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SATELLITE MEASUREMENTS OF SURFACE WATER TEMPERATURE IN THE GREAT LAKES: GREAT LAKES COASTWATCH

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ABSTRACT. This paper describes the NOAA CoastWatch program for the Great Lakes and discusses the applications and limitations of satellite-measured surface water temperature images received as a result of this program in mapping and analyzing physical features of the Great Lakes environment. The initial product of the CoastWatch program is a set of surface water temperature images derived from NOAA AVHRR (Advanced Very High Resolution Radiometer) data. These temperature maps are produced on a routine basis (usually 2-3 sufficiently cloud-free images per week) and are made available within hours of acquisition. The satellite-derived water temperatures from images acquired during the period May 1990 to May 1991 were compared to temperatures measured at NOAA weather buoys and found to be highly correlated. We found the satellite-derived temperatures were consistently 1-1.5C° cooler than buoy temperatures. Root mean square deviations between buoy and satellite temperatures ranged from 0.8 to 1.6C°. There was also a consistent pattern to the geographic registration errors of the images, ranging from 8.4 km westward for the NOAA 10 nighttime pass to 8.3 km northeast for the NOAA 11 nighttime pass. Potential application of the imagery to detection and location of thermal fronts, analysis of circulation patterns, and ice and snow mapping are also discussed.
INDEX WORDS: Great Lakes, satellite, water temperature.

INTRODUCTION

In 1988, in response to an outbreak of "Red Tide" along the Carolina coastline, a program was developed by NOAA's Environmental Satellite and Data Information Services Division (NESDIS) to provide the NOAA National Marine Fisheries Service Laboratory at Beaufort, North Carolina, with satellite-derived temperature maps of the Gulf Stream so that future occurrences of this phenomenon could be better anticipated (Pyke 1989). This program has since been extended to other coastal regions in the United States, including the Great Lakes, and has been expanded to become the CoastWatch program, a part of NOAA's Coastal Ocean Program. The objectives of CoastWatch are: 1) to provide access to near real-time and retrospective satellite and aircraft observations for the coastal ocean of the U.S. for federal, state, and local decision making; 2) to develop workstations and associated software systems for integrated analyses of environmental quality, coastal hazards, and wetlands change; 3) to develop a communications system supporting distribution of near real-time and historical satellite and *in situ* observations to national and regional coastal users; and 4) to develop and implement a database management and display system supporting integrated coastal ocean applications. NOAA CoastWatch directly supports agency statutory responsibilities in estuarine and marine science, living marine resource protection, and ecosystem monitoring and management contained in several federal environmental statutes including the U.S.-Canadian Great Lakes Water Quality Agreement.

In 1990, as part of the CoastWatch program, NOAA's Great Lakes Environmental Research Laboratory (GLERL) was chosen as the CoastWatch Regional Site for the Great Lakes. The first CoastWatch products for the Great Lakes were digital images of lake surface temperature at resolutions of 1.3 and 2.6 km which are derived from NOAA satellite imagery. Several of these images per week have been received at GLERL since April 1990. As the CoastWatch Regional

Site, GLERL will make Great Lakes CoastWatch products available to other federal agencies, state and local government agencies, academic institutions, and other organizations engaged in cooperative research programs with NOAA. The first regional user site in the Great Lakes was established at the Center for Great Lakes Studies at the University of Wisconsin-Milwaukee in 1990.

Satellite imagery of the Great Lakes has been used to map and analyze surface water temperature and other features for some limited case studies by Strong (1967, 1974) using data from the Nimbus 2 and then the NOAA 2 satellites; by Sabatini (1971) using data from Nimbus 1, 2, and 3; by Wiesnet *et al.* (1974) using NOAA 2 and Earth Resources Technology Satellite (ERTS 1) imagery; by Leshkevich (1985) using Landsat multi-spectral scanner (MSS) digital data; by Lathrop and Lillesand (1987) using Thematic Mapper (TM) data; by Mortimer (1988) with Coastal Zone Color Scanner (CZCS) data; and by Lathrop *et al.* (1990) using NOAA 9 infrared data. Strong and Eadie (1978) examined imagery from Landsat, NOAA polar orbiting satellites, and the Skylab Earth Terrain Camera system to investigate lake surface temperature and calcium carbonate precipitation patterns in the Great Lakes. There has also been a continuing program in Canada to map surface temperatures with data from aircraft overflights using ART (Airborne Radiation Thermometer) and from AVHRR satellite data. Webb (1974) described results of ART surveys of Lake Erie. Irbe *et al.* (1979) discussed techniques used for AVHRR data. These studies demonstrated the feasibility of using satellite imagery and airborne radiometry to determine surface water temperature in the lakes and provided analyses of many common features of Great Lakes thermal structure. The CoastWatch program intends to build on the success of these studies by providing a mechanism for making NOAA satellite imagery conveniently available to Great Lakes researchers and managers on a routine basis. Bolgrien and Brooks (1992) demonstrate the potential utility of CoastWatch imagery for Great Lakes research.

This paper will describe the characteristics of the CoastWatch imagery, including satellite characteristics and image mapping parameters. Several examples of applications of the imagery will be discussed. Preliminary analysis shows good correlation of satellite-derived temperatures with *in situ* measurements at mid-lake NOAA weather buoys. Other CoastWatch products are planned including turbidity, ocean color, ice mapping, etc., many using new satellite sensors such as the Sea Wide Field Sensor (SeaWiFS) and Synthetic Aperture Radar (SAR).

