The Keweenaw Current and Ice Rafting: Use of Satellite Imagery to Investigate Copper-rich Particle Dispersal

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ABSTRACT. The immense surface area and large volume of Lake Superior causes thermal characteristics to resemble marine waters, yet the completely bounded shoreline and low flushing rate introduce unique features. Previously, shoreline inputs were considered minor, as annual river discharges account for only 0.36% of the total hydrologic volume of the lake. However, thermal bar formation and wind shear from prevailing westerlies impound warm waters along the southern coastline, creating a coastal exposure corridor with strong counterclockwise circulation known as the Keweenaw Current. Discharges from rivers and industrial sources are confined, then entrained. Here infrared AVHRR (Advanced Very High Resolution Radiometer) satellite imagery was utilized, verified by NDBC (NOAA National Data Buoy Center) buoy surface data, to document thermal features of offshore waters and the coastal zone.

Five stamp mills at Freda/Redridge discharged over 45 million metric tons of stamp sands between 1895 and 1922. The coarse fraction forms beach sands that now extend 23 kilometers north from their sources and that blanket shallow-water sandy sediments. The finer fractions disperse much farther than the coarse fractions, moving along the primary track of the Keweenaw Current. SPOT and TM (Thematic Mapper) imagery were used to document how Ontonagon clays and Freda/Redridge stamp sand particles are entrained by the Keweenaw Current. The two particle types have distinctive reflective spectra.

An additional transport mechanism, revealed by RADARSAT ScanSAR (Synthetic Aperature Radar) imagery, is ice rafting. Nearshore ice incorporates large amounts of coastal sands and deeper-water sediments. Spring break-up of coastal ice results in large drifting ice packs that are pushed by prevailing westerlies and currents around the tip of the Keweenaw Peninsula into the Caribou Basin.

INDEX WORDS: Keweenaw Current, ice rafting, AVHRR, copper, water temperature, Lake Superior.

INTRODUCTION

The immense size of Lake Superior, its bounded waters and latitudinal position generate intriguing temperature and water circulation patterns. The lake is the largest freshwater body in the world from an aerial extent, covering 82,100 km², with a length of 563 km and a breadth of 259 km. As in many of the Laurentian Great Lakes, the watershed is characterized by a relatively high water to terrestrial surface area ratio (39.1% water surface, 61.9% terrestrial). Lake dominance of the hydrologic cycle is further enhanced by evapotranspiration. Although the terrestrial area constitutes 61.9% of the total surface area, evapotranspiration reduces the surface water-stream inputs to only 46% of the annual total. Thus most (54%) of the vast stored waters in the lake originally fell as direct precipitation onto its water surface, explaining why the surface waters are both very dilute and simultaneously sensitive to long-distance atmospheric contaminants (IJC 1977, EC & USEPA 1987).

The volume of water stored is so large relative to discharge, there is a tendency to discount the yearly shoreline inputs and to emphasize the atmospheric component. The best available estimates are that the lake discharges only 0.56% of its volume annually through the St. Marys River at Sault St.Marie, leading to a long water residence time (191 yrs). The total discharged annually into the lake from river, stream, and surface runoff constitutes only 0.36%
of the volume of the lake (IJC 1977, EC & USEPA 1987).

Shoreline discharges can be important and are intimately tied to coastal thermal structure and circulation patterns. Early knowledge of Lake Superior warming cycles (Beeton et al. 1959, Phillips 1978), thermal fronts and bar formation (Smith 1974, Spain et al. 1975), currents (Harrington 1895, Adams 1970, Smith 1972, Sloss and Saylor 1976, Green and Terrell 1980, Pickett 1980), and zones of upwelling and downwelling (Ragotzkie 1974, Green and Terrell 1980, Pickett 1980), and thermal properties, water circulation patterns, and ice rafting.

Based on the long renewal time and the relatively rapid seasonal mixing, there is a tendency to discount shoreline dynamics and to emphasize the stability of offshore characteristics. This is further underscored by the observation that 95% of the pollutants that enter the lake ecosystem do so through atmospheric inputs (EC & USEPA 1987). Whereas that assessment may be correct for certain organic contaminants, it can not be generalized to many inorganic contaminants. Here it is illustrated how the seasonal development of thermal regimes combine with prevailing westerly winds to create strong counter-clockwise coastal currents. The coastal regime constitutes a corridor that transports dissolved and suspended particulate materials along shorelines and into deeper waters.

Various industrial operations historically discharged materials into the coastal zone of Lake Superior. At the turn of the century, large-volume stamp mills from copper mining operations opened along the shorelines of the Keweenaw Peninsula (Kerfoot et al. 1994, Kerfoot and Robbins 1999). On the western coast near Freda and Redridge, 46 × 10^6 metric tons of stamp sands were discharged by five high-volume stamp mills between 1895 and 1922, with 2.4 × 10^6 metric tons reworked by reclamation efforts between 1956 and 1964. Along the eastern shoreline near Gay, two large mills discharged 38 × 10^6 tons (Fig. 1). The coarse-grained fraction of the stamp sands discharged at Freda and Redridge are plastered 22.6 km northeastward as beach sands or are present underwater as vast fields peppering shallow-water sands (Kraft 1979), whereas the discharges at Gay formed black sand beaches that stretch 8.1 km south to the Traverse River.

