

Satellite Monitoring of Lake Ice Breakup on the Laurentian Shield (1980–1994)

Randolph H. Wynne, Thomas M. Lillesand, Murray K. Clayton, and John J. Magnuson

Abstract

Lake ice breakup dates from 1980 to 1994 for 81 selected lakes and reservoirs in the U.S. upper Midwest and portions of Canada (60°N, 105°W to 40°N, 85°W) were determined employing analysis of 1,830 archival images from the visible band (0.54 to 0.70 μm) of the GOES-VISSR. The objectives were to investigate the utility of monitoring ice phenology as a climate indicator and to assess regional trends in lake ice breakup dates. The dates of imagery represented the range available in the national archive at the time of this study. Comparison of satellite-derived breakup dates with available ground reference data revealed a mean absolute difference of ± 3.2 days and a mean difference of -0.4 days, well within the natural variability in lake ice breakup dates ($\sigma \approx \pm 12$ days) for a single lake over time. The predominant spatial trends of mean ice breakup dates can be attributed to latitude and snowfall ($R^2 = 93$ percent). Analysis of the pooled data for all 81 lakes revealed a significant ($p < 0.001$) trend toward earlier ice breakup dates. All of the individual lakes exhibiting significant trends toward earlier ice breakup from 1980 to 1994 are located in southern Wisconsin.

Introduction

Lake ice cover occurs in winter at higher latitudes. Fortunately, this corresponds to the season and location where temperature increases from enhanced greenhouse effects are expected to be greatest (e.g., National Research Council, 1982; Manabe and Wetherald, 1986; Mitchell *et al.*, 1990; Kattenberg *et al.*, 1996). Numerous studies suggest the utility of lake ice phenology as an index of long-term climate variability and change (e.g., Palecki and Barry, 1986; Schindler *et al.*, 1990; Robertson *et al.*, 1992; Wynne and Lillesand, 1993; Assel and Robertson, 1995; Anderson *et al.*, 1996). Long-term data from inland lakes and Great Lakes bays reveal trends toward decreased ice duration, primarily from earlier breakup dates (Comb, 1990; Schindler *et al.*, 1990; Hanson *et al.*, 1992; Robertson *et al.*, 1992; Assel and Robertson, 1995; Anderson *et al.*, 1996). These trends are not mono-

R.H. Wynne is with the Department of Forestry, Virginia Polytechnic Institute and State University, 319 Cheatham Hall (0324), Blacksburg, VA 24061 (wynne@vt.edu).

T.M. Lillesand is with the Environmental Remote Sensing Center, University of Wisconsin-Madison, 1225 West Dayton Street, Madison, WI 53706.

M.K. Clayton is with the Department of Statistics and Department of Plant Pathology, University of Wisconsin-Madison, 1210 West Dayton Street, Madison, WI 53706.

J.J. Magnuson is with the Center for Limnology, University of Wisconsin-Madison, 680 North Park Street, Madison, WI 53706.

tonic. Marked trends toward earlier ice breakup are evident at the end of the "Little Ice Age" (*circa* 1890) and since 1980. Optical image data from spaceborne sensors in the latter period are potentially useful for lake ice detection (e.g., Maslanik and Barry, 1987; Wynne and Lillesand, 1993).¹ While the satellite data we analyzed are for fewer years than many direct observations of ice phenology, they greatly increase the spatial extent of potential data sets and can be analyzed retrospectively utilizing consistent criteria for the presence or absence of ice.

We determined lake ice breakup dates over the 15-year period from 1980 through 1994 for 81 lakes and reservoirs located in the U.S. upper Midwest and portions of Canada by analyzing 1,830 archived images from the visible band (0.54 to 0.70 μm) of the GOES-VISSR (Geostationary Operational Environmental Satellite Visible and Infrared Spin-Scan Radiometer). Our objectives were (1) to assess the utility of monitoring phenological changes in lake ice using satellite data as an integrative indicator of regional climate change, and (2) to assess the presence or absence of any trends in the resulting data both in space and time.

Methods

Study Lakes

We selected 81 lakes across the U.S. upper Midwest and south-central Canada (60°N, 105°W to 40°N, 85°W; Figure 1, keyed to Table 1) with surface areas ranging from 169 to 120,000 ha and maximum depths from 1.5 to 117 m. Lake selection was governed by the necessity for consistent image resolvability and the rapid transition from ice cover to open water, as well as the availability of ground-derived ice breakup dates and proximity to other lakes.

Lakes had to be large enough to be identified on the 0.9-km resolution GOES-VISSR images, yet small enough to exhibit a single discrete ice breakup date. Robertson *et al.* (1992) call lakes characterized by single-date ice breakup *rapid transition lakes*. The lakes also had to be unique enough in shape and spatial context to be easily identifiable on the image. Ground-derived ice breakup dates were available for only a few lakes, so the majority of these were selected. Most lakes were chosen in spatially proximate groups of two or more. This was done primarily to determine whether similar cli-

¹Specifically, Maslanik and Barry (1987) and Wynne and Lillesand (1993) showed that Defense Meteorological Satellite Program optical sensors and the AVHRR (respectively) are effective in the detection of ice on small inland lakes. The GOES-VISSR had not been similarly evaluated prior to this study.

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matic forcing would produce temporally coherent ice breakup dates among adjacent lakes (Wynne *et al.*, 1996).

Lake selection criteria often competed with each other. For instance, some Canadian lakes selected were too large to exhibit discrete ice breakup dates, but were chosen because (1) they could be easily identified in concentrated lake districts or (2) ground-based ice breakup data were available. Overall, larger lakes had to be chosen in the higher latitudes simply because the angle of incidence between the normal to the Earth's surface and the sensor increased with latitude, resulting in coarser spatial resolution at higher latitudes (Rodman *et al.*, 1995; Wynne *et al.*, 1995).

Data

Image Data

For each of the 15 years in the national archive we utilized 122 scenes from the 0.9-km resolution visible band (0.54 to 0.70 μm) of the GOES-VISSR for a total of 1,830 scenes. Sensors/bands from four different GOES satellites were used: (1) SMS-2 Visible from 1980 through 1982, (2) GOES-5 Visible from 1983 through 1984, (3) GOES-6 Visible from 1985 through 24 March 1987, and (4) GOES-7 Visible from 25 March 1987 through 1994. Each annual period of analysis consisted of daily images acquired from 1 March through 30 June at approximately 19:00 hours Coordinated Universal Time (UTC), corresponding to 12 to 2 PM local time across the image. Each image spanned the entire study area (upper left, 105°W, 60°N; lower right, 85°W, 40°N).

Supplementary Advanced Very High Resolution Radiometer (AVHRR) data were acquired from three sources: (1) near real-time acquisition; (2) the NOAA National Operational Hydrologic Remote Sensing Center (NOHRSC) CD-ROM series (1990–1993); and (3) the NOAA National Environmental Satellite, Data, and Information Service (NESDIS).

Lake Morphometry

Lake morphometry (surface area, maximum depth, and mean depth) was obtained primarily from state or provincial natural resource management agencies. When information on surface area was otherwise unavailable, the area was taken to be that of the polygon representing the lake or reservoir in the Digital Chart of the World (e.g., Danko, 1992). While data were predominantly from unpublished sources, two published compendia were used (Environment Canada, 1973; Wisconsin Department of Natural Resources, 1991). Elevations were obtained from the above sources and the *Omni Gazetteer of the United States of America* (1991). Latitude and longitude were determined from the above sources, the *Gazetteer of Canada: Manitoba* (Canadian Permanent Committee on Geographical Names, 1981), and the *Gazetteer of Canada: Ontario* (Canadian Permanent Committee on Geographical Names, 1988). When location was otherwise unavailable, it was taken to be the center of the corresponding polygon in the Digital Chart of the World.