DATA

The initial CoastWatch product, i.e., water surface temperature imagery, is obtained from NOAA polar-orbiting weather satellites. NOAA currently operates three polar-orbiting weather satellites (NOAA 10, 11, and 12) which each carry (among other sensors) the Advanced Very High Resolution Radiometer (AVHRR). The polar-orbiting satellites are in a sun synchronous orbit at an altitude of approximately 833 km. Each satellite passes over a given area twice a day, NOAA 11 at about 2 A.M. and 2 P.M. local time, and NOAA 10 at about 7 A.M. and 7 P.M. local time. The AVHRR scans a swath of approximately 2,700 km on the earth's surface beneath the satellite in five radiometric bands, one visible (0.58–0.68 μm), one reflected infrared (0.725–1.0 μm), and three thermal infrared (3.55–3.93 μm, 10.3-11.3 μm, 11.5-12.5 μm) (Koczor 1987). The AVHRR data are processed at two resolutions, 4 km Global Area Coverage (GAC) and 1.1 km Local Area Coverage (LAC) and High Resolution Picture Transmission (HRPT). The HRPT data are used for Great Lakes CoastWatch imagery. These data are transmitted from satellite receiving stations to NESDIS facilities in Suitland, Maryland, where they are calibrated, earth located, quality controlled, and made available in a form called AVHRR level lb data sets (see Kidwell 1991 and Pichel *et al.* 1991 for details of this process). For the CoastWatch program, the level 1b data are mapped to a Mercator projection and resampled to a 512×512 pixel grid. Four scenes are extracted as shown in Figure 1 and listed in Table 1. One scene covers all five lakes at 2.56 km central resolution. The other three scenes cover Lake Superior, Lakes Michigan and Huron, and Lakes Erie and Ontario at twice the resolution of the five-lake scene. The grid spacing for the 512×512 grids is specified at the equator as 3.6 km for the five-lake scene and 1.8 km for the three other scenes. Actual grid resolution is d $\cos\phi$ where d is the spatial resolution at the equator and ϕ is the latitude. The grid spacing for the three high resolution Great Lakes scenes ranges from 1.24 to 1.30 km as indicated in Table 1.

The accuracy of the mapping algorithms used to generate the level lb and Mercator projection

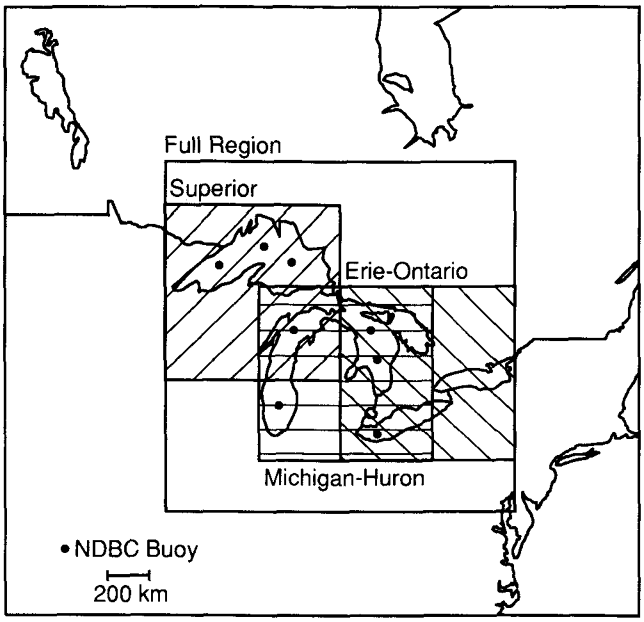

FIG. 1. Location of four CoastWatch satellite scenes and NOAA Data Buoy Center (NDBC) weather buoys in the Great Lakes.

depends on the precision with which satellite orbital characteristics are known. From experience, we have found that the automatically mapped images usually require adjustments of from 5–10 km to be correctly located with respect to the scene windows in Figure 1.

NESDIS initially used a manually-initiated procedure called SSTMAP to process CoastWatch scenes for the Great Lakes. From May 1990 through May 1991, 630 images were processed as shown in Figure 2. More five-lake scenes (201) were processed than the other scenes (133, 147, and 149 for the Superior, Michigan-Huron, and Erie-Ontario scenes respectively). The number of images processed decreased significantly during

TABLE 1. CoastWatch scenes for the Great Lakes.

	Latitude Range (°N)	Longitude Range (°W)	Pixel Size (km) (at mid-latitude)
Full Region	38.89–50.58	75.88–92.41	2.56
Superior	43.59–49.28	84.19–92.45	1.24
Michigan-Huron	40.76–46.73	79.78–88.05	1.30
Erie Ontario	40.76–46.73	75.88–84.16	1.30

November, December, and January when cloud cover limited the amount of useful temperature data that could be retrieved to one or two images per week. On average, about 16 of the five lake scenes were processed each month, and about 10 of each of the other 3 scenes were processed.

Lake surface temperature is calculated for each pixel in the scene, regardless of whether it is land or water. For NOAA 11, the equations used to calculate surface water temperature are (J. Sapper, NESDIS, personal communication 1991):

Daytime split-window: $$SST = 0.9712(T4) + 2.0663(T4-T5) + 1.8983(T4-T5)(\sec\theta - 1) - 1.979(\sec\theta - 1) + 8.36$$

Nighttime triple-window: $$SST = 0.99(T4) + 0.9528(T3-T5) + 0.6335(T3-T5)(\sec\theta - 1) + .5215\ (\sec\theta - 1) + 3.93$$

where SST is the surface water temperature (in degrees Kelvin), T3, T4, and T5 are the calibrated brightness temperatures (in degrees Kelvin) of the 3.7, 11, and 12 μm channels (3, 4, and 5) respectively, and θ is the satellite zenith angle (the angle between the local vertical and a line from the pixel to the satellite). The multi-channel approach attempts to indirectly correct for some of the atmospheric effects inherent in the recorded satellite data. However, the coefficients used in the NOAA-11 equations were derived and validated for ocean conditions. If coefficients can be refined for the Great Lakes environment, a more accurate SST product may result. For NOAA 10, the channel 4 (10.5-11.5 μm) brightness temperature is used directly as surface water temperature for both daytime and nighttime scenes, without any attempt to correct for atmospheric effects.

The mapped lake surface temperature images are stored in a computer file as 11 bit integers which can be converted to temperature as follows:

$$
\begin{aligned}
0 < n \le 920 &: SST = 0.10n + 178 \\
920 < n \le 1720 &: SST = 270 + 0.05(n - 920) \\
1720 < n \le 4095 &: SST = 310 + 0.10(n - 1720)
\end{aligned}
$$

where n is the 11 bit integer and SST is in °K. This mapping provides 0.05 C° resolution over the main region of interest for water temperatures. To minimize data storage, a data compression technique is used. The temperature values are stored row by row as 16 bit integers, except where a value is within 63 counts of the previous value, in which case it is stored as an 8-bit integer offset in the range −63 to +63. Four bits of graphics overlay information, including lake shorelines, and a

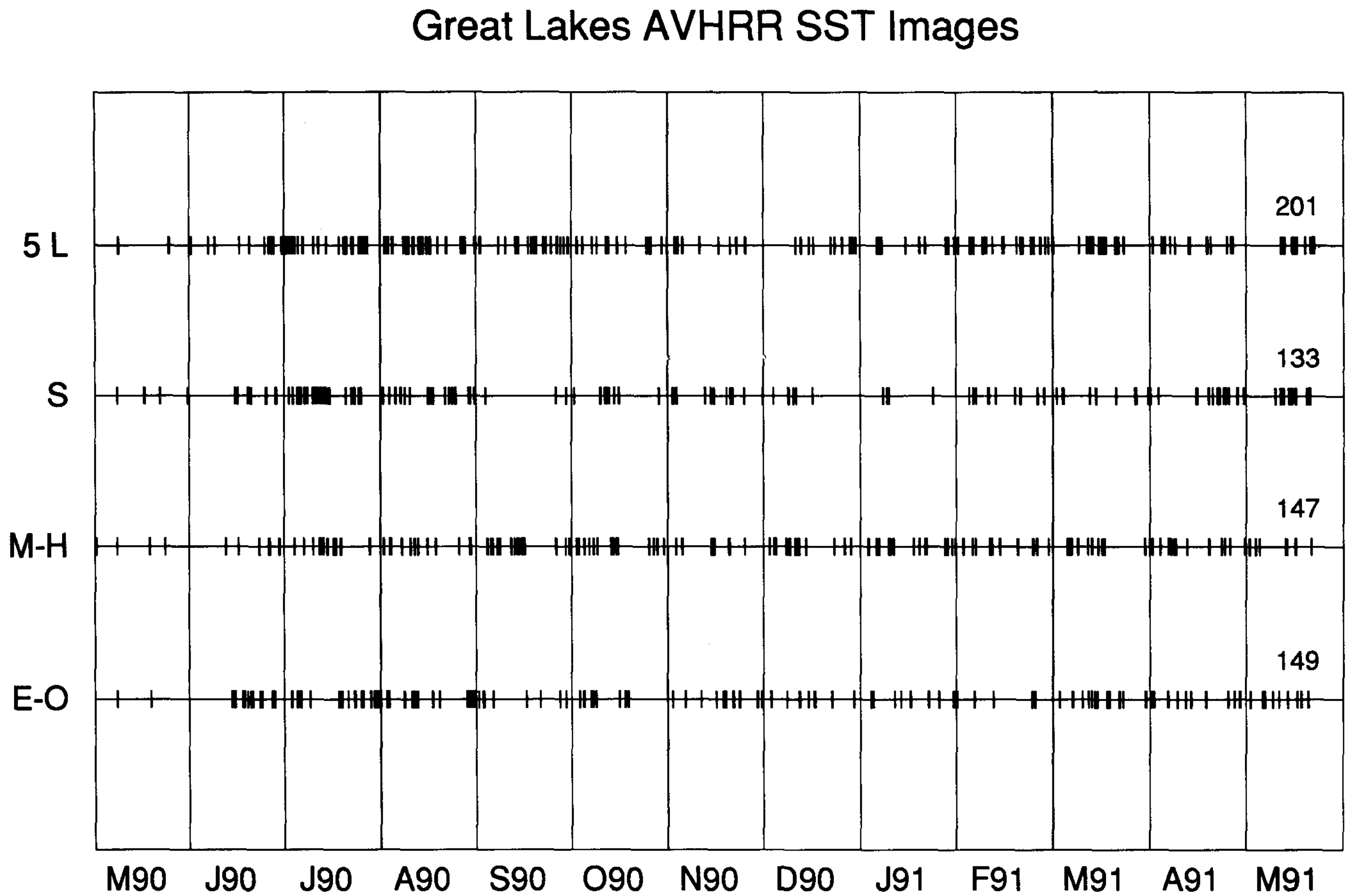

FIG. 2. CoastWatch water surface temperature images processed during the period May 1990 to May 1991. The four geographic scenes are the 5-lake scene (5L), Superior (S), Michigan-Huron (M-H), and Erie-Ontario (E-O).

latitude-longitude reference grid are also included in the files.

The files are downloaded daily from the NOAA Ocean Products Center (OPC), stored on a computer at GLERL, and made available to CoastWatch users over dial-in telephone lines. At 9,600 baud, it takes approximately 5–10 minutes to download a single image. Image files for the previous 2 months are available at GLERL to regional participants in the CoastWatch program. After that period, image files will be available from an archive at the NOAA Ocean Data Center (NODC).

In June of 1991, an automated procedure called IMGMAP was implemented to generate the Great Lakes CoastWatch imagery. Only NOAA 11 scenes are processed, but all available scenes for each satellite pass are processed. A comparison and correlation with buoy data similar to that performed on SSTMAP data will be performed on IMGMAP data when a sufficient number of images have been received. The IMGMAP equations and procedure are described here as they will be the source for all future CoastWatch SST products. The algorithms to be used are the multi-channel SST (MCSST) linear equations developed for global sea surface temperature analysis as described in Pichel *et al.* (1991). For NOAA 11, the equations are:

$$\text{Daytime split-window: SST} = 1.02455(T4) + 2.4522(T4-T5) + 0.6406(T4-T5)(\sec\theta - 1) - 7.52$$

$$\text{Nighttime triple-window: SST} = 1.036027(T4) + 0.892857(T3-T5) + 0.520056(T3-T5)(\sec\theta - 1) - 9.224.$$

For more information on SST algorithms see Tadepalli (1990) and Walton *et al.* (1990). Images of visible (Channel 1) and reflected infrared (Channel 2) data will also be available from

TABLE 2. Average geographic corrections for Great Lakes CoastWatch images (E-W displacemants are positive eastward, N-S displacements are positive northward).

Satellite	Number of Images	Displacement (km)		RMS deviation (km)	
		E-W	N-S	E-W	N-S
NOAA 10 Daytime	122	4.2	6.6	2.8	4.2
NOAA 10 Nighttime	192	-8.4	0.8	5.3	2.9
NOAA 11 Daytime	189	-8.2	4.9	4.8	4.0
NOAA 11 Nighttime	127	7.6	3.4	3.2	3.5

IMGMAP for the NOAA 11 daytime passes and may provide more information on cloud cover.

CALIBRATION

During the period May 1990 through May 1991, all satellite images of lake surface temperature were compared with water temperature data recorded at the NOAA Data Buoy Center (NDBC) weather buoys. The buoys are deployed in the lakes only during the ice-free season. The buoys provide hourly readings of wind speed, wind direction, air temperature, water temperature, wave height, and wave period. The locations of the buoys are shown in Figure 1. All images that were sufficiently cloud-free were manually geocorrected to optimally align shorelines with the fixed graphics overlay for each scene to assess the absolute navigational accuracy of the AVHRR data and to accurately locate buoy positions. The E-W and N-S distances by which each scene was adjusted were tabulated and found to depend primarily on which satellite produced the image and whether it was on its daytime or nighttime pass. As shown in Table 2, the geographic adjustments ranged from 8.4 km almost due west for the NOAA 10 nighttime pass to 8.3 km northeast for the NOAA 11 nighttime pass. Root mean square deviations from the mean displacement for each image were on the order of 5 km.

If an image was determined (visually) to be essentially cloudfree over the area near the buoy, the average surface temperature of the nine pixels nearest the buoy was determined and compared to the water temperature reported by the buoy at the time of the satellite overpass. The NDBC buoys measure water temperature with a hull-mounted thermistor about 0.5 m below the water surface. In all, 971 pairs of temperatures were recorded. The results were analyzed for any systematic differences. The differences found did not depend significantly on wind speed, air temperature, water temperature, air-water temperature difference, or buoy location. There were, however, significant differences between results for NOAA 10 and NOAA 11 satellites and also between NOAA 11 daytime and NOAA 11 nighttime algorithms. The results are shown in Table 3 and Figure 3. Satellite-derived water temperatures are generally cooler than buoy temperatures, with mean differences of about 1° for NOAA 10 and daytime NOAA 11, to 1.7° for nighttime NOAA 11. Scatter about the mean is significantly lower for the NOAA 11 multichannel algorithms than for the NOAA 10 Channel 4 data (1.17° and 0.79° for the NOAA 11 daytime and nighttime passes respectively, and 1.42° and 1.56° for the NOAA 10 passes). These values are comparable to the 1C° accuracy reported for NOAA 2 imagery by Strong (1974) and for Landsat TM infrared data by Lathrop and Lillesand (1987). There is a slight tendency for the bias to increase at higher water temperatures but this tendency is not significant compared to the mean bias.

EXAMPLES

Three examples were chosen to illustrate possible applications of temperature imagery to analysis of lake physics. The examples that were chosen are representative of some of the "better" images in terms of cloud cover. Many other images are largely obscured by clouds, or only a small portion of the lake surface is visible, even though the images that were processed by OPC in 1990–91 were manually selected (implying that many completely obscured images were never processed). Previously, Sabatini (1971) found that only 26% of the Nimbus 1, 2, and 3 observations of Lake Michigan during April-November in 1966, 1969, and 1970 were cloud-free. Lathrop *et al.* (1990) mention that during two July-through-September

TABLE 3. Comparison of AVHRR water temperatures and buoy temperatures (°C) for the period May 1990–May 1991.

	Observation Pairs	Buoy Mean	Satellite Mean	Mean Offset	RMS Deviation
NOAA 10 Daytime	171	9.67	8.63	1.05	1.42
NOAA 10 Nighttime	281	11.32	10.27	1.05	1.56
NOAA 11 Daytime	315	11.00	9.88	1.13	1.17
NOAA 11 Nighttime	204	10.24	8.53	1.72	0.79

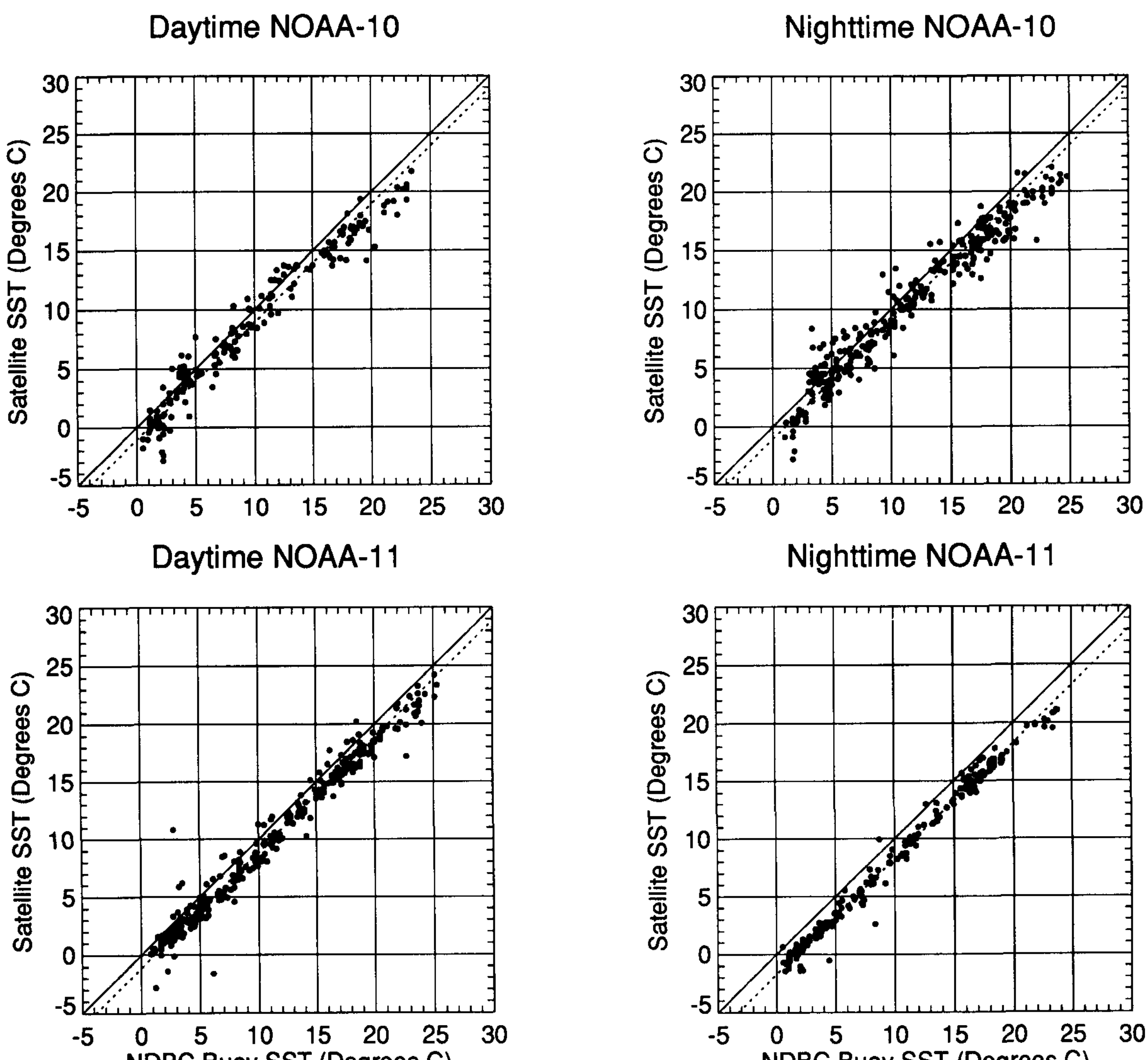

FIG. 3. Comparison of water temperatures measured at NDBC buoys with satellite-derived temperatures.

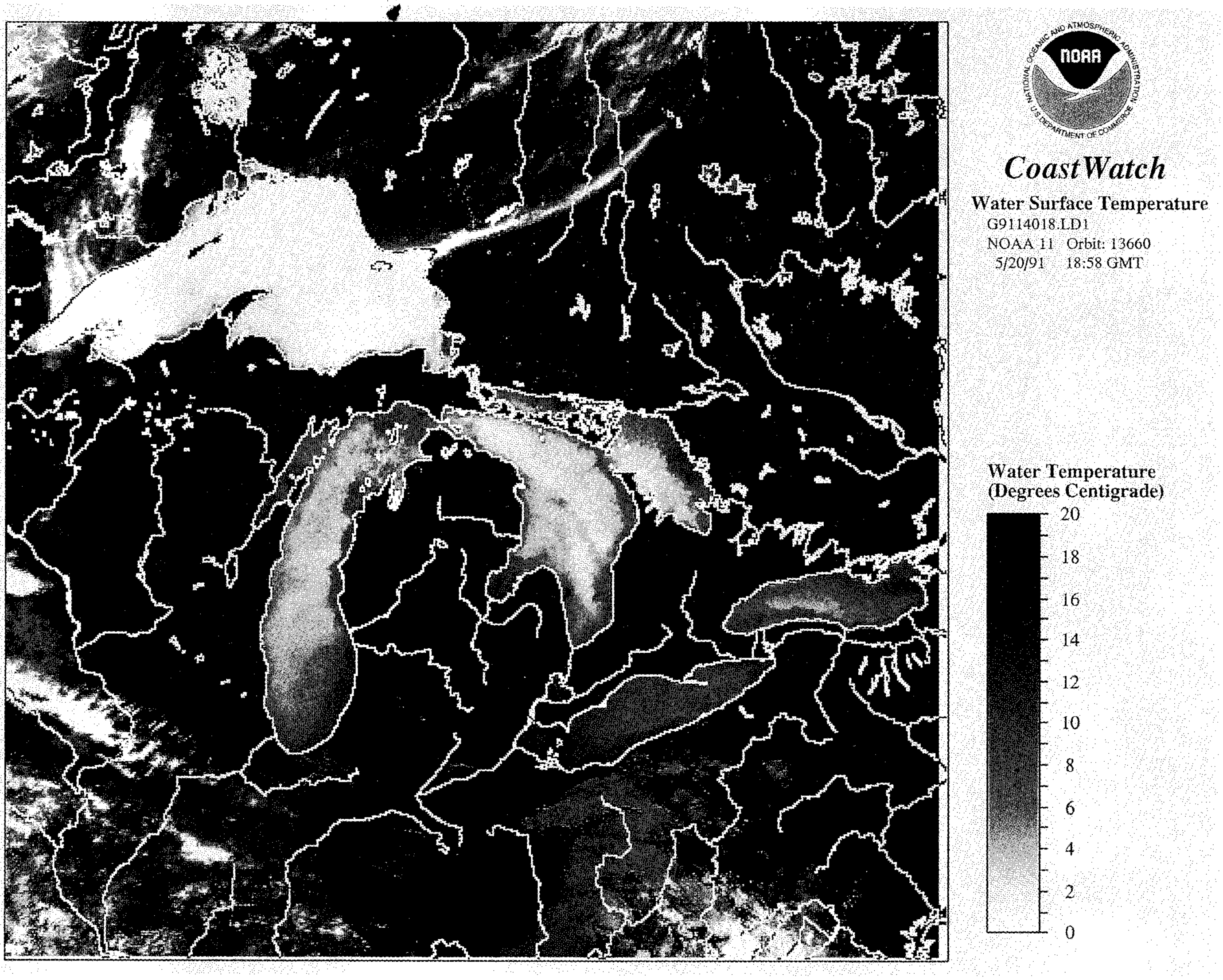

FIG. 4. CoastWatch water surface temperature imagery (5-lake scene) from 20 May 1991.

experimental periods, only three cloud-free scenes of Green Bay were acquired out of a possible 16 Landsat TM overpasses. These return rates are very comparable to return rates for the AVHRR imagery from 1990–91 described here.

