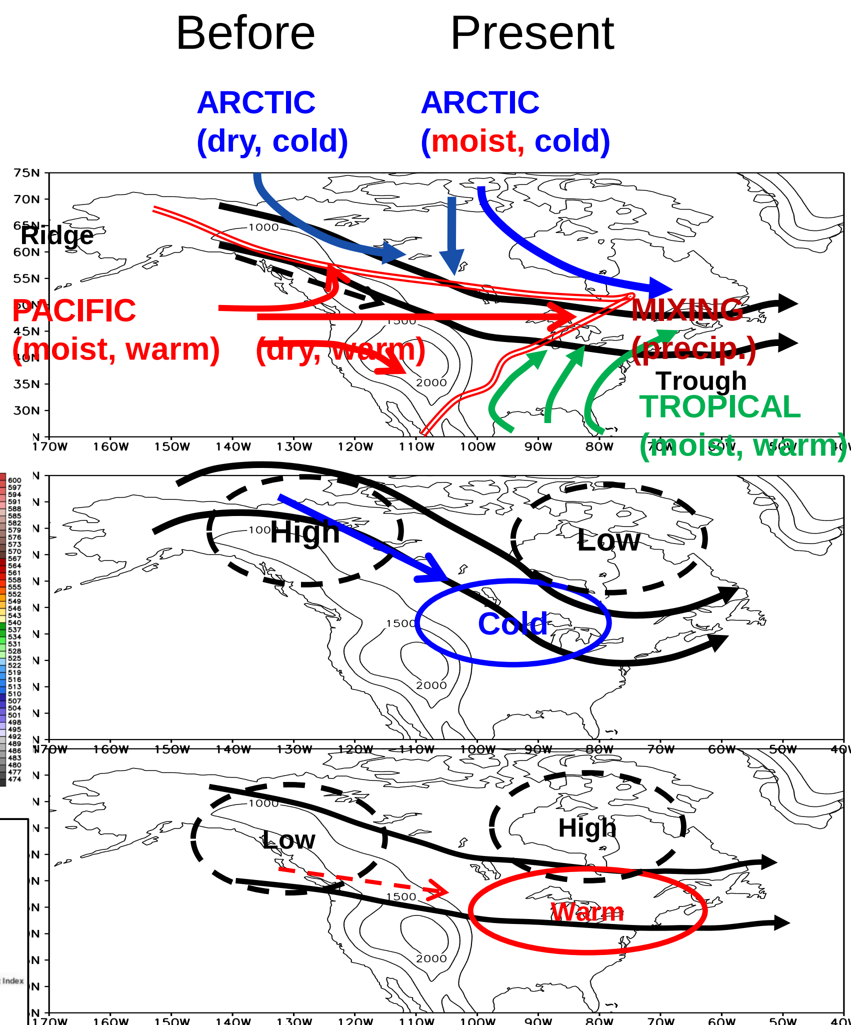


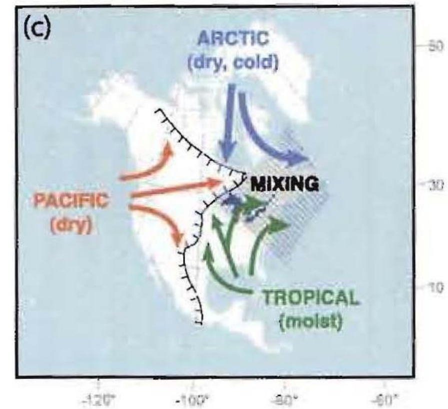
Climate Teleconnection and Lake Ice

Polar vortex on January 5, 2014





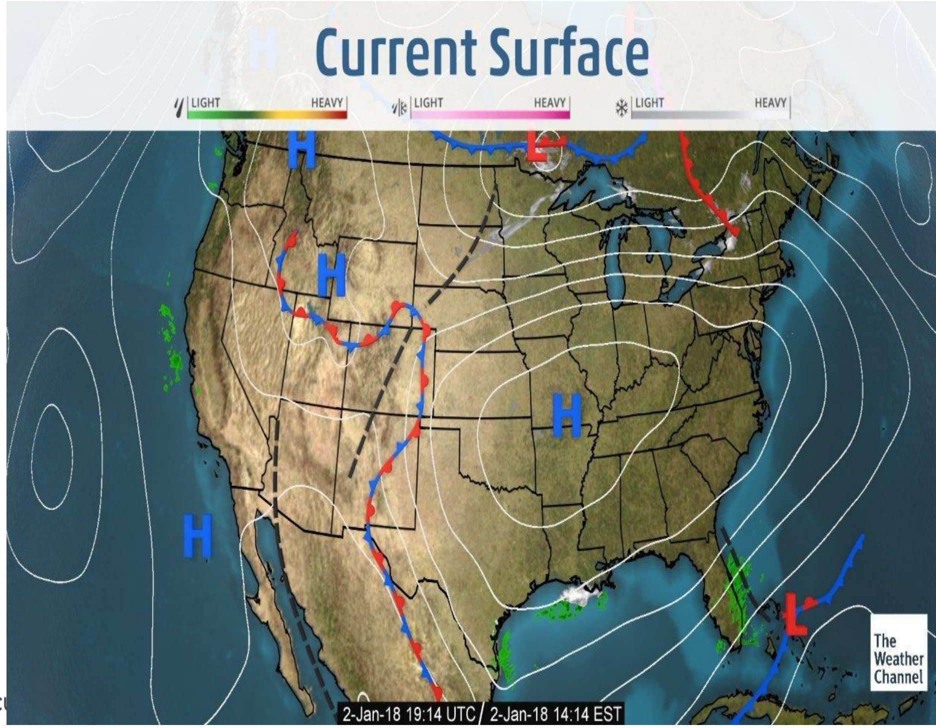


