# Satellite Observation of Lake Ice as a Climate Indicator: Initial Results from Statewide Monitoring in Wisconsin

## Abstract

*The research reported herein focused on the general hypothesis that satellite remote sensing of large-area, long-term trends in lake ice phenology (formation and breakup) is a robust, integrated measure of regional and global climate change. To validate this hypothesis, we explored the use of data from the Advanced Very High Resolution Radiometer (AVHRR) to discriminate the presence and extent of lake ice during the winter of 1990-1991 on the 45 lakes and reservoirs in Wisconsin with a surface area greater than 1,000 hectares. Our results suggest both the feasibility of using the AVHRR to determine the date of lake ice breakup as well as the strong correlation (R = −0.87) of the date so derived with local surface-based temperature measurements. These results suggest the potential of using current and archival satellite data to monitor changes in the date of lake ice breakup as a means of detecting regional "signals" of greenhouse warming.*

## Introduction

The rapid increase in atmospheric concentrations of greenhouse gases since the industrial revolution has been well documented. General circulation models predict that global average equilibrium temperatures should increase from 1.9 to 5.2° C from the preindustrial equilibrium average, given a concomitant doubling of atmospheric carbon dioxide from preindustrial levels (National Academy of Sciences, 1991). Perhaps not coincidentally, the NASA Goddard Institute of Space Studies, NOAA's Climate Analysis Center, and the British Meteorological Office have all reported that 1990 and 1991 were the warmest years on record (Kerr, 1992). This observed warming, coming on the heels of the considerable increase in greenhouse gases from preindustrial times to the present, has led to substantial efforts by many researchers to begin to ferret out the actual presence of the greenhouse warming signal predicted by the general circulation models. These efforts have made use of temperature measurements, both surface and satellite based, as well as various climate indicators. The focus of this paper is upon one such indicator—remotely sensed variation in the annual duration of lake ice. We have explored the use of data from the Advanced Very High Resolution Radiometer (AVHRR) to discriminate the presence and extent of lake ice on the 45 lakes and reservoirs in the state of Wisconsin with a surface area greater than 1,000 hectares (Figure 1).

## The Need for Climate Indicators

Direct global surface temperature data measured from 1850 to the present reveal a warming of approximately 0.5° C (e.g., Jones *et al.*, 1991). Known complicating factors, such as urban heat islands and changes in instrumentation (Lillesand, 1993), have been nominally addressed in the statistical manipulation of these temperature data (e.g., Jones *et al.*, 1986; Hansen and Lebedeff, 1987; Houghton and Woodwell, 1989; Intergovernmental Panel on Climate Change, 1990). However, neither these researchers nor the broader scientific community have been able to actually validate the reliability of either the trend or magnitude of temperature change established from these observations. This is due to the extreme difficulty in trying to separate a clear absolute indication of climate warming from the background of natural variability in temperature measurement. This problem is illustrated in Figure 2, which depicts the mean annual temperature in south-central Wisconsin over the period from 1895-1991. (Note the inherent variability of these data and the absence of a long-term trend in the average value.)

Due to the presence of the factors complicating surface temperature measurement, NASA is now in its 14th year of measuring surface temperatures using passive microwave radiometry (at a frequency of 53.74 GHz) from the NOAA series of satellites. Analysis of the first ten years of data (1979-1988) revealed a monthly precision of 0.01° C, but showed no obvious trend (Spencer and Christy, 1990). Among the problems with these data is the poor spatial resolution attendant to the longer wavelengths used to produce the distributed product, composed of 2.5° latitude by 2.5° longitude grid cells (only four cells of this size would cover Wisconsin). Furthermore, these measures actually make use of another "indicator," the interaction of molecular oxygen with microwave energy in the middle troposphere. Thus, their relationship with surface air temperature is not a direct one.

While measurement of sea surface temperatures using satellite remote sensing of thermal infrared energy has been very successful, precise land surface temperatures have been more troublesome to obtain (e.g., Lillesand and Kiefer, 1987). This is largely due to variations in the emissivity of surface features, substantial variation in temperature over short distances (McClatchey, 1992), and the lack of a systematic means of correcting for variations in atmospheric transmittance, sun angle, and other factors in the process of data normalization (e.g., Cooper and Asrar, 1989; Caselles *et al.*, 1992). Among the six atmospheric correction models assessed by Cooper and Asrar, only the NOAA split-window model was able to calibrate the temperature data to within

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Figure 1. Study area: Wisconsin lakes with a surface area greater than 1,000 ha. A △ denotes a National Weather Service station at which daily January through March temperatures were measured. A ▼ denotes a National Weather Service division at which the data shown in Figure 4 were measured. (Derived from USGS 1:2,000,000-scale digital line graph hydrography data.)