Surface temperature imagery is an excellent tool for monitoring development of springtime thermal fronts as pointed out by Strong (1974) and Mortimer (1988). Bolgrien and Brooks (1992) describe in detail the development of thermal features in Lake Michigan during 1990 using some of the Coastwatch SST imagery described in this paper. Figure 4 shows an example of the five-lake scene from the NOAA 11 daytime pass on 20 May 1991. Lakes Michigan and Huron show well-developed thermal fronts along their eastern and western shores. The fronts along the western shores are about 10 km offshore while the fronts along the eastern shores are further offshore, around 20 km. Measured satellite water temperatures (uncorrected for the biases described above) are 3–4°C offshore of the front and 9–10°C inshore. A large area of 10–12°C water covers the southeastern part of southern Lake Michigan. Temperatures in southern Green Bay and Saginaw Bay are 13–16°C. There is also a front along the eastern shore of Georgian Bay about 25 km offshore separating 3–4°C water in the bay from 10–12°C water inshore. The western basin of Lake Erie has already warmed up to 13–16°C, while the central

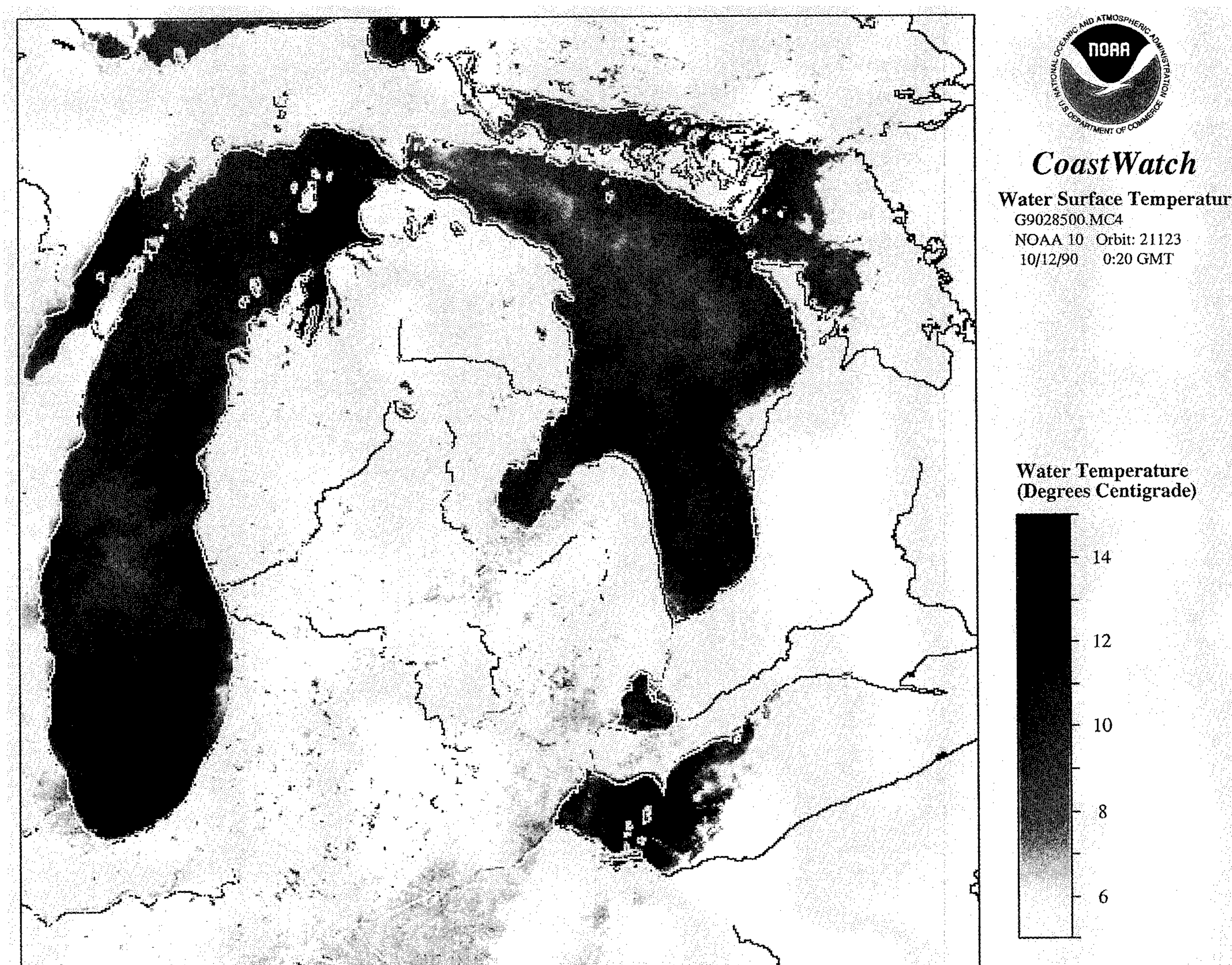

FIG. 5. CoastWatch water surface temperature imagery (Michigan-Huron scene) from 12 October 1990.

basin shows a mild front along the south shore with 9°C water offshore and 12–13°C water inshore. In Lake Ontario, only a small area of 5–6°C water in the center of the lake remains. The 9–11°C nearshore water extends almost all the way across the lake. A plume of warmer water from the Niagara River extends 20 km out from the mouth of the river. This image illustrates how the CoastWatch surface water temperature images could be used to monitor the location and strength of springtime thermal fronts.

Figure 5 is a Michigan-Huron scene from the NOAA 10 nighttime pass on 12 October 1990. Surface water temperatures (again, uncorrected for bias) are in the 9–14°C range over almost all of Lakes Michigan and Huron. In both lakes, large gyres are apparent in the surface temperature images with horizontal scales on the order of 50–100 km. These are much larger than the smaller scale eddies and meanders (5–10 km) previously observed in satellite imagery that have been attributed to various types of coastal flow instabilities by Rao and Doughty (1981) and Mortimer (1988). These features are also not characteristic of the shore-trapped internal Kelvin wave that is sometimes observed as the northward propagation of a cold upwelling area along the eastern shore of Lake Michigan (Mortimer 1988). These features are similar to patterns seen in the calcium carbonate whitings reported by Strong and Eadie (1978),

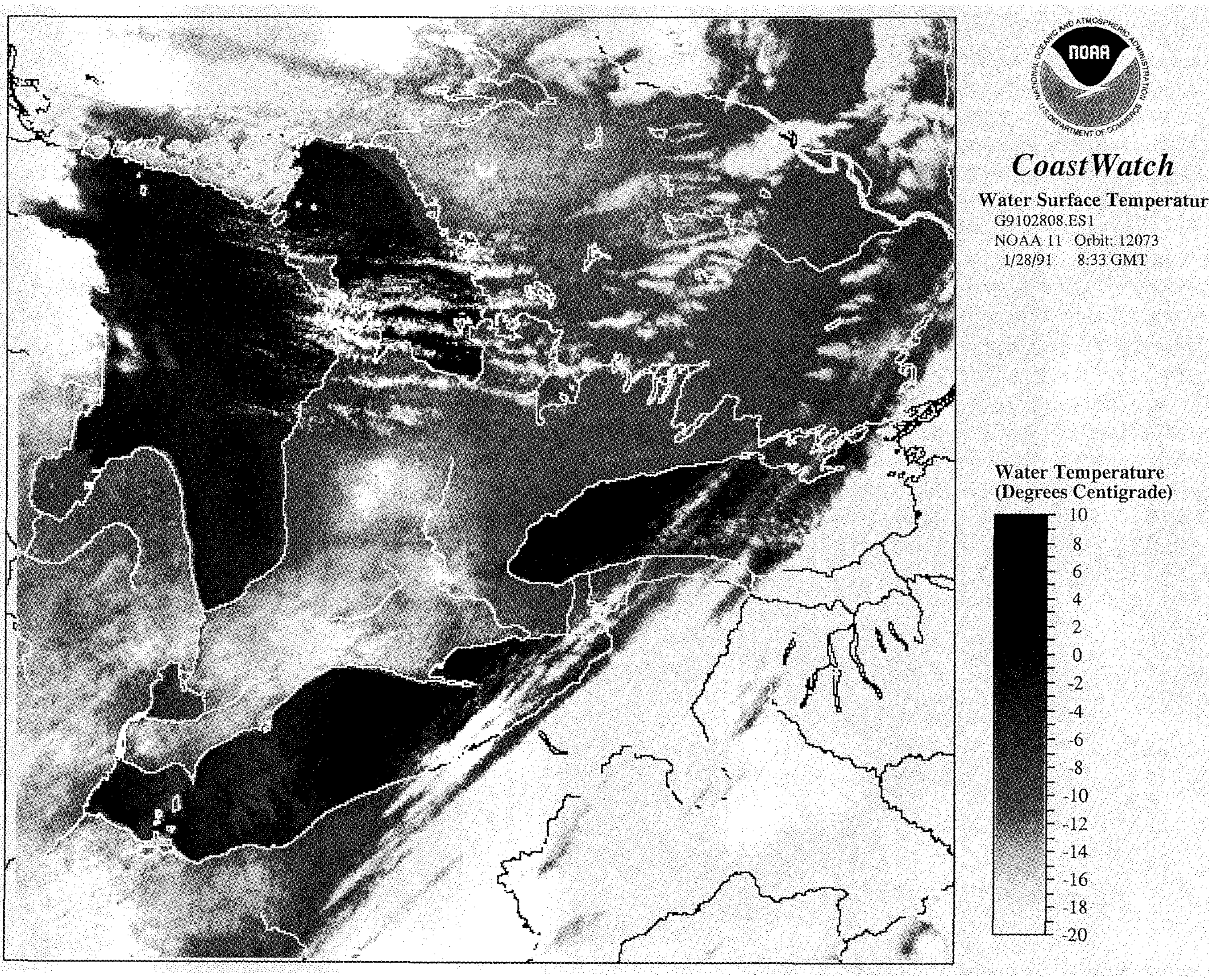

FIG. 6. CoastWatch water surface temperature imagery (Erie-Ontario scene) from 28 January 1991.

although the whitings were seen in visible imagery, not surface temperature.

The Erie-Ontario scene from the NOAA 11 nighttime pass on 28 January 1991 is shown in Figure 6. In Saginaw Bay, Lake St. Clair, northeast Georgian Bay, and the western basin of Lake Erie, large areas of the water surface exhibit temperatures below -5°C. These temperatures are below the range of normal surface water temperatures and are interpreted as indication of ice cover. In the central basin of Lake Erie, there is some indication of fingers of ice about 5 km wide and 10–15 km long forming off of a consolidated ice pack in the western part of the central basin. There is an area of warmer water in the southwestern end of Lake Erie near Toledo, possibly indicating open water. There are also areas that appear to be shorefast ice along the southeastern shore of Lake Huron.

DISCUSSION

As shown in Table 2, the SST imagery was consistently misaligned within the image window. The average amount of misalignment was as much as 8.4 km for the NOAA 10 nighttime pass. There are several possible sources of error in image geolocation, including spacecraft clock drift, orbit parameter errors, spacecraft attitude errors, and instrument alignment errors. The operational navigation system for earth location of satellite imagery assumes that all spacecraft navigational and orbital parameters are known precisely. In actuality, there are residual errors in these parameters that can result in earth location errors comparable to those reported in Table 2. NESDIS is currently implementing an advanced real-time earth location system that will provide dynamic adjustment of assumed navigational parameters which should result in a 1 km earth location accuracy for SST imagery.

Table 3 compares satellite-derived water temperatures to temperatures measured from NDBC buoys. The brightness temperature for each radiometric band measured from the satellite (and used to derive SST estimates) represents conditions only in the first few millimeters below the water surface. The SST temperature algorithms, however, were derived from calibrations with ground truth data very similar to the NDBC buoy data, so the average difference between skin temperature and temperature at 0.5 m depth should be accounted for by the algorithms. However, although the equations were derived based on corrected brightness temperatures, channel nonlinearity calibration corrections were not applied to all or most of the NOAA 10 and NOAA 11 channel data under the SSTMAP procedure for the Great Lakes. If the mean offsets between satellite-derived temperatures and buoy temperatures in Table 3 are used as calibration factors for the satellite-derived temperatures, the resulting water temperatures will be directly comparable, with zero bias, to the NDBC buoy temperatures with a standard deviation of about 1.5° for the NOAA 10 daytime and nighttime algorithms, 1.2° for the NOAA 11 daytime algorithm, and 0.8° for NOAA 11 nighttime algorithm. These deviations are comparable to those reported between monthly mean satellite-derived SST and ship observations by McClain *et al.* (1985). Note that no special procedures were followed to account for atmospheric effects on SST estimates, other than the daytime split-window and nighttime triple-window equations mentioned above for NOAA-11, which indirectly account for these effects. The use of the channel nonlinearity calibration corrections in the IMGMAP procedure, the future use of nonlinear SST algorithms (which better account for atmospheric water vapor), and the fact that the SST algorithms can be applied to NOAA 12 data should further improve the accuracy of the SST product.

Gyre-like patterns like those in Figure 5 have been observed in visible imagery of Lake Michigan by Strong and Eadie (1978), but not in surface temperature imagery. It is possible that these patterns are the surface signature of wind-induced vorticity-mode oscillations, found to be dominant in southern Lake Michigan by Saylor *et al.* (1980) and described numerically by Schwab (1983). These oscillations are characterized by basin-scale counterrotating gyres that exchange positions with a periodicity in the range of 3–8 days. During this time of year, vertical stratification has weakened, and the mixed layer has deepened to the point where internal motions could produce patterns like those in Figure 5. This type of pattern might also be reflected in visible imagery of calcium carbonate whitings. It would be very interesting to compare SST imagery to visible imagery during a whiting episode.

In Figure 6, large areas in Lake Huron and Lake Erie exhibit surface temperatures below -5°C. This is well below the range for which the satellite SST algorithms were calibrated, but the clear implication from the imagery is that these areas are ice covered. In particular, the areas of temperature from -10°C to -5°C terminate at the lake shoreline and are seen in AVHRR images both before and after the 28 January image in Figure 6. The characteristics of these features indicate a persistent water surface temperature feature rather than clouds. The Great Lakes ice analysis for 28 January 1991 produced by the Navy/NOAA Joint Ice Center from several data sources shows these areas to be ice covered with concentrations ranging from 50–100%. Close analysis of SST imagery may also reveal information about varied ice surface thermal characteristics in addition to ice extent or concentration. Field measurements taken in conjunction with high thermal resolution airborne FLIR (forward-looking infrared radiometer) data suggest that ice surfaces have distinct thermal characteristics that vary with type, thickness, crystal structure, and age. However, the lower absolute accuracy of satellite-derived surface temperatures (standard deviation around 1°C) may limit their application in ice type classification but should prove useful for ice detection and mapping ice extent. As noted by Wiesnet *et al.* (1974), the AVHRR water temperature imagery may not be the ideal tool for quantitatively describing ice extent and characteristics, but it can be extremely useful as corroborative information about synoptic ice conditions.

The visible and reflected infrared data that will be available from the IMGMAP procedure will be very useful for ice and snow mapping. Leshkevich (1985) classified and mapped the ice cover on northern Green Bay using reflectance measurements as "training data" in the computer processing of digital Landsat MSS data. However, due to varying overpass times of NOAA satellites and the large field of view (i.e., varying look angles) it will be important to correct for solar and satellite zenith angles, especially for any operational mapping uses. The usefulness of the CoastWatch imagery for many applications may well depend on how frequently a particular area can be successfully imaged without interference from cloud cover. However, unlike the Landsat or Satellite Pour l'Observation de la Terre (SPOT) satellites, the area imaged is much larger and the frequency of coverage much greater. The future use of Synthetic Aperture Radar (SAR) data should greatly improve operational, all-weather ice detection and mapping capabilities.

SUMMARY AND CONCLUSIONS

The NOAA CoastWatch program is designed to provide real-time access to satellite imagery and image products for U.S. coastal regions. The Great Lakes are included as four 512 × 512 pixel "scenes" covering the lakes at 1.3 and 2.6 km resolution. During the period May 1990 to May 1991, 630 images of surface water temperature for these four scene areas were processed. Comparison of satellite-derived water temperatures with temperatures measured by NOAA weather buoys in the lakes shows satellite temperatures an average of about 1C° cooler than buoy temperatures with an RMS deviation of 1-1.5C°. Three examples of the surface temperature imagery showed the potential for applications in detecting and locating thermal fronts, analyzing circulation patterns, and ice and snow mapping. In 1992, the CoastWatch NOAA 11 imagery will also include visible and reflected infrared channels that should prove useful for examining turbidity, and for ice and snow mapping. Future CoastWatch products are planned based on new satellite sensors such as SeaWifs and Synthetic Aperture Radar.

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