Snowfall Data

Monthly snowfall for U.S. stations was obtained from National Weather Service cooperative observers as archived by the NOAA National Climatic Data Center. These were provided by the Wisconsin State Climatologist. Corresponding snowfall data were purchased from Environment Canada. Each station was paired with one or more lakes; there were 36 stations for the 81 study lakes. The station paired with a particular lake was the closest station to that lake with a continuous record of monthly temperature and/or snowfall over the study period.

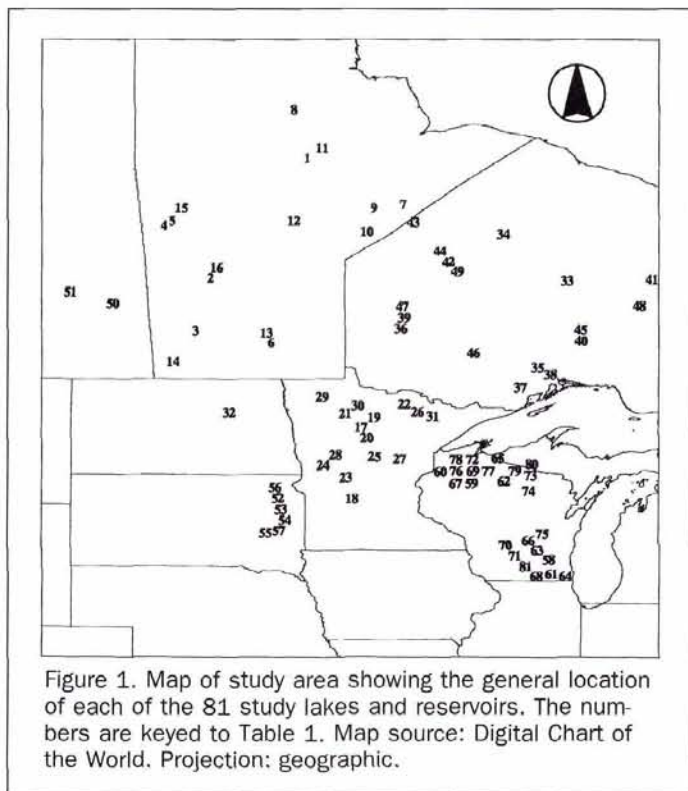


Figure 1. Map of study area showing the general location of each of the 81 study lakes and reservoirs. The numbers are keyed to Table 1. Map source: Digital Chart of the World. Projection: geographic.

Ground Reference Data

Ground-based data on lake ice breakup dates were only available for five of the 81 lakes. Data for Lakes Mendota and Monona were provided by the Wisconsin State Climatologist. The ice breakup dates for Trout Lake are part of the North Temperate Lakes Long-Term Ecological Research (NTL-LTER) core data set. Big Trout Lake, Ontario and Island Lake, Manitoba ice breakup information was obtained from Cote (1992).

Image Analysis

Preprocessing

The GOES data presented various problems not encountered in earlier work with data from the AVHRR (e.g., Wynne and Lillesand, 1993). Most notable was the extensive striping caused by differences in gain among the GOES' eight photomultipliers and the substantive quantization effect arising from the 6-bit radiometric resolution of the sensor. While stripes can be removed by matching empirical distribution functions for data from each detector (e.g., Weinreb *et al.*, 1989), we utilized a fast Fourier transform (FFT) notch filter (written by Professor Frank L. Scarpace of the University of Wisconsin-Madison) tailored to this data set (Wynne *et al.*, 1995).

The FFT used in the notch filter is based on the algorithm published in Press *et al.* (1992). This algorithm is an efficient implementation of the FFT that calculates the minimum number of Fourier coefficients and derives those remaining through assumptions of symmetry. The notch filter used to eliminate the noise in the frequency domain has a configuration similar to the cross-section of a U-shaped gully (Figure 2). The steepness and roundness of the slopes forming the gully sides depend on the size of the image under analysis. The intent is to minimize "ringing" in the image data while maintaining computational efficiency. The notch filter required geometrically constrained image dimensions;

TABLE 1. STUDY LAKES; KEYED TO FIGURE 1

#	Lake	State/Province	#	Lake	State/Province
1	Assean	Manitoba	41	Marshall	Ontario
2	Chitek	Manitoba	42	Mississa	Ontario
3	Clear	Manitoba	43	Nikip	Ontario
4	Clearwater	Manitoba	44	Pierce	Ontario
5	Cormorant	Manitoba	45	Sakwaso	Ontario
6	East Shoal	Manitoba	46	Stone	Ontario
7	Edmund	Manitoba	47	Sturgeon	Ontario
8	Etowney	Manitoba	48	Trout	Ontario
9	Gods	Manitoba	49	Wabimeig	Ontario
10	Good Spirit	Manitoba	50	Windigo	Ontario
11	Island	Manitoba	51	Little Quill	Saskatchewan
12	Limestone	Manitoba	52	Bitter	South Dakota
13	Molson	Manitoba	53	Kampeska	South Dakota
14	North Shoal	Manitoba	54	Poinsett	South Dakota
15	Oak	Manitoba	55	Thompson	South Dakota
16	Reed	Manitoba	56	Waubay	South Dakota
17	Sisib	Manitoba	57	Whitewood	South Dakota
18	Cass	Minnesota	58	Beaver Dam	Wisconsin
19	Green	Minnesota	59	Chippewa	Wisconsin
20	Island	Minnesota	60	Clear	Wisconsin
21	Leech	Minnesota	61	Delavan	Wisconsin
22	Lower Red	Minnesota	62	Fence	Wisconsin
23	Nett	Minnesota	63	Fox	Wisconsin
24	Osakis	Minnesota	64	Geneva	Wisconsin
25	Otter Tail	Minnesota	65	Gile	Wisconsin
26	Pelican	Minnesota	66	Green	Wisconsin
27	Pelican	Minnesota	67	Grindstone	Wisconsin
28	Rice	Minnesota	68	Kegonsa	Wisconsin
29	Rush	Minnesota	69	Lost Land	Wisconsin
30	Thief	Minnesota	70	Mendota	Wisconsin
31	Upper Red	Minnesota	71	Monona	Wisconsin
32	Vermillion	Minnesota	72	Namekegon	Wisconsin
33	Devils	North Dakota	73	North Twin	Wisconsin
34	Attawapiskat	Ontario	74	Pelican	Wisconsin
35	Big Trout	Ontario	75	Rush	Wisconsin
36	Black Sturgeon	Ontario	76	Spider	Wisconsin
37	Bruce	Ontario	77	Teal	Wisconsin
38	Dog	Ontario	78	Totagatic	Wisconsin
39	Frazer	Ontario	79	Trout	Wisconsin
40	Little Trout	Ontario	80	Vieux Desert	Wisconsin
			81	Waubesa	Wisconsin

we used 1024 rows by 2048 columns. Part of each image was lost in the filtering process because most of the pre-filtered images were approximately 1300 rows by 2400 columns. The filtered area of each image was selected to capture the spatial extent of ice change—more southerly closer to 1 March, more northerly toward 30 June. Also, image column boundaries were selected to include the 81 lakes for each year. See Figure 3 for an example of the improvement that occurs to image quality as a consequence of filtration.

GOES² Image Interpretation

LAKE ICE CONDITIONS

The objective of this interpretation was to determine the first ice-free day (ice breakup) for each lake, each year. Given the coarse resolution of the GOES-VISSR, the interpretation was limited to determining the earliest day on which there was

²AVHRR data were only used in the interpretation process in the "analyst training" stage, as well as to verify early visual interpretations of the GOES-VISSR data. This latter activity illustrated that there was no important difference in results obtained using the AVHRR and the GOES-VISSR. Two other factors also contributed to the decision to use exclusively data from the GOES-VISSR: (1) lack of availability of AVHRR Local Area Coverage (LAC) data (1.1 by 0.8-km resolution at nadir) before 1985, and (2) the greater cost of AVHRR data.

no observable difference between a lake's appearance compared with a much later date with ice known to be absent. A three-class scheme was used for ice condition, and an extra class (4) denoted occlusion by clouds. These were

- (1) Lake appears much brighter than surrounding land—snow covered ice with high reflectance.
- (2) Lake appears about the same as or slightly darker than surrounding land—probably bare, opaque ice.
- (3) Lake appears much darker than surrounding land and there is no observable difference from its appearance during following weeks/months, allowing for atmospheric variation (e.g., haze).
- (4) Clouds occluded lake. The most extreme example of this was a lake that was covered by clouds at the time of imaging for 28 consecutive days, making interpretation impossible on those days.

Setting boundaries for these classes was subjective; the most difficult distinction was between bare (black) ice and open water.

INTERPRETATION APPROACH

The approach was to compare daily images of each lake to images of "known" ice condition for that lake as both a radiometric and geometric reference. This "multi-temporal" classification procedure is described below³:

- (1) Identify definite ice-on and ice-off dates for a lake:
Ice-on: Snow-covered; appears much brighter than surrounding land.
Ice-off: Appears much darker than surrounding land; lakes within a 500-km radius appear ice-free as well.
- (2) Examine image mid-way between these known ice conditions. If a reliable ice-on/ice-off interpretation can be made relative to the two reference images, then the number of days necessary to examine is reduced by half.
- (3) Continue halving the time series until a time span of a week

³Rodman *et al.* (1996) contains additional details on the interpretation process, as well as a graphical example of that process.

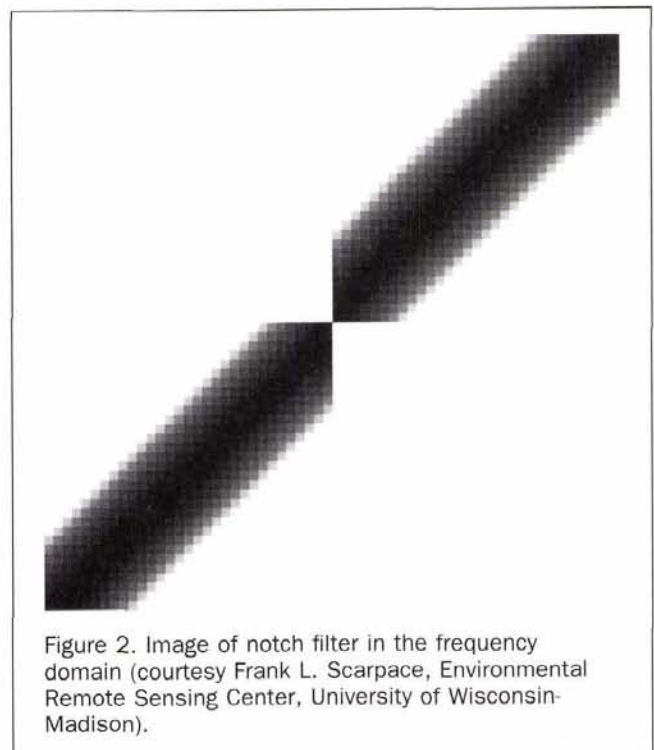


Figure 2. Image of notch filter in the frequency domain (courtesy Frank L. Scarpace, Environmental Remote Sensing Center, University of Wisconsin-Madison).

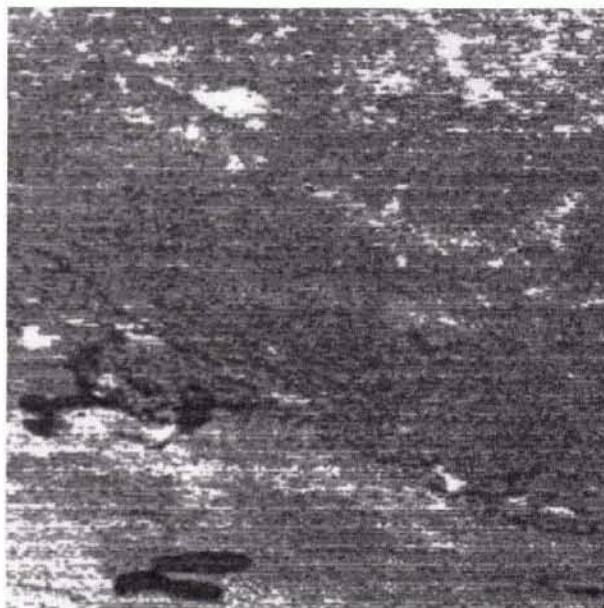


Figure 3. Subset of GOES-VISSR scene acquired on 25 April 1993. The top scene has not yet been filtered; the scene below shows the results of applying the notch filter. Notice the reduction in striping in the lower image. Note also the gradation from open water to ice covered lakes as one proceeds to higher latitudes (from bottom to top in either image). The large water bodies at lower left are Upper and Lower Red lakes in northwestern Minnesota (Wynne *et al.*, 1995).

or so is reached. Then view images sequentially by day, using the definite ice-off image for reference.

Certain weather events helped and hindered classification. Recent snowfall helped greatly by producing a sharp distinction between ice covered lakes (or surrounding land) and open water. Cloud shadow hindered classification by making lakes appear darker than on the preceding cloudless day; these cloud-influenced days were not classified.

Some lakes were easily identifiable as snow covered, but difficult to identify as open water. They never appeared as dark as others, even months after ice breakup on surrounding lakes. This phenomenon varied over the years for these lakes. It was not related absolutely to lake size, but was more common on smaller lakes. A possible explanation is sensor falloff with increasing latitude (typical of the GOES-VISSR series) in conjunction with poor modulation transfer.

POSITIONAL CONTROL

Consistent location of each of the 81 lakes was critical. While interpreting the first few years of images, atlases containing large-scale maps were examined to ensure that the correct lakes had been identified. After viewing many images, locating lakes became easier, especially in relation to easily identifiable lakes and lake patterns in a region.

Locating a lake when it had the same reflectance as surrounding land was difficult. This problem was circumvented by overlaying the ambiguous image with a reference image where the lake could be easily identified. The two images were spatially matched using identifiable points such as angular shorelines of nearby lakes.

Image overlay was possible because the GOES satellites are geostationary. Rotation or scale changes in the GOES images resulted in differences of only a few pixels across the image from day to day, making two-dimensional translation the only necessary image transformation. However, cumulative changes over weeks necessitated a new fit when overlaying temporally disparate images.

Metadata

The satellite data are an important product in themselves and will be an important archive. We utilized a relational database to store both reduced imagery and relevant metadata. Fields for the GOES data include, for example, the original archival file name, the name of the destriped image, the sensor source, date, day number, UTC, number of rows and columns, number of bands, and byte order. Each filtered image was reduced three times vertically and horizontally and incorporated into the database to provide browse functionality. For reference, we added fields for the upper left, scene center, and lower right (latitude and longitude). A composite key (consisting of date, UTC, sensor source, scene center longitude, and scene center latitude) precludes duplicate entries, maintains a sort order, and allows for relational tables and queries.