The circumstantial evidence for long-distance transport of shoreline-discharged particles is very suggestive. If reported surface copper concentra-
tions across eastern Lake Superior are divided by presettlement concentrations to produce an enrichment index, surface plots reveal high values that follow the path of the Keweenaw Current (Kerfoot et al. 1994). The pattern suggests that copper from mining activities was transported a considerable distance from the original Keweenaw Peninsula sources, extending well into the Caribou Basin, despite low mass sedimentation rates in the interior basin (Fig. 2). Yet the exact track of the Keweenaw Current, the amounts of sediment transported, or other transport mechanisms are poorly understood.

Here AVHRR satellite imagery is used to describe the seasonal development of thermal structure that, with prevailing westerlies, leads to the formation of the Keweenaw Current. In addition, TM and SPOT imagery are used to document offshore movement of shoreline stamp sand particles and their entrainment in the Keweenaw Current. RADARSAT ScanSAR satellite imagery reveals an additional seasonal transportation mechanism, i.e., ice rafting, which also moves sediments off the tip of the Keweenaw Peninsula into the Caribou Basin and which contributes to observed patterns of coarse and fine copper-rich particle dispersal.

**METHODS AND MATERIALS**

**NDBC Buoy Data**

To obtain values for long-term water surface temperature trends, NDBC (National Data Buoy Center) data for 1984 to 1989 were purchased. Additional records were obtained for the detailed 1993 to 1994 AVHRR studies. As part of the National Weather Service (NWS), NDBC operates automated data acquisition systems from moored buoys and fixed monitoring stations throughout the Great Lakes. The location of the three open-lake NOMAD buoys in Lake Superior (Isle Royale Basin, buoy 45001; Caribou Basin, buoy 45004; Chefswet Basin, buoy 45006) were purchased. Additional records were obtained for the detailed 1993 to 1994 AVHRR studies. As part of the National Weather Service (NWS), NDBC operates automated data acquisition systems from moored buoys and fixed monitoring stations throughout the Great Lakes. The location of the three open-lake NOMAD buoys in Lake Superior (Isle Royale Basin, buoy 45001; Caribou Basin, buoy 45004; Chefswet Basin, buoy 45006) were purchased. Additional records were obtained for the detailed 1993 to 1994 AVHRR studies. As part of the National Weather Service (NWS), NDBC operates automated data acquisition systems from moored buoys and fixed monitoring stations throughout the Great Lakes. The location of the three open-lake NOMAD buoys in Lake Superior (Isle Royale Basin, buoy 45001; Caribou Basin, buoy 45004; Chefswet Basin, buoy 45006) and

![FIG. 1. Locations of buoys and shoreline sites shows the three open-lake NDBC (National Data Buoy Center) buoys in Lake Superior (45001, Isle Royale Basin; 45004, Caribou Basin; 45006, Chefswet Basin) and four other fixed CMAN monitoring stations (PILM4 and ROAM4, both off Isle Royale; DISW3, off the Apostle Islands; and STDM4, at Stannard Rock); main figure Peninsula localities discussed in the text (circles, mines; triangles, stamp mills).](image-url)
Satellite Imagery of the Keweenaw Current and Ice Rafting

four other fixed monitoring CMAN stations (PILM4 48.2N 88.4W, ROAM4 47.9N 87.2W, both off Isle Royale; DISW3 47.1N 90.7W, off the Apostle Islands; and STDM4, 47.2N 87.2W at Stannard Rock) are shown in Figure 1. Temperature records for the fixed stations extend throughout the year, whereas buoys are removed from December through March.

The weather data were available on 9 track magnetic tape in a 152 character-string format. Imbedded in this character-string was information on the station, time of day, and weather parameters. The weather data consisted of hourly climatological readings. Programs were written within the statistical package Statistical Analysis System (SAS) to calculate and extract daily averages of six variables: 1) air temperature, 2) surface temperature, 3) wind speed, 4) wind direction, 5) wave height, and 6) wave period. After the daily averages were extracted, they were imported into the database DBASE IV, which served as a link to the image processing software, and as a means of archiving the information. Here the air temperature and bulk surface temperature are used directly, while referring in text to the other variables. While long-term averages are useful, it should be pointed out that time-averaging across years may obscure certain seasonal events, such as abrupt warming following collapse of thermal bars (rate of early season warming).

**AVHRR Sensor and CoastWatch Images**

AVHRR sensors are mounted on polar-orbiting, sun-synchronous NOAA Television and Infrared Observation Satellite (TIROS-N, currently NOAA-10 and NOAA-11) weather platforms. Two satellites orbit the earth every 102 minutes at an altitude of 833 km. One satellite images Lake Superior at about 0230 UTC (Universal Coordinate Time, otherwise known as Greenwich Mean Time) and 1430 UTC, whereas the other images at about 0730 UTC and 1930 UTC. The devices record a continuous image that covers a 2,400 km swath width with a basic spatial resolution (pixel size) of 1.1 km at nadir. The sensors are five-band multispectral scanners that detect radiation from the red to thermal infrared regions of the electromagnetic spectrum (Table 1). Kidwell (1991) summarizes sensor specifications and Planet (1988) lists prelaunch calibrations for channels 1 to 5.

AVHRR has real-time radiometric calibration

![FIG. 2. Copper enrichment in surface sediments off the tip of the Keweenaw Peninsula (after Kerfoot et al. 1994). Pie diagrams indicate % enrichment, where 0% = background (i.e., pre-1870).](image-url)
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Image processing (IP) utilized ERDAS Software Programs (Table 2). The > 90% cloud free images for portions of Lake Superior were based on visual analysis of near infrared (channel 2), aerosol-corrected reflectance (channel 1 minus 2), and channel 4 for SST images. Upon receipt, the data were manually adjusted to a base map overlay provided by CoastWatch. Because of a clock error on the satