Ice-out timing trend analysis for Minnesota lakes 1948-2008

Dave Staples[1], Lucinda Johnson[2], Dan Brenneman[2], Virginia Card[3]
[1]Minnesota Department of Natural Resources
[2] Center for Water and the Environment, Natural Resources Research Institute, University of Minnesota Duluth
[3] Metropolitan State University

Data from 71 lakes in MN were used to show trends in both observed and modeled ice out dates (in day-of-year format with Jan 1 = 1). [One observation for Isle Lake (DOW 270040) in 1991 was dropped as a suspected data entry error; it listed ice out day as 460.] To account for repeated measures of lakes over time and correlated annual variation in ice out date among lakes, we used a mixed model (Venables & Ripley,2002) to estimate the temporal trend in ice out date using the *lmer* function from the lme4 package in version 2.8.1 of the R statistical program (R Development Core Team, 2008).

Methods: The model contained fixed intercept and trend parameters in addition to 2 random effects representing a lake-specific intercept and within-year correlations in ice out date:

$$IO_{ij} = \beta_0 + \beta_1 * j + \lambda_i + \psi_j + \varepsilon_{ij}$$

where IO_{ij} was ice out date for the i^{th} lake (i = 1,…, 72) in year j (j = 0,…, 61 representing the years 1948-2008). The fixed intercept and trend parameters, β_0 and β_1 described the overall change in ice out date for the group of lakes. For inference on statewide changes in ice out date, β_1 was the parameter of interest ;i.e., this parameter represented the yearly change in ice out date for the 'population' of lakes in this data set. Since the year data were shifted by subtracting 1948, the intercept parameter, β_0, represented the average ice out date for the lakes in 1948 (excluding the random year effect).

The lake-specific adjustment for the i^{th} lake, λ_i, was assumed to be distributed $N(0, \sigma_L)$; for model fitting purposes, the only parameter to be estimated concerning the random lake effects is σ_L, though we can get unbiased predictors for the individual λ_i's (usually denoted as BLUPs for 'best linear unbiased predictor').. The λ_i's account for correlations among observed ice out dates for a single lake over time (e.g., a more northerly lake will tend to have a later ice out date); the σ_L parameter represents the variability in ice out date among lakes in the data set. The effect of the j^{th} year, ψ_j, accounts for correlations among lake in ice out date within a single year (e.g., all lakes statewide have early ice out dates because of a particularly early spring) and was assumed to be distributed as $N(0, \sigma_Y)$; the σ_Y parameter describes the variability in average ice out date among years. We used the ψ_j BLUPs for inference on yearly deviations in ice out date from the long-term fixed trend.

The model was fit with the observed and modeled data separately, both models had practically identical trend estimates and very similar variance estimates as the model fit to the full data set, confirming no differences between the observed and modeled ice out data; all results shown below reflect the full data set with observed and modeled data combined.

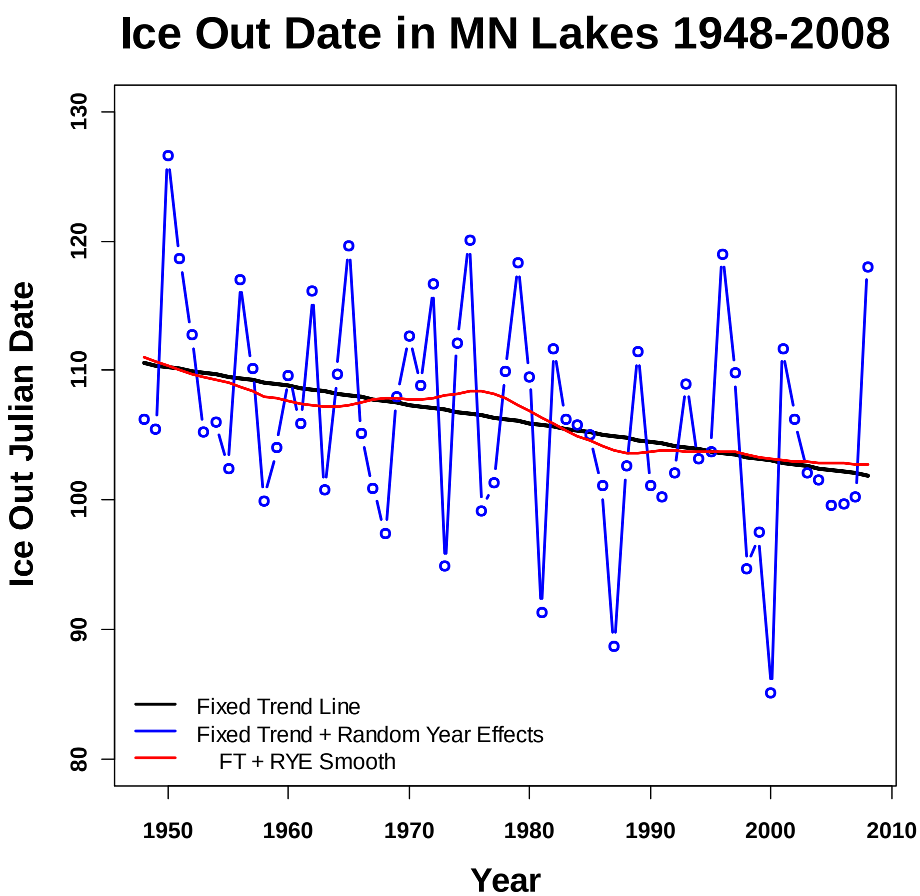
Results: There was a significantly negative estimate of the fixed trend in ice out date; ice out dates were 1.44 days earlier per decade (see Ice Out Date.. Figure). The average ice out date, excluding random year effects, for the earliest measurements (1948-1950) was approximately the 111th day of the year.

There was large deviation from the fixed trend among years in ice out date (σ_Y = 7.6 days). Over time, the year effects show a consistent up & down pattern, with more extreme early ice out events happening in recent years. In addition to the variation among lakes and years, in some years there was an inconsistent geographical split in how the observed ice-out date differed from the predicted date. For example, ice-out was earlier than predicted in the southern parts of MN for 1966, 1987, and 2007, while later than predicted in northern parts of Minnesota for those same years. The reverse occurred in 1951, 1952, and 1993, when ice-out was later than predicted in the southern regions and earlier than predicted in the northern regions.

There was large variation among lakes (σ_L = 7.29 days) which represent the large variation in climate and lake morphologies across the state; however, when compared to spatial location (UTM coordinates) there did not appear to be a spatial pattern in the random lake effects.

There was a slight trend in model residuals versus UTM northing coordinates, more southerly points tended to ice out earlier than predicted and northerly points tended to be a little later than predicted. When a centered UTM northing variable was added to the mixed model, the North-South predictor variable was highly significant: going North 1 km makes ice out tend to be .06 days later. Although the variation among lakes is decreased in this model (much of the random lake effects in the above model likely reflected latitudinal differences in ice out date), the estimated fixed trend in ice-out date is nearly identical to the original model which did not include UTM northing (-0.1448 here, -0.1441 in the previous model).

Figure X: The fixed ice-out trend and year effects (added to show the annual deviations about the trend), in additional to a smooth fit of the trend plus year effects.



Random effects:		
Groups Name	Variance	Std.Dev.
Lakename (Intercept)	53.191	7.2932[a]
year (Intercept)	57.782	7.6015[b]
Residual	13.102	3.6196[c]
Number of obs: 4334, groups: Lakename, 72; year, 61		

[a] Std. Dev is among-lake variation in the mean ice-out date
$\sigma_L = 7.29$
[b] Std. Dev is among year variation in mean ice-out date
$\sigma_Y = 7.6$
[c] Residual Std. Dev = 3.6
[d] Estimated fixed trend in ice out date = - 0.14

Fixed effects:			
	Estimate	Std. Error	t value
(Intercept)	110.5514	2.15268	51.36
yr	- 0.14411d	0.05536	-2.6

Figure XXX. Spatial distribution of random lake effect BLUPs on ice out date. Blue points represent lakes that tend to ice out the earliest, red points are lakes that tend to ice out latest.

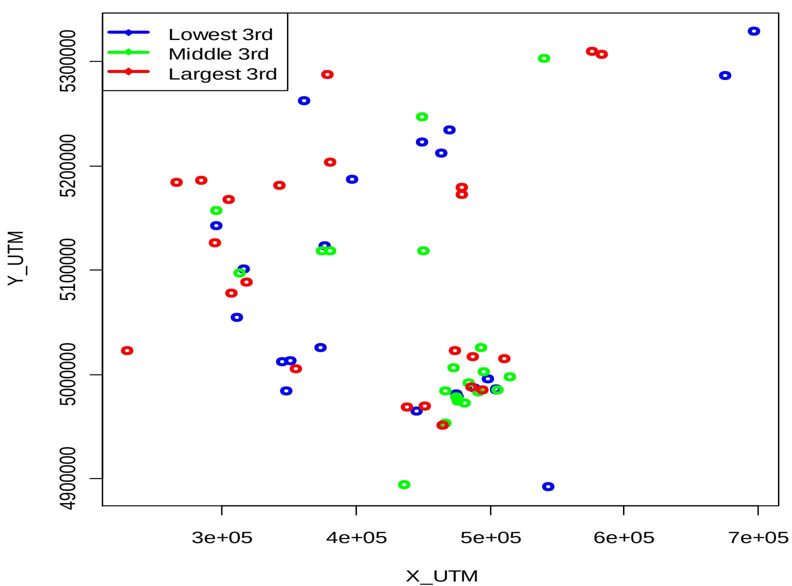
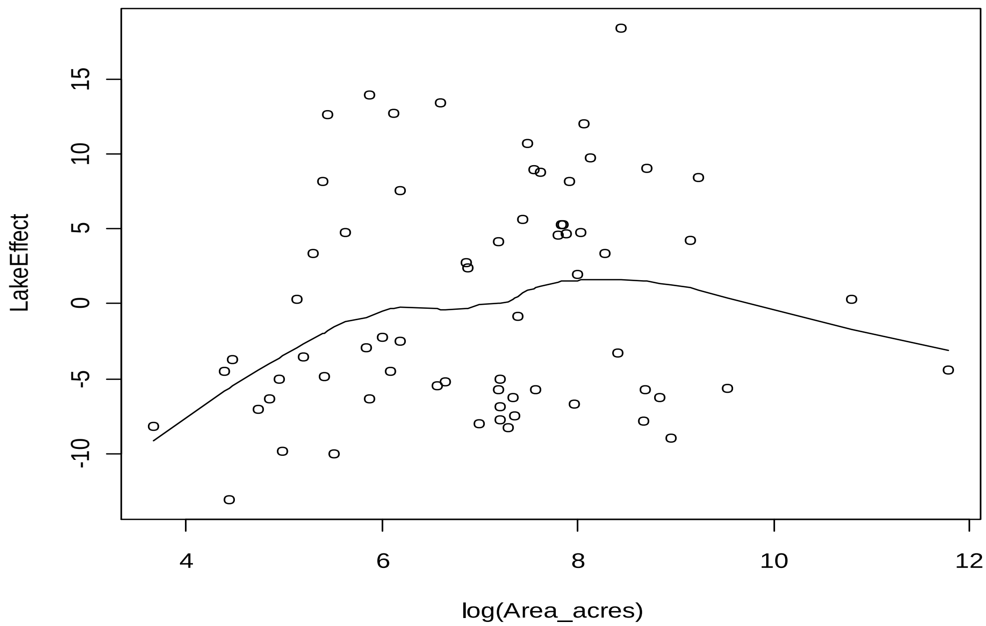


Figure XXX. Random lake effect BLUPs versus $\log_e$ lake area and maximum depth.