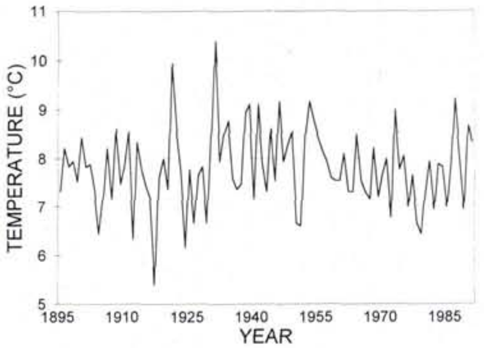

Figure 2. Mean annual temperatures in south-central Wisconsin over the period from 1895-1991. (National Weather Service data courtesy of the Wisconsin State Climatologist.)

± 3.0° C of *in situ* measurements. Furthermore, the multispectral algorithms used for correcting atmospheric attenuation, though effective for deriving sea-surface temperatures, have significantly less utility in the derivation of the low temperatures encountered over high latitudes in winter[1] (McClatchey *et al.*, 1987; McClatchey, 1992).

The use of indicators or proxy methods (such as air trapped in ice cores, pollen distribution, oxygen isotopes in ocean or lake sediments, noble gases in groundwater, etc.) has long been an integral part of paleoclimatology. However, constraints on the use of direct or satellite based temperature measurements, such as those mentioned above, have dictated the need to supplement the information gleaned from direct measurement of temperature, precipitation, or other climatic variables. These proxy measurements have come in many guises, one of the most recent of which is the Schumann resonance, a sensitive indicator of tropical temperature variation (Williams, 1992). Our research has focused on another such climate proxy—the interannual changes in the phenology of lake ice.

## Lake Ice as a Climate Indicator

### Background

Limnologists have long recognized lakes as homogenous landscape features that can serve as thermal integrators of short-term atmospheric climatic fluctuations (Birge, 1915; Juday, 1940). The thermal integration of lakes is due both to the low latent heat of fusion of water and the high heat capacity and thermal diffusivity of ice and water (Scott, 1964; Robertson, 1989; Robertson *et al.*, 1992). In that the thermal properties of lakes are relatively well known, changes in the thermal features of a lake can be used to detect climatic changes (Robertson, 1989). Scott (1964) found that formation date, maximum thickness, and breakup or "ice-off" date are the lake ice characteristics most useful as climatic indicators.

Numerous previous studies have used lake ice phenology as a robust indicator of climate change (Scott, 1964; McFadden, 1965; Tramoni *et al.*, 1985; Maslanik and Barry, 1987; Robertson, 1989; Magnuson, 1990; Schindler *et al.*, 1990; Wynne and Lillesand, 1992; Robertson *et al.*, 1992). Robertson studied data spanning 135 years on the dates of annual formation and breakup of lake ice on Lake Mendota in Madison, Wisconsin. This is one of the longest such continuous records of its kind in North America (even pre-dating the temperature record for the area). Analysis of this record suggested a strong correlation between the duration of lake ice cover and the end of the Little Ice Age at the end of the nineteenth century, as well as the repeated signal of the El Niño Southern Oscillations (Lillesand, 1993). Most important, Robertson detected evidence of a general warming trend since the beginning of this century, expressed in terms of an 11- to 12-day decrease in ice duration, largely due to changes in the spring breakup date (Figure 3). This trend is not reflected in the local temperature record (Figure 2), aptly illustrating the problems associated with direct temperature measurement mentioned previously.

Schindler *et al.* (1990) examined the effects of climatic warming on a lake in Canada's central boreal forest over the preceding 20 years and also detected a recent warming trend. This included an increase in the mean annual lake temperature of 2° C, a 21-day decrease in ice duration, and higher concentrations of nutrients. Similarly, Comb (1990) has reported that ice breakup on Moosehead Lake in Maine now occurs approximately 10 days earlier than in 1848, the first year in which such data had been recorded. All of the above

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[1] Ironically, it is at high latitudes in winter that the impact of greenhouse warming is predicted to be greatest.