Results and Discussion

GOES Image Analysis

General Utility

A histogram derived from the visible band of an AVHRR image of areas with and without snow reveals a bimodal spectral response (e.g., Wynne and Lillesand, 1993). Lower digital numbers denote open water or land with no snow, while higher digital numbers represent ice, snow, or clouds. This pattern is repeated with the visible band (0.54 to 0.70 μm) of the GOES-VISSR (Figure 4). In the scene used to generate this figure, lake ice was differentiable from open water and cloud cover. This was not always the case, because digital numbers from clouds often were quite comparable to those from ice, especially when the latter was snow covered. Once the ice was snow free, it often was difficult or impossible to differentiate between black ice and open water. Both interpretation difficulties were exacerbated by the low radiometric resolution (6 bits = 64 gray levels) as well as the low spectral resolution, because only the visible band of the GOES-VISSR has suitable spatial resolution (0.9 km at nadir). The limitation to only one

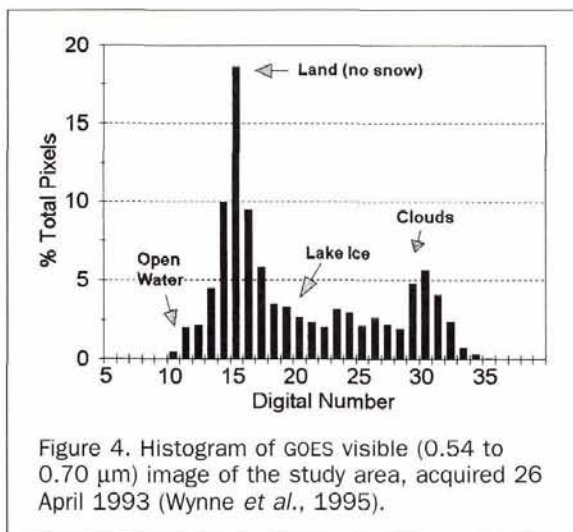


Figure 4. Histogram of GOES visible (0.54 to 0.70 μm) image of the study area, acquired 26 April 1993 (Wynne *et al.*, 1995).

spectral band precluded the use of semi-automated, multispectral classification techniques and thwarted spectral discrimination of certain features from each other, such as snow from clouds. These two problems, in addition to the need for spatiotemporal pattern recognition, led to our decision to employ visual interpretation techniques.

Accuracy

The GOES-determined dates of lake ice breakup compare favorably to the available ground-based reference data. The mean absolute difference was ± 3.2 days and the mean difference (observed minus reference) was -0.4 days. These are relatively low errors, given the one-day temporal resolution of the data. Even the mean absolute difference is well within the range of natural variability. For example, the standard deviation of Lake Mendota's ice breakup date from 1962 to 1990 is 11.8 days (Vavrus *et al.*, 1996). The GOES-VISSR is thus a viable means of determining the date of lake ice breakup. Additionally, unlike ground-based data sets, this data set was developed using a uniform criterion for the "ice-off" condition. Ground-based information on ice formation and breakup dates is plagued by some of the same types of errors in other climatological data, such as changes in observers and protocol. Difficulties in distinguishing black ice from open water produced satellite-derived average ice breakup dates that were earlier than those derived from direct observation.

Another obstacle to satellite interpretation of ice breakup dates was cloud cover. In many instances, a series of cloudy days prevented daily interpretation, and the lake first appeared open on the next cloud free day. The average occlusion from cloud cover prior to a visible ice breakup date was 3.7 days for all lakes over all years, and ranged from 0 to 28 days. We chose not to interpolate ice breakup dates within this cloudy period. The two major biases (inability to distinguish black ice from open water and cloud cover occlusion) tended to cancel each other, as indicated by the agreement between the satellite-derived and ground reference data.

Ice Breakup Dates

The mean date of ice breakup was day 118 (assuming 1 January as day 1). The average ranged from day 80 (Lake Geneva, Wisconsin) to day 170 (Etawney Lake, Manitoba), with a standard deviation of 20.5 days and a median of 116 days. The latest date in any year was day 180 (Etawney Lake,

Manitoba in 1988) and the earliest was day 66 (Lake White-wood, South Dakota in 1987).

Spatiotemporal Analysis of Ice Breakup Dates

This section concentrates on the identification of spatiotemporal trends in ice breakup dates, and their attribution (where possible) to attendant causes. First, we examine the spatial distribution of mean ice breakup dates. Then we detail the spatial distribution of temporal trends. Finally, we present models that describe the entire data set.

Spatial Distribution of Mean Ice Breakup Dates

This analysis entailed description (semivariograms), visualization (kriging), and modeling (multiple regression) of spatial pattern. The goal was to remove as much of the spatial pattern as possible through the use of appropriate explanatory variables.

Figure 5 shows the (omnidirectional) semivariogram calculated from the mean ice breakup date from each lake. The (Euclidean) lag distance (h) is in degrees latitude and/or longitude. These data were kriged using a Gaussian semivariogram model, with $h = 0.992$. The spherical model was used in all subsequent kriging. Two features are of special interest. First, there is no sill in the classic sense; thus, there is evidence of (spatial) non-stationarity. Second, the overall semivariance is extraordinarily high (the "sill," i.e., the semivariogram at $h = h_{\text{max}}$, was calculated as 1426 days²).

The kriged mean ice breakup dates (Figure 6) reveal the source of the pattern: a strong gradient associated with latitude, ranging from the 80-day contour in the south to the 170-day contour in the northeast. Subsequent regression analysis (Figure 7) confirmed the significance of latitude as an explanatory variable, with $R^2 = 92$ percent, $p < 0.0001$, and standard deviation = 6.0 days.

With an R^2 of 92 percent, much of the error variance—and spatial pattern—was removed. The semivariogram calculated from the residuals of the latitude regression (Figure 8a) is much flatter, with a sill of 51 days². The substantial decrease in spatial pattern is also apparent in the sills of the semivariograms from raw data and the residuals of the latitude regression; the sill decreased from 1426 to 51 days².

The kriged residuals of the latitude regression (Figure 9) still exhibit a strong spatial pattern. Contours range from -10 days (i.e., the breakup date was 10 days earlier than would be predicted from latitude alone) to $+8$ days. The highest negative residuals are predominantly in the west, while the highest positive residuals are just below Lake Superior and Hudson Bay. Evidence of the strong latitudinal

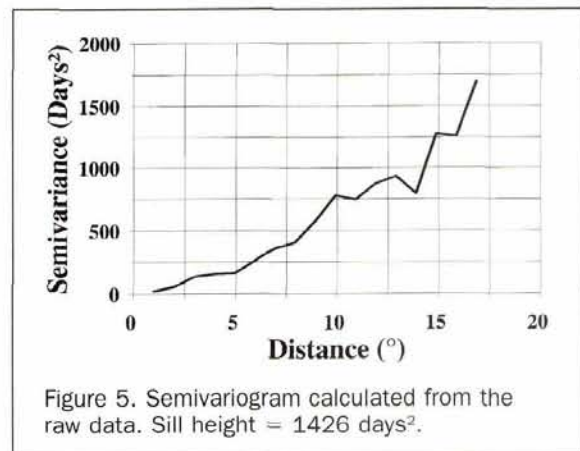


Figure 5. Semivariogram calculated from the raw data. Sill height = 1426 days².