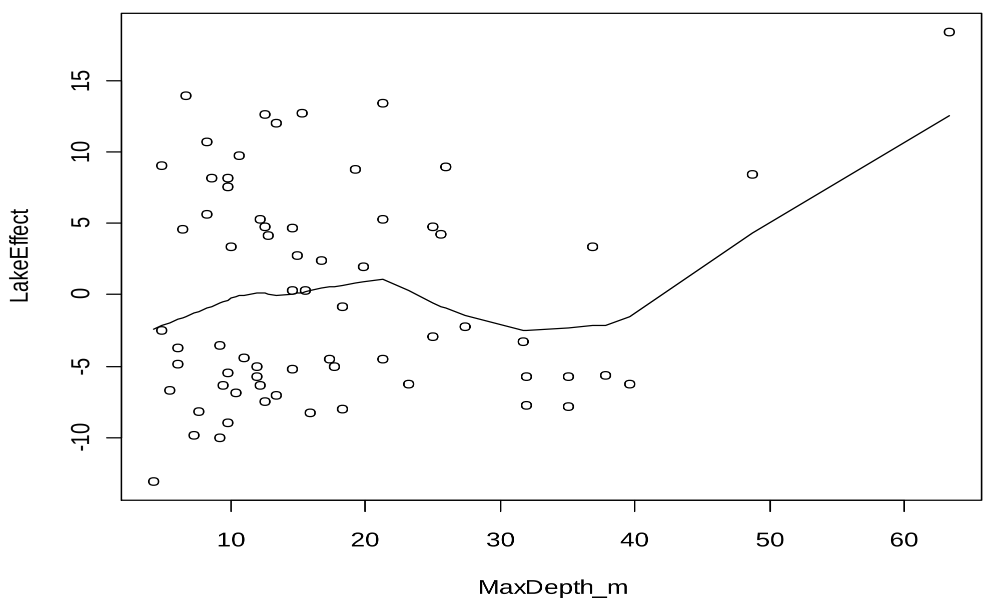


Figure XXX. Mixed model residuals versus year. Note bimodal residual distributions for some years (e.g., 1966 and 1987).

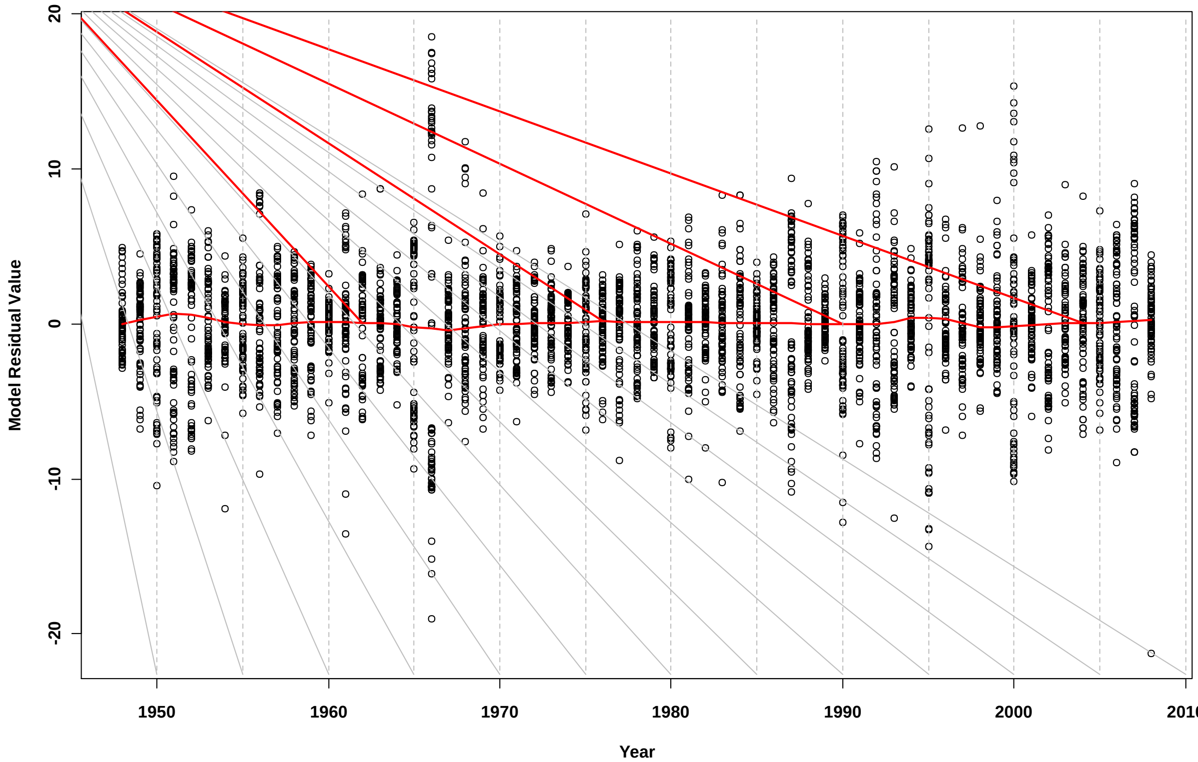
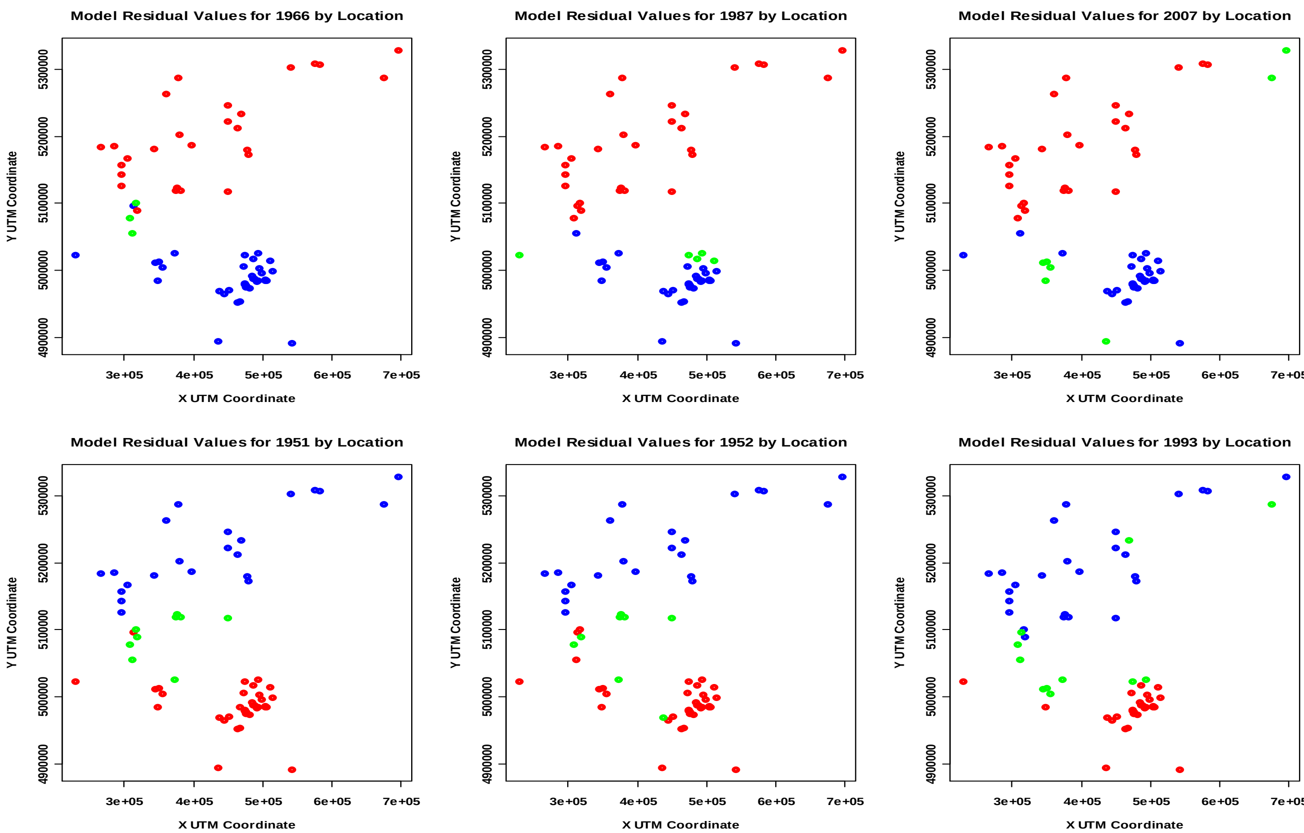


Figure XXX. Spatial plots of model residuals for selected year. There is a spatial split in those years with bimodal residuals; however, the pattern is not consistent. In figure below, ice out was earlier than predicted in the southern parts of MN for 1966, 1987, and 2007. In contrast, ice out in the years 1951, 1952, and 1993 was later than predicted in the southern region.



Blue- Ice out was earlier than predicted; Red- Ice out later than predicted; Green- Ice out with 2 days of predicted

When Y coordinate (UTM) added to the mixed model:

Random effects:		
Groups Name	Variance	Std.Dev.
Lakename (Intercept)	4.9786	2.2313
year (Intercept)	57.601	7.5895
Residual	13.2144	3.6352
Number of obs: 4029, groups: Lakename, 67; year 61		

Fixed effects:		
Estimate	Std. Error	t value
(Intercept) 98.77641	1.99455	49.52
yr -0.14483	0.05528	-2.62
Y_UTM 0.06119	0.00243	25.18

Correlation of Fixed Effects		
	(Intr)	yr
yr	-0.831	
Y_UTM	-0.228	0

The results from the lake ice-out trend analysis are included in a presentation along with the lake surface water trend analyses (see Appendix F.)