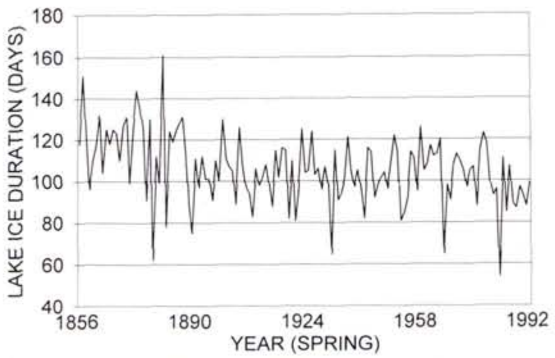

Figure 3. Total days of winter ice cover (ice duration) for Lake Mendota, Wisconsin. Note long-term trend toward shorter ice durations. (After Robertson *et al.*, 1992.)

studies based on analysis of lake ice seem to contradict the study by Spencer and Christy (1990) based on passive microwave measurements showing no atmospheric warming in the previous ten years . However, this apparent contradiction is quite possibly a further indication not only of the need for analyzing data spanning a period longer than ten years, but also of the inherent importance of climate indicators.

As stated previously, most general circulation models predict that not only will the *magnitude* of $CO_2$-induced warming be greatest in high latitudes, but also that *winter* temperatures will manifest a relatively greater increase than summer temperatures in those latitudes (National Research Council, 1982; Manabe and Wetherald, 1986). Ideally, then, a climate indicator should be sensitive to these subtle seasonal changes within the broader context of interannual variability. Lake ice cover is uniquely suited to this task due to both its intrinsic link with winter[2] *and* higher latitudes.

Figure 4 illustrates the remarkable intra-annual coherence of temperatures recorded at widely separated weather stations (see Figure 1 for their locations) in Wisconsin during the 1990-1991 winter months. The characteristic seasonal pattern is evident, yet the most striking phenomenon is the high degree of correlation among locales. While it might seem that lake ice monitoring would be amenable to discriminating only the regional variations of temperature given this high correlation among locales, our results (see subsequent discussion) indicate that lake ice is even sensitive to the extremely subtle differences among local temperature regimes graphically illustrated in Figure 4.

We mentioned earlier some of the impediments to the accurate estimation of surface temperature in higher latitudes (i.e., the large grid cells involved with passive microwave radiometry and the problems with atmospheric normalization of AVHRR data). Perhaps most important is the paucity of meteorological stations in these latitudes. All of these factors may limit early detection and/or verification of a statistically significant change in climate. It is suggested that lake ice monitoring is ideally suited as a proxy for air temperature trends under such conditions (Palecki and Barry, 1986; Robertson *et al.*, 1992; Wynne and Lillesand, 1992).

### Influence of Lake Morphology on Ice Phenology

The heat balance of a lake is a function of both the characteristics of the lake itself and climatic variables. Scott (1964) identified morphometric features as the most important limnological parameters determining the thermal response of lakes to climate. Lake area and depth are the most important of these morphometric measures (Scott, 1964; McFadden, 1965; Tramoni *et al.*, 1985; Magnuson *et al.*, 1990). McFadden found the correlation between mean lake depth and freezing date strong enough to accurately predict the relative depths of several lakes along a latitudinal transect between The Pas and Lynn Lake, Manitoba, Canada based on their freezing dates. It is thus necessary to fully address the issue of the relationship between lake ice seasonality and lake morphometry to effectively utilize the phenology of lake ice as a climate indicator.

## Remote Sensing of Lake Ice

### Previous Studies

The utility of remotely sensed data for the study and monitoring of lake ice has long been recognized. For example, McFadden (1965) studied the distribution of lake ice over a large portion of north-central North America (from northern Wisconsin to the Arctic ocean) using a combination of time lapse 16-mm movies, black-and-white prints, and 35-mm transparencies. Many other studies have used both airborne (e.g., Leshkevich and Reid, 1984) and satellite sensors (e.g., Maslanik and Barry, 1987) for ice detection.

Extensive use has been made of AVHRR data for lake ice detection on water bodies such as the Laurentian Great Lakes (e.g., Leshkevich, 1988), though prior to the present study no formal assessment had been made of the utility of AVHRR data on the smaller lakes[3] known to be more useful as climate indicators. The characteristic favoring smaller lakes is their tendency to freeze and thaw relatively rapidly, leading to the ability to resolve these events to within a period of one to two days. Our work concentrated on such lakes.

A complete discussion of the physical properties of ice and snow (the latter must be examined in that frozen lakes often become "snow platforms") as they relate to all forms of remote sensing would normally include electrical as well as optical and thermal properties. However, the poor spatial resolution attendant to passive microwave data and the lack of a suitable historical data set in the case of active microwave sensors preclude their use in a historical context. As the goal of our study was to assess the feasibility of utilizing existing historical data sets to detect the climate change expected as a result of greenhouse warming, only the characteristics of the AVHRR (data from which are available since 1979) germane to the study objectives will be considered in

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[2] Note that only the air temperatures in the two to three months immediately preceding lake freezing or thawing are reflected in the timing of these events (Scott, 1964; McFadden, 1965; Palecki and Barry, 1986); thus, lake ice phenology does not necessarily reflect temperatures for the entire winter. This also leads one to conclude that the expected increases in winter and early spring temperatures in higher latitudes as a result of greenhouse warming would have the greater effect on the dates of spring thaw rather than fall formation, which is supported by the work of Robertson *et al.* (1992) and Schindler *et al.* (1990).

[3] Only those lakes with a surface area greater than 1,000 hectares were included in the study due to the constraint imposed by the 1.1-km spatial resolution of the sensor. Of the estimated 15,000 lakes in Wisconsin, only 45 meet this criterion. These lakes are "small" only in comparison with the Great Lakes.

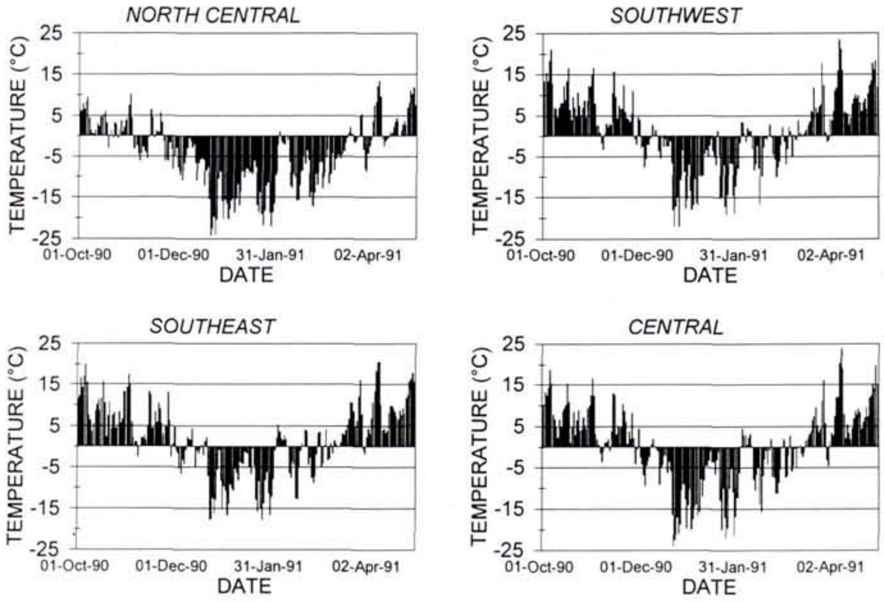

Figure 4. Daily 1991 winter air temperatures from four National Weather Service divisions. (Data courtesy of the Wisconsin State Climatologist.)

Table 1. AVHRR Spectral Bands for Odd-Numbered Satellites in the NOAA Series. Band 5 is Simply a Repeat of Band 4 (10.5 to 11.5 μm) on the Even-Numbered NOAA Platforms. All Bands Have a Spatial Resolution of 1.1 Km at Nadir (Adapted from Lillesand and Kiefer, 1987).

| Band | Wavelength (μm) |
|---|---|
| 1 | 0.58 – 0.68 |
| 2 | 0.72 – 1.10 |
| 3 | 3.55 – 3.93 |
| 4 | 10.3 – 11.3 |
| 5 | 11.5 – 12.5 |

subsequent discussion. (Table 1 lists the wavelength range of the AVHRR bands.)

### Spectral Basis for Lake Ice Monitoring Using the AVHRR

The spectral reflectance of snow is dependent on solar elevation, near-surface liquid water content, roughness, the presence of impurities, and the size and shape of individual grains (Hall and Martinec, 1985). In the visible and near infrared wavelengths, freshly fallen snow has a very high reflectance. Reflectance in the visible and near infrared wavelengths decreases as snow ages, due to the introduction of impurities and increase in mean grain size caused by melting and refreezing. The spectral albedo of ice is dominated by specular reflection from the ice surface in the near infrared (AVHRR band 2). The visible albedo (AVHRR band 1) is dominated by multiple scattering by bubbles beneath the surface (Mullen and Warren, 1988). Nonetheless, ice reflectance varies tremendously due to impurities, the presence or absence of surficial meltwater, and the overlying material (Hall and Martinec, 1985). Snow harbors the same intrinsic variability in albedo. However, snowcover will usually increase the albedo in the visible range, but in the presence of a low sun angle can reduce the near infrared albedo due to a decrease in the specular reflection, thus potentially confounding the differentiation between snow and ice cover. In a typical scene, containing both ice and snow covered areas in concert with areas free of ice and snow, a characteristically bimodal spectral response in both the visible and near infrared is exhibited (Figure 5). In both of the wavelength bands, the lower digital numbers denote open water or land with no snow, while the higher digital numbers represent ice, snow, or clouds.

Band 3 of the AVHRR (the shorter wavelength thermal infrared region) is sensitive to the apparent temperature in that range (3.55 to 3.93 μm, Table 1). These differences in temperature yield the bimodal histogram characteristic of band 3 (Figure 5). The lower digital numbers (and, thus, temperatures) represent clouds. The longer wavelength thermal infrared (AVHRR bands 4 and 5, Figure 5) is also sensitive to the corresponding temperature differences. In fact, the United States National Operational Hydrologic Remote Sensing Center (NOHRSC) and the United Kingdom Meteorological Office (e.g., Harrison and Lucas, 1989) now use these properties as the basis for a multispectral clustering approach employing AVHRR bands 1, 3, and 4 to operationally discriminate between snow, clouds, and land.

## Data

### Imagery

Our data analysis was conducted using the facilities of the University of Wisconsin-Madison (UW) Environmental Remote Sensing Center (ERSC). AVHRR data (73 images) were acquired from three different sources. The bulk of the imagery (54 images) was systematically captured in near real-time via ERSC's Pronet connection to the Man Computer Interactive Data Access System (McIDAS) and receiving antennas maintained by the UW Space Science and Engineering Center. These images were previewed daily on a near real-time basis. Only those images meeting a combination of qualitative criteria were selected and subsequently downloaded. These cri-

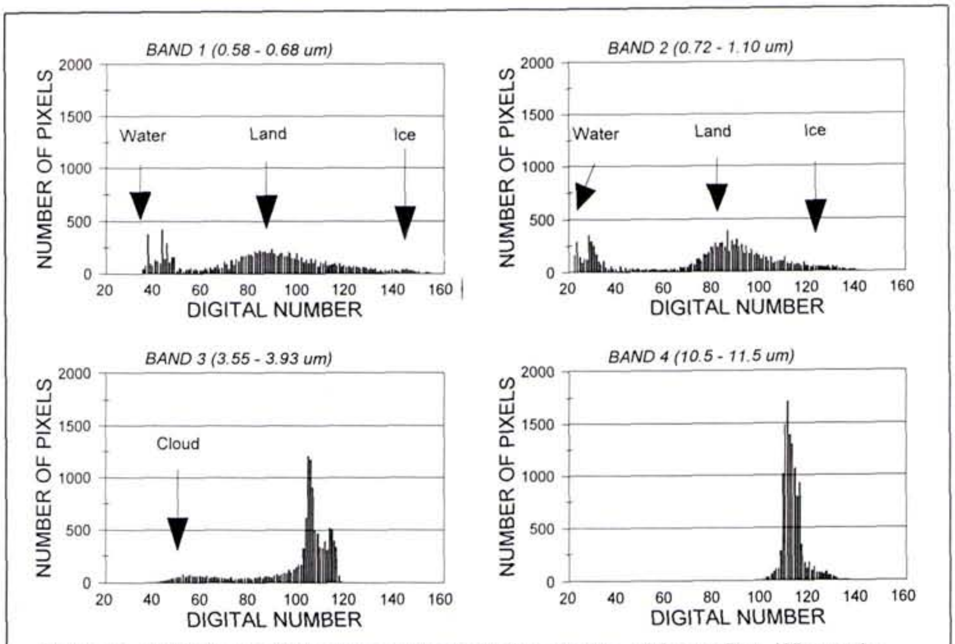

Figure 5. AVHRR image histograms. Extracted from image of Green Bay, Wisconsin and vicinity, 10 March 1991. Band 5 (not shown) is highly correlated with band 4.

teria included the minimization of cloud cover, image noise, and off-nadir views. In addition, more images were downloaded in the months in which we expected ice formation or breakup to occur, i.e., December, March, and April. With minor exceptions, only scenes from the NOAA-11 satellite (afternoon overpass) were acquired to avoid interpretation difficulties due to changes in sun angle and sensor. Preprocessing, which included rectification to a Mercator projection, resampling to the nominal 1.1-km pixel size, and rescaling to an 8-bit quantization range, was effected in McIDAS. The data were subsequently converted from McIDAS files to band-interleaved ERDAS image files for further analysis.

In addition to the above images, we obtained 12 derived digital sea surface temperature images from the NOAA CoastWatch program[4] (Bolgrien and Brooks, 1992; Schwab *et al.*, 1992), as well as seven AVHRR images from Window 7 of the 1991 Airborne and Satellite Snow Data CD-ROM produced by the NOAA National Operational Hydrologic Remote Sensing Center (NOHRSC, Carroll *et al.*, 1989). These preprocessed images were also converted to the ERDAS file format.

### Ground-Based Data

Lake morphometric indices were obtained from a published compendium by the Wisconsin Department of Natural Resources (1991). Daily temperature data (maxima and minima) for each of the 31 National Weather Service (NWS) stations utilized in this study were obtained from the relevant NOAA National Climatic Data Center publications (National Oceanic and Atmospheric Administration, 1991), courtesy of the office of the Wisconsin State Climatologist. The NWS station paired with a particular lake was the most proximate station to that lake with a continuous daily temperature record over the study period. Due to the juxtaposition of many of the lakes in the study (Figure 1), one station was occasionally the most proximate to several neighboring lakes; thus, the difference between the number of NWS stations (31) and the number of lakes in the study (45)[5].

Ground-based reference data on lake ice formation or breakup were obtained from the Wisconsin State Climatologist, University of Wisconsin-Madison Center for Limnology, and Wisconsin Audubon Society. All of the available ground-based reference data were utilized in the study, even though only ice breakup data could be obtained in the case of two lakes (Turtle-Flambeau and St. Croix in Table 3).

## Image Analysis Procedure

The determination of the presence or absence of ice on a given date was made through visual image interpretation of digital displays of each of the 73 images.[6] Each entire scene was first displayed, then each of the 45 lakes in turn was examined under magnification utilizing a hardware zoom. An overlay of the United States Geological Survey 1:2,000,000-scale digital line graph GIS coverage (Figure 1) helped in locating each lake. The *de facto* display standard was band 2,1,1 (R,G,B) for the McIDAS and NOHRSC images, but the presence of clouds or fog complicated the visual interpretation, leading to the incorporation of the short and long wavelength thermal bands when necessary (see previous discussion). The CoastWatch SST images were more problematic in terms of interpretation, as even a lake much warmer than the surrounding lakes or land surface can actually still be ice covered. Thus, when use of these images was essential to ensure

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[4] Fortuitously, the digital sea surface temperature images for Lake Michigan or Lake Superior contain considerable portions of the state of Wisconsin, which borders both lakes.

[5] Not all of the lakes or NWS stations are represented in Figure 1.

[6] Image interpretation and analysis were conducted utilizing PC-ERDAS Version 7.5. The Live-Link developed cooperatively by ERDAS and ESRI allowed the integration of raster image data (ERDAS) and vector GIS data (ARC/INFO) such as the statewide hydrography derived from USGS digital line graph data or the long-term average isotherms for a particular month.

TABLE 2. SATELLITE-DERIVED DATES OF LAKE ICE FORMATION VERSUS GROUND-BASED REFERENCE DATA.

| Lake | County | Ice-On AVHRR | Ice-On Reference | Difference (Days) |
|---|---|---|---|---|
| Lake Mendota | Dane | 03 Jan 91 | 26 Dec 90 | 8 |
| Lake Monona | Dane | 22 Dec 90 | 23 Dec 90 | −1 |
| Green Lake | Green Lake | 07 Jan 91 | 05 Jan 91 | 2 |
| Shawano Lake | Shawano | 13 Dec 90 | 03 Dec 91 | 10 |
| Trout Lake | Vilas | 22 Dec 90 | 14 Dec 90 | 8 |
| | | | Mean Difference (Days) | 5.4 |

TABLE 3. SATELLITE-DERIVED DATES OF LAKE ICE BREAKUP VERSUS GROUND-BASED REFERENCE DATA.

| Lake | County | Ice-Off AVHRR | Ice-Off Reference | Difference (Days) |
|---|---|---|---|---|
| Lake Mendota | Dane | 21 Mar 91 | 24 Mar 91 | −3 |
| Lake Monona | Dane | 21 Mar 91 | 21 Mar 91 | 0 |
| Green Lake | Green Lake | 25 Mar 91 | 26 Mar 91 | −1 |
| Turtle-Flambeau | Iron | 20 Apr 91 | 16 Apr 91 | 4 |
| St. Croix Lake | St. Croix | 10 Apr 91 | 11 Apr 91 | −1 |
| Shawano Lake | Shawano | 10 Apr 91 | 07 Apr 91 | 3 |
| Trout Lake | Vilas | 28 Apr 91 | 26 Apr 91 | 2 |
| | | | Mean Difference (Days) | 0.6 |

adequate temporal resolution, the digital numbers representing the surface of individual lakes were first determined by interactive query, then converted to temperature values using the thermal calibration for the selected images. If the lake surface temperature thus derived was at least 2° C below freezing,[7] the lake was considered to be ice-covered, though the preceding and subsequent dates of multispectral imagery were then re-examined to ensure accuracy and internal consistency. This process would likely not have been as reliable if the SST images were not temporally bracketed by the multispectral imagery. The entire interpretation process was carried out by a single image analyst.