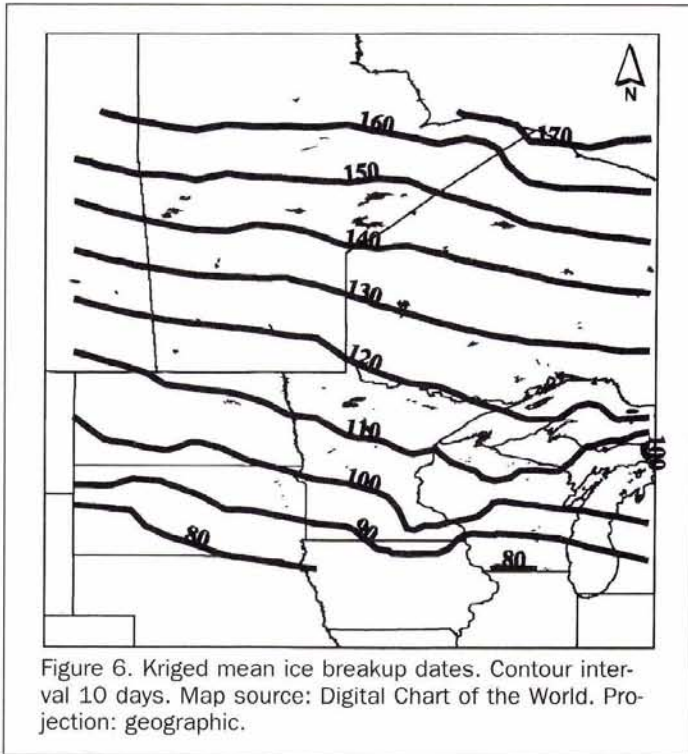


Figure 6. Kriged mean ice breakup dates. Contour interval 10 days. Map source: Digital Chart of the World. Projection: geographic.

gradient (Figure 6) has largely vanished, though there is still a north-south gradient in Wisconsin.

The strong pattern in the kriged residuals from the latitude regression is a clear indication that latitude alone is an

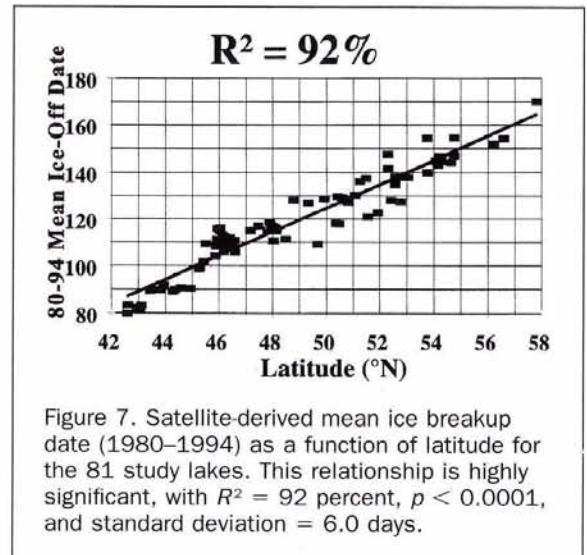


Figure 7. Satellite-derived mean ice breakup date (1980–1994) as a function of latitude for the 81 study lakes. This relationship is highly significant, with $R^2 = 92$ percent, $p < 0.0001$, and standard deviation = 6.0 days.

inadequate predictor of mean ice breakup dates. Surface area, maximum depth, surface area/maximum depth ratio, longitude, and elevation all were insignificant. The finding that lake morphometry is unimportant to the date of lake ice breakup as determined by the GOES-VISSR echoes earlier work (Wynne and Lillesand, 1993) utilizing the AVHRR.

Sensitivity analyses performed using a thermodynamic lake ice model (Vavrus *et al.*, 1996) revealed that snowfall was also an important parameter to consider in this analysis. A comparison of the kriged residuals from the latitude regression (Figure 9) and the kriged mean snowfall (Figure 10) reveals similarities. Of particular note is the correspondence

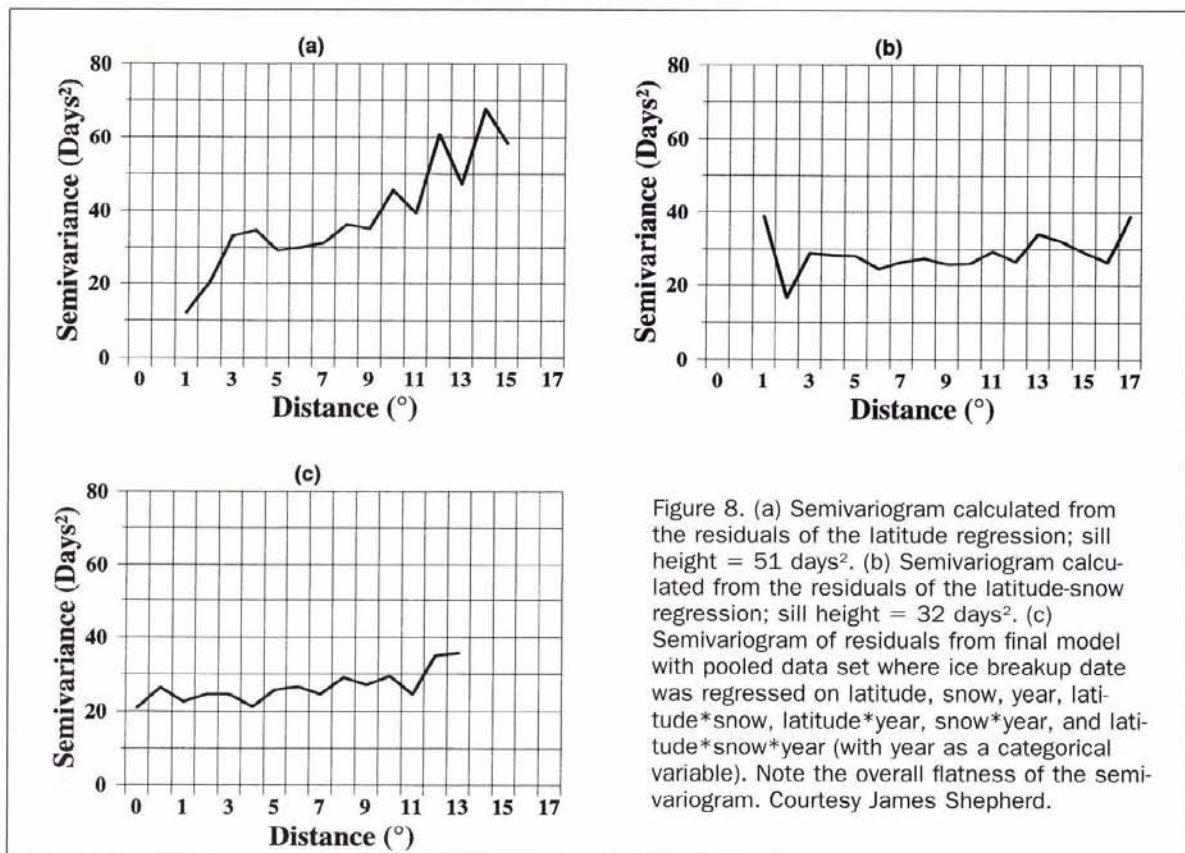


Figure 8. (a) Semivariogram calculated from the residuals of the latitude regression; sill height = 51 days². (b) Semivariogram calculated from the residuals of the latitude-snow regression; sill height = 32 days². (c) Semivariogram of residuals from final model with pooled data set where ice breakup date was regressed on latitude, snow, year, latitude*snow, latitude*year, snow*year, and latitude*snow*year (with year as a categorical variable). Note the overall flatness of the semivariogram. Courtesy James Shepherd.

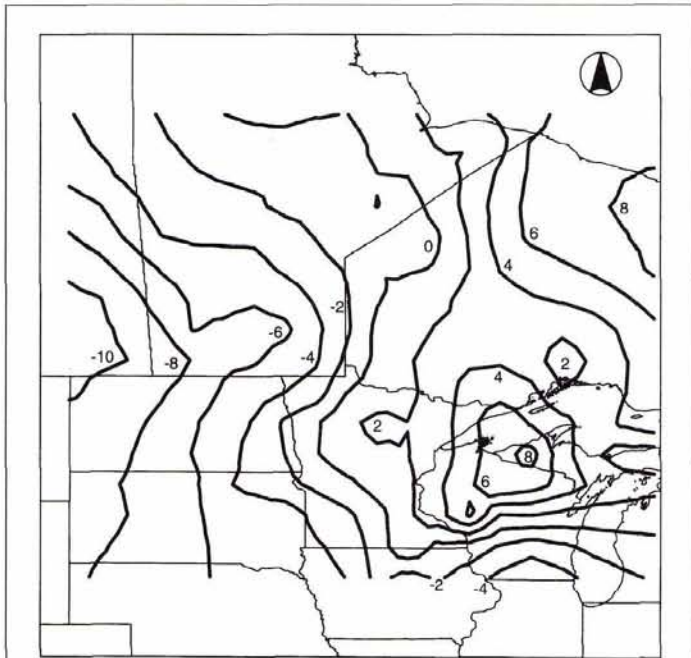


Figure 9. Kriged residuals from the latitude regression. Contour interval 2 days. Negative residual contours indicate that the mean ice breakup date in that area is earlier than predicted by latitude alone. Map source: Digital Chart of the World. Projection: geographic.

between (1) the high positive residuals and high snowfall south of lake Superior and Hudson Bay, (2) the latitudinal residual contours and latitudinal snowfall contours in southern Wisconsin, and (3) the southwest-northeast gradients in both contour plots. Regression analysis confirmed the signifi-

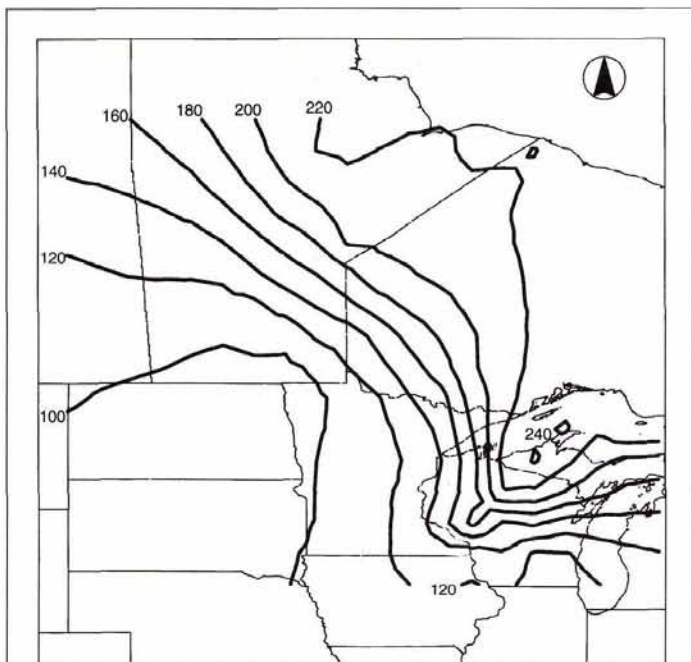


Figure 10. Kriged mean snowfall. Contour interval 20 cm. Note resemblance to Figure 9. Map source: Digital Chart of the World. Projection: geographic.

TABLE 2. FINAL MODEL TO PREDICT MEAN ICE BREAKUP DATE GIVEN MEAN SNOWFALL (CM) AND LATITUDE ($^{\circ}$). $R^2 = 93$ PERCENT, STANDARD DEVIATION = 5.2 DAYS, AND $p = 0.0001$

Parameter	Estimate	t	p	Standard Error
Intercept	-111.94	-14.65	0.0001	7.64
Latitude	4.57	26.99	0.0001	0.17
Snowfall	0.05	4.64	0.0001	0.01

cant relationship between snowfall and ice breakup dates. While the R^2 only increased to 93 percent, the standard deviation decreased to 5.2 days, and p for the overall model was 0.0001. When snowfall alone is used as the predictor of ice breakup dates, the R^2 is 31 percent. Latitude and snow are the only significant explanatory variables. (Other variables tested, and found to be insignificant, were surface area, maximum depth, surface area/maximum depth, longitude, and elevation.) The final model to predict mean ice breakup date for the study lakes given average snowfall and latitude is shown as Table 2.

The addition of snowfall leads to a flatter semivariogram with a much lower sill (32 days², Figure 8b; $\sigma = 5.2$ days, Table 2) and an absence of spatial pattern in the kriged residuals (Figure 11). Throughout most of the study area, we can predict the mean date of lake ice breakup within ± 2 days using simply the latitude and mean annual snowfall. The overall decrease in spatial pattern from the raw data to the residuals obtained from regressing out latitude and snow is striking, as evidenced by the notable decrease in sill heights (1426 to 32 days²).

Spatial Distribution of Trend Slopes

Coupled atmosphere-ocean general circulation model scenarios suggest that temperature increases resulting from an en-

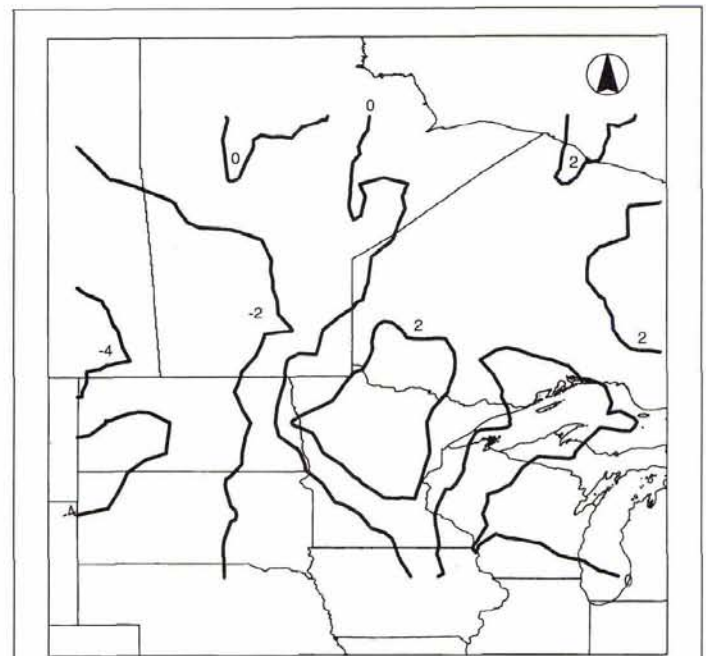


Figure 11. Kriged residuals from the latitude-snow regression. Note the general absence of remaining spatial pattern — latitude and mean snowfall are able to predict the mean ice breakup date within ± 2 days throughout most of the study area. Map source: Digital Chart of the World. Projection: geographic.

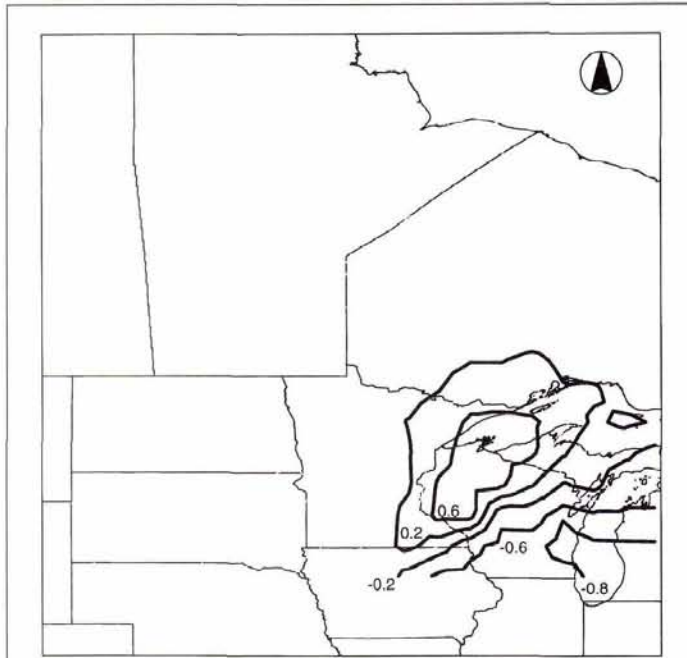


Figure 12. Kriged ice breakup date trend slopes from 1980 to 1994. Note (1) the trends toward earlier ice breakup dates in northwestern Wisconsin, (2) the trends toward later ice breakup dates in southeastern Wisconsin, and (3) the lack of any noticeable trend in the remainder of the study area. There is also a resemblance (albeit rotated 90°) between the observed Wisconsin gradient and the vegetation "tension zone" described by Curtis (1971). Map source: Digital Chart of the World. Projection: geographic.

hanced greenhouse effect will be greatest in the mid- to high latitudes in winter. Thus, the more northerly portions of our study area should show significant trends toward earlier ice breakup dates if greenhouse warming is occurring. This was not the case; the observed pattern (Figure 12) is toward earlier ice breakup dates only in the southern portion of the study area from 1980 to 1994.

Figure 12 was constructed from the slopes in the regressions of ice breakup dates versus year for each lake from 1980 to 1994. Ice breakup dates show no significant autocorrelation (Wynne *et al.*, 1996). The slopes were kriged using a spherical model ($h = 0.992^\circ$). The resulting lattice was contoured using a contour interval of 0.2 days/year.

Only eight of the 81 slopes (Table 3) are significant at $p < 0.05$. The four lakes with significant positive slopes corre-

TABLE 3. 1980 TO 1994 ICE BREAKUP DATE TREND SLOPES SIGNIFICANT AT $p < 0.05$

Lake	Slope (days/year)	p
Gile	2.18	0.0219
Namekegon	2.19	0.0205
Lost Land	1.81	0.0434
Fence	1.91	0.0376

Rush	-1.71	0.0113
Fox	-2.12	0.0206
Mendota	-1.93	0.0231
Kegonsa	-2.18	0.0118

TABLE 4. MODEL TO DESCRIBE ICE BREAKUP DATE FOR THE STUDY LAKES GIVEN SNOWFALL (CM), LATITUDE ($^\circ$), AND YEAR AS A CONTINUOUS VARIABLE. $R^2 = 77$ PERCENT AND STANDARD DEVIATION = 10.6 DAYS

Parameter	Estimate	t	p	Standard Error
Intercept	22098	3.45	0.0006	6397
Latitude	-435	-3.23	0.0013	135.0
Snowfall	-99.1	-2.59	0.0096	38.2
Year	-11.2	-3.47	0.0005	3.22
Latitude*Snow	1.97	2.50	0.0127	0.787
Latitude*Year	0.22	3.26	0.0012	0.0680
Snow*Year	0.05	2.60	0.0096	0.0192
Latitude*Snow*Year	-0.00099	-2.50	0.0127	0.000397

spond to the 0.6-days/year contour in northwestern Wisconsin (Figure 12). The four lakes with significant negative slopes correspond with the -0.6 and -0.8 days/year contours in southeastern Wisconsin. The remainder of the lakes show no significant trends.

We also calculated and kriged the 1980 to 1991 trend slopes because the documented cooling (e.g., Parker *et al.*, 1996) following the eruption of Mount Pinatubo in the summer of 1991 might have had an effect on spring temperatures in the study area. The overall picture is much the same, except that (1) there are not significant trends toward later ice breakup dates before the eruption, and (2) the trends toward earlier ice breakup dates in southeastern Wisconsin are even more pronounced.

Final Models

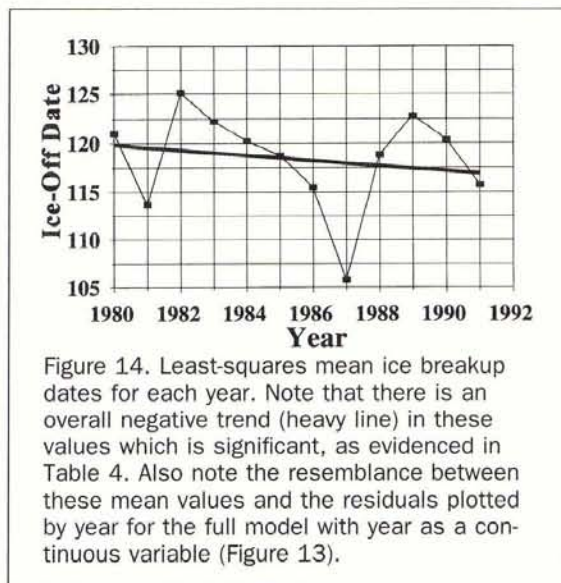
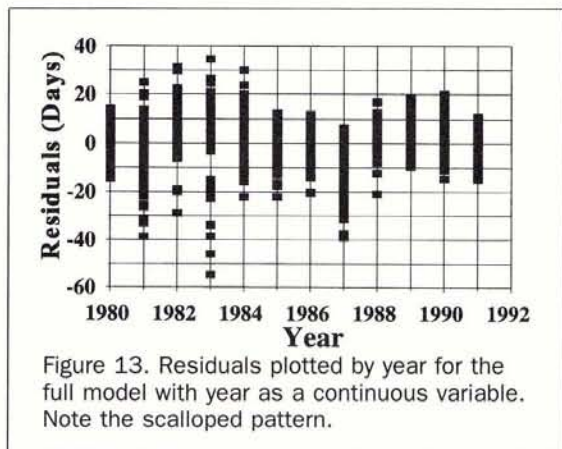
The goal of the final modeling effort was to (1) utilize annual data on each lake and (2) explicitly model time to find the best portable descriptive model that pools across lakes. Like the analysis of the mean ice breakup dates, the statistical goal was to remove as much of the spatial pattern (and error variance) as possible through the use of explanatory variables. We had *a priori* knowledge that time might be difficult to incorporate into the final empirical model (Wynne *et al.*, 1996). We modeled year in two different ways: once as a continuous variable, and once as a categorical variable.

The independent variables were latitude, snow, year, and all of their interactions. A term in any model was considered significant if either the term itself or any interaction term in which it was included was significant at $p \leq 0.01$. Hierarchical backwards elimination was used to eliminate terms that did not meet this criterion, starting with the highest level interaction. Because the three-way interaction (latitude*snow*year) was always significant, the backwards elimination step was never necessary.

YEAR AS A CONTINUOUS VARIABLE

The model using year as a continuous variable (Table 4) had an R^2 of 77 percent; all terms were significant, given the established criteria. Thus, a statistically significant (negative) trend occurred over time using the full data set. An examination of the residuals plotted against year revealed a "scallop" pattern (Figure 13). Thus, while a significant trend over time exists, it is certainly not linear.

Owing to the "split plot" nature of the data, latitude could be considered a "treatment" that gets applied to lakes, a feature not accounted for in the above model (Table 4). To test for significance of a latitude effect, ice breakup date was regressed on latitude, lake, snow, year, latitude*snow, latitude*year, snow*year, and latitude*snow*year. This model is highly significant ($R^2 = 90$ percent, standard deviation = 7.4 days), and, using the Type I mean square for lake (fitted as a categorical variable) for an error term, latitude is highly significant ($p = 0.0001$).



YEAR AS A CATEGORICAL VARIABLE

All dependent variables (main effects and interactions) are significant in the model using year as a categorical variable (Table 5). The R^2 for this model is 85 percent and the standard deviation is 8.8 days. The parameter estimates are not shown, because every term in which year is involved (main effect or interactions) has 12 estimates. However, one can get a feel for the trend over time by using the least-squares mean ice breakup dates for each year (Figure 14). Note that there is a significant overall negative trend in time (Table 4).

Revisiting the residuals by year, but with year as a categorical variable (Figure 15), one notes that (1) the previous scalloped pattern (Figure 13) has largely disappeared, and (2) the year with the largest residuals is 1983, the peak of the strongest recorded ENSO event. This last point is especially interesting, because work by Anderson *et al.* (1996) in particular showed the correlation of earlier ice breakup dates (in Wisconsin) with peak ENSO years. The high range in the 1983 residuals shows the temporal association between a strong ENSO event and an increase in the variability of ice breakup dates in a region, presumably because certain lakes were affected more than others.

Examination of the semivariogram resulting from the residuals (Figure 8c) reveals the success of this model in spatial terms. The semivariogram appears quite flat; bootstrapped samples indicate that the slope is not significantly different from zero.

Conclusions and Recommendations

Conclusions

The following conclusions are indicated with respect to satellite remote sensing of lake ice breakup on the Laurentian Shield as a climate proxy:

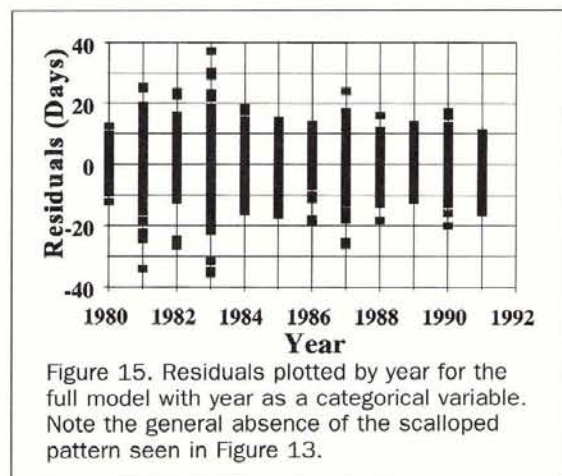
- The GOES-VISSR is a reliable means of determining lake ice breakup dates;

TABLE 5. SUM OF SQUARES FOR THE FINAL MODEL TO DESCRIBE ICE BREAKUP DATE FOR THE STUDY LAKES GIVEN SNOWFALL (CM), LATITUDE ($^{\circ}$), AND YEAR AS A CATEGORICAL VARIABLE. $R^2 = 85$ PERCENT AND STANDARD DEVIATION = 8.8 DAYS

Parameter	df	Mean Square	F	p
Latitude	1	34576.45	442.99	0.0001
Snow	1	29.21	0.37	0.5409
Year	11	473.98	6.07	0.0001
Latitude*Snow	1	0.51	0.01	0.9354
Latitude*Year	11	458.76	5.88	0.0001
Snow*Year	11	228.59	2.93	0.0008
Latitude*Snow*Year	11	224.74	2.88	0.0010

- The predominant spatial trend in ice breakup dates can be attributed to latitude;
- Snowfall is an important determinant of the date of lake ice breakup;
- Analysis of the pooled data set for all 81 lakes revealed a significant ($p < 0.001$) overall trend toward earlier ice breakup dates; and
- Lake morphology, longitude, and elevation are relatively unimportant factors in the date of lake ice breakup as determined by metsats.

In general, satellite monitoring of lake ice breakup is a robust climate proxy inherently amenable to operational monitoring on a regional to global scale. This is suggested by (1) the generally excellent agreement of metsat-derived ice breakup dates with ground reference data, (2) the lack of significance of lake morphometry to the date of ice breakup, (3) the strong relationship between air temperature and ice breakup dates (Robertson *et al.*, 1992; Wynne and Lillesand, 1993; Åssel and Robertson, 1995), (4) the coincidence of lake ice in time (winter/early spring) and space (higher latitudes) with those for which warming from enhanced greenhouse effects is predicted to be greatest, and (5) the general paucity of meteorological stations in the higher latitudes. Limitations to the technique include cloud cover at the time of imaging, difficulty in discriminating dark ice without snow cover from open water, attribution of the observed signal to climatic var-



ibles, the shortness of the satellite-based time series, and the limited range of lake morphologies.

Recommendations

- As noted by Wynne and Lillesand (1993), two of the major limitations to the use of optical satellite data in discriminating ice from open water, dark ice and cloud cover, would both be eliminated by the use of passive or active microwave sensors. There is a great deal of recent and current research on utilizing microwave sensors for the detection and characterization of sea ice, but there has been relatively little work to date on freshwater ice.⁴ Further research in the use of these sensors in the detection (and characterization) of freshwater ice is warranted.
- While economic considerations dictated the use of single-band imagery in this particular study, multi-spectral imagery is clearly superior, because it affords better visual discrimination and allows implementation of semiautomated multispectral classifiers.
- While satellite detection of lake ice is clearly a robust method, much would be gained by the addition of data from ground-based observers. Of particular importance in this regard is the much longer time series available and the ability to include smaller lakes. These gains come, however, at the cost of losing the uniformity of protocol that satellite image analysis affords.
- The importance of snow to the ice breakup date reveals the need for caution in attributing all changes in ice phenology to changes in air temperature. Snow is not the only "ancillary" forcing affecting lake ice, because cloud cover (and, thus, solar insolation) and wind, among others, could well be important factors. As such, analysis of continental or hemispheric ice breakup patterns will be impossible without the concurrent implementation of a process model. One possible scenario would be to move a hypothetical lake along a global climatic grid using a process model (e.g., Liston and Hall, 1995; Vavrus *et al.*, 1996), analogous to the work by McLain *et al.* (1994) for fish thermal habitat.

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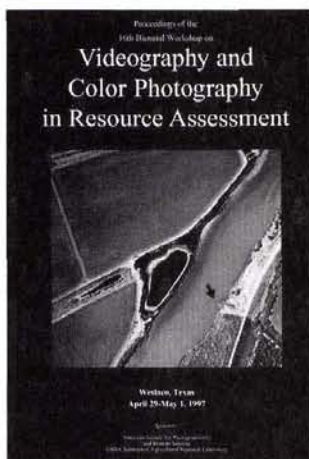
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