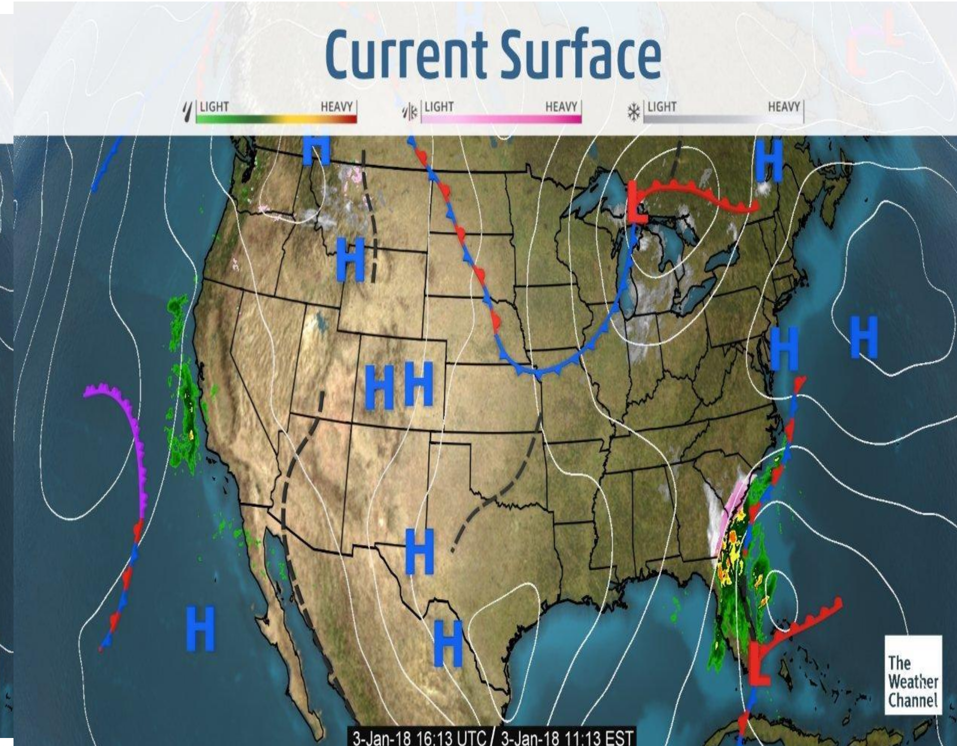


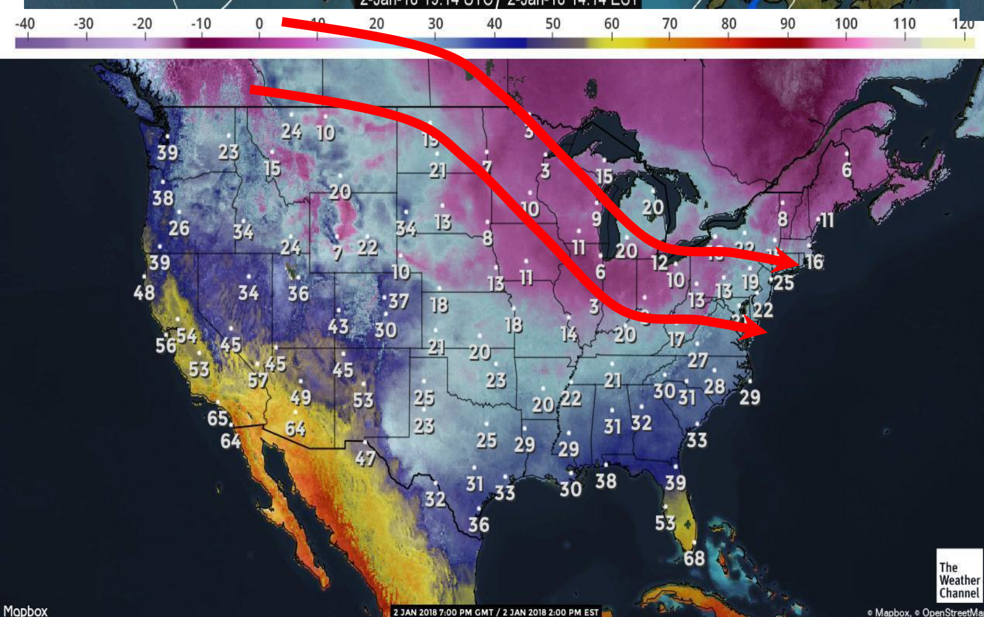
Lewis et al. 2008, EOS

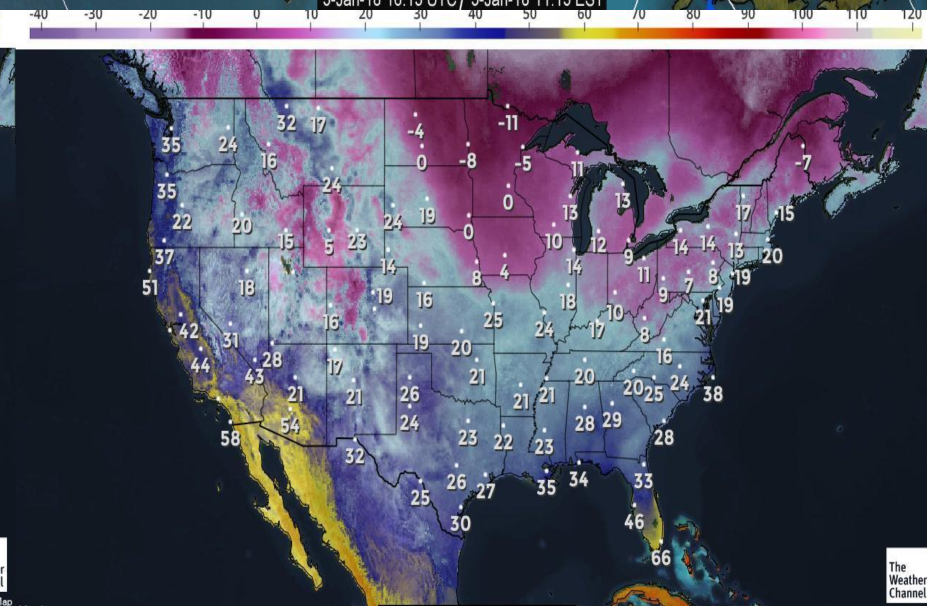
Conceptual diagram for the development of teleconnection patterns associated with severe and least ice cover, through the Westerly Jet ridge-trough system's intensification and weakening (Bai and Wang, 2012)

Current weather maps, Jan 2, 2018

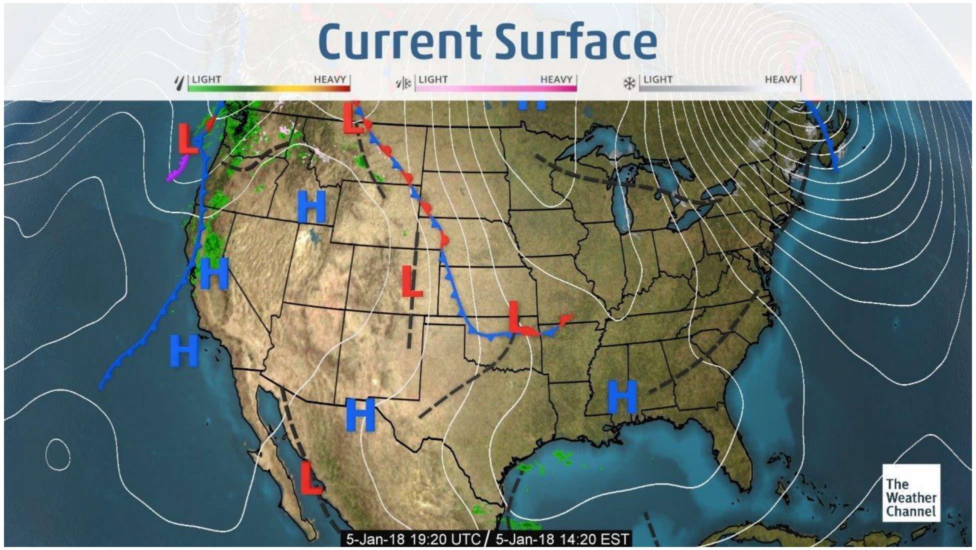


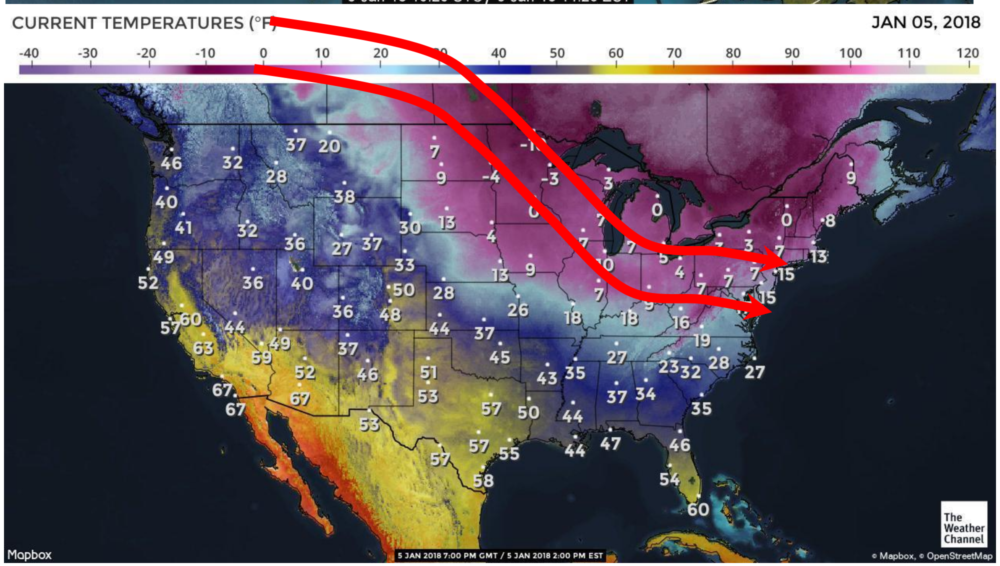






Current weather maps, Jan 3, 2018





Cold bombs or polar vortexes, Jan 3, 2018

Projecting annual maximum ice coverage in 2018 based on data from 1963-2017

Y=0.45 -0.13*Nino34 -0.4*Nino342 -0.4*NAO+ 0.21*NAO*Nino34**2 (ENSO&NAO on intera.)**
-0.5*AMO+0.15*PDO+0.05*PDO2 (AMO&PDO linear and squared on decadal)**
+0.01*AMO*NAO-0.08*PDO2*Nino34**2 (crossing decadal and interannual interactions)**
+0.16*PDO2*AMO (AMO&PDO interactions on decadal time scales)**