## Results and Discussion

### Accuracy

In our results to date, the AVHRR-determined dates of lake ice formation and breakup compare very favorably with the available ground-based reference data (Tables 2 to 4). Note, however, that the determination of the dates of ice-off in the spring (mean difference = 0.6 days) is much more accurate than the concomitant determination of the freeze dates (mean difference = 5.4 days). This finding echoes that by Maslanik and Barry (1987), who analyzed transparencies of visible wavelength data from the Defense Meteorological Satellite Program (DMSP) satellites for similar purposes in a study conducted over Finland. They noted that the lack of a separate near-infrared channel hampered their ability to resolve blue or black ice types, thereby increasing the discrepancy between satellite and ground-based observations. While these dark ice types also confounded our results, use of the near-infrared and thermal bands of the AVHRR effectively reduced the variance attributable to this cause.

In both our study and that by Maslanik and Barry, the major constraint to effective determination of the time of lake ice formation was the extensive cloud cover associated with the fall to early winter period of imaging. For example, as indicated in Table 2, Trout Lake (in north-central Wisconsin), actually froze on 14 December 1990. Cloud cover over that area of the state effectively precluded determination of the presence of ice on Trout Lake (as well as the other lakes in the area) between 8 December and 22 December, a two week period. As illustrated, this magnitude of departure from the reference data in terms of the date of lake ice formation was by no means an anomaly. Given the magnitude of the discrepancies, we were forced to exclude the satellite-derived dates of lake ice formation, as well as the length of lake ice duration thereby affected, from further analysis. (Note that the two major limitations to the use of the AVHRR or other multispectral sensors in this context—dark ice and cloud cover—would both be eliminated by the use of active microwave sensors.)

### Utility

As shown in the previous section, it is indeed feasible to monitor lake ice phenology (at least in terms of breakup date) using the AVHRR. We turn our current attention to the specific link between the satellite-based data on lake ice breakup and regional climate. This is aptly illustrated both qualitatively on a synoptic basis and by means of a more formal analysis on a lake by lake basis. Supporting both approaches is the contention that a single-year latitudinal transect can be viewed as a proxy for projected multi-year climate change, i.e., that the magnitude of the predicted climatic changes as a result of greenhouse warming is on the order of the climatic differences currently observed along such a transect. The ability to discriminate among these small differences in the current spatial context is analogous to the equivalent effort at a given fixed location in the temporal domain.

White's (1990) review article indicated that the projected annual temperature increase in the Great Lakes region with a doubling of atmospheric $CO_2$ scenario could be over 6° C (Geophysical Fluid Dynamics Laboratory model). Also, as we previously indicated, general circulation models predict that

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[7] Schwab *et al.* (1992) noted that the CoastWatch satellite-derived temperatures are consistently 1 to 1.5° C cooler than reference buoy temperatures.

TABLE 4. TOTAL DURATION OF LAKE ICE AS DERIVED BY SATELLITE VERSUS GROUND-BASED REFERENCE DATA.

| Lake | County | Duration (Days) AVHRR | Duration (Days) Reference | Difference (Days) |
|---|---|---|---|---|
| Lake Mendota | Dane | 77 | 88 | −11 |
| Lake Monona | Dane | 89 | 88 | 1 |
| Green Lake | Green Lake | 77 | 80 | −3 |
| Shawano Lake | Shawano | 118 | 125 | −7 |
| Trout Lake | Vilas | 127 | 133 | −6 |
| | | | Mean Difference (Days) | −5.2 |

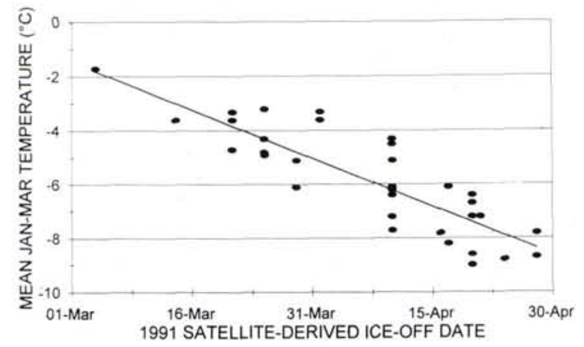

Figure 6. Regression of the mean January through March air temperature versus the satellite-derived ice-off date for each lake.

winter and early spring temperatures will manifest a greater relative increase than summer temperatures. The range in January through March mean temperatures (1991) for the 31 National Weather Service stations utilized in our study was −3.3° C to −9.0° C, very much on the order of the changes predicted as a result of greenhouse warming. By extension, the spatial domain (latitudinal transect) can be substituted for the temporal domain (historical context) for the purposes of demonstrating our underlying hypothesis; namely, that ice phenology can serve as a reliable indicator of regional climate change.