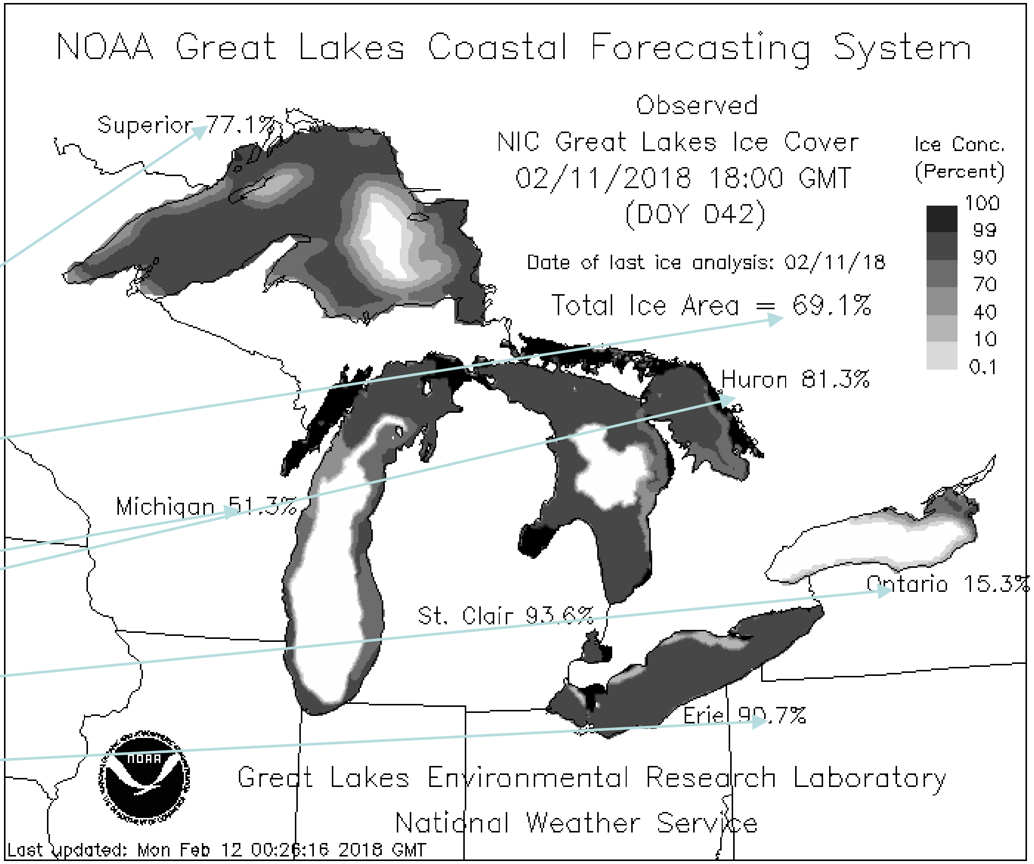
On Dec 28, 2017:

With projected
Nino3.4=-1.0
PDO= 0.5
NAO= -1.0
AMO= +0.4

we project:

AMIC=60%
Superior: 67
Michigan: 48
Huron: 70
Ontario: 31
Erie: 91

With new models



IV. Summary and future effort

- Similar to NAO, AMO has a linear, negative correlation with lake ice cover (r=-0.29, -0.31); similar to Nino3.4 (r=-0.22), PDO has a quadratic correlation with lake ice cover, but with positive sign (r=0.19)
- Adding PDO and AMO, and their interactions/competing to each other, and with NAO, and Nino3.4, the correlation increases from original 0.44 to 0. 68, a significant improvement.
- November LST has impact on ice formation. However, time series is 20 years shorter. The longer the time series, the better the regression models constructed
- In late December 2017, the projected indices changes signs:

Early Dec ➔ Late Dec of 2017

PDO (-0.5➔+0.5: warm to cold)

AMO (0.4➔ 0.3: same)

NAO (+0.5➔ -1.0: warm to cold)

Nino3.4 (-1.5➔-1.0: strong La Nina (warm)➔weak La Nina (cold)

- Regression model-projected overall Great Lakes AMIC➔60%;

y_super = 68; y_mich = 43; y_huron = 62; y_ont = 29; y_erie = 90%, very cose to the observations (~10% relative error)

Future effort

- Projected indices determine the accuracy of the projection
- Research and development of FVCOM+ice will be another approach to conduct seasonal ice prediction near the future.