### INFLUENCE OF LAKE MORPHOLOGY

A multiple regression of the lake ice-off dates (dependent variable) with four independent variables—(1) January through March mean temperature for the closest National Weather Service (NWS) station to each lake, (2) mean depth, (3) maximum depth, and (4) surface area of each lake for which all such data were available—revealed that only the late winter temperatures were significant. $R^2 = 86.7$ percent in the full model (with all four independent variables included) while $R^2 = 86.2$ percent in the reduced model (with the January-March mean local temperature as the only independent variable); $n = 27$ in both cases. Though we were surprised at the lack of importance of the morphometric variables in the response of the lakes we studied to the ambient air temperature (given the previously discussed findings by other researchers), this is likely attributable to the relatively large minimum size constraint (1,000 ha) imposed in our study by the spatial resolution of the AVHRR. This constraint effectively limits the range, and therefore the influence, of lake morphometric variables—a pleasant side effect in terms of the use of AVHRR-derived lake ice phenology as a climate indicator.

### LINK WITH LOCAL TEMPERATURE

Subsequent regression analysis on 45 lakes with the satellite-derived date of ice breakup as the independent variable, and the respective January through March mean temperatures as the dependent variable, yielded the best fit line shown in Figure 6 ($R^2 = 0.76$, $SE_{estimate} = \pm 0.93°$ C, $R = -0.87$). Qualitative analysis of the residuals indicated that the assumptions inherent to the regression (i.e., linearity and independent, normally distributed errors with constant variance) were not violated[8]. In addition, the spans of both the ice-off dates (4 March through 28 April) and the corresponding temperature range (−3.3 to −9.0° C) are on the general order of the historical variation in these parameters on Lake Mendota as shown by Robertson *et al.* (1992). The resulting empirical model predicting the 1991 January through March mean temperatures from the satellite data is as follows:

$$\text{MEAN JAN-MAR TEMP (° C)} = (-1.32° \text{ C}) - (0.12 \cdot \text{ADJUSTED ICE-OFF DATE})$$

where the ADJUSTED ICE-OFF DATE is the number of days between 28 February 1991 and the AVHRR-derived ice-off date.

The above model predicts a 0.12 (± 0.01) ° C change in mean air temperature in the January through March time frame per one day change in breakup date. This finding utilizing a suite of lakes over a single year corresponds very closely to the model developed by Robertson *et al.* (1992) for a single lake in the same locale in a historical context (0.15 ± 0.03 ° C per one-day change). These results are also quite similar to those of Palecki and Barry (1986), who studied a suite of lakes in southern Finland utilizing historical ground-based observations (0.16 ± 0.04 ° C employing March-May mean temperatures). Moreover, our correlation of lake ice breakup with the mean of a fixed period of air temperatures ($R = -0.87$) was higher than that found by Robertson *et al.* in their study of the Lake Mendota ice record ($R = -0.70$) as well as those determined by Palecki and Barry ($R = -0.28$ to $-0.82$) in their analyses of the Finnish data.[9]

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[8] Note, however, that observational constraints such as cloud cover cause the ice-off dates to proceed in a step-wise fasion, i.e., a scene acquired on the first clear day in a period of rapid phase transition will reveal a number of ice-free lakes.

[9] Note, however, that Robertson *et al.* established that a sensible heat transfer model was better than either a fixed-window or moving-window model at estimating changes in air temperature based on breakup date for Lake Mendota. We have not attempted to evaluate these models in the expanded spatial and reduced temporal context of our study, merely to demonstrate that the date of ice-off as determined utilizing the AVHRR is a sensitive climatic indicator.

## Summary and Conclusions

The dates of lake ice formation and breakup on the 45 lakes and reservoirs in Wisconsin with a surface area greater than 1,000 hectares were determined through visual interpretation of 73 AVHRR images acquired during a single ice season (1990-1991). While cloud cover inhibited precise determination of the dates of ice formation, the dates of breakup derived from the satellite data:

- exhibited a high degree of accuracy in relation to available ground-based reference data (with a mean difference of 0.6 days), and
- highly correlated with mean January through March local temperatures (with $R = -0.87$).

Surprisingly, and presumably due to limiting our analysis to relatively large lakes, lake morphology did not significantly affect the response of the study lakes to ambient air temperature.

We propose that further investigation be undertaken to evaluate both the spatial and temporal extendability of these initial findings. If this future research further confirms that satellite monitoring of lake ice phenology is a robust, sensitive climate indicator, the procedure could become an operational climate change sentinel—one inherently amenable to automation and regional to global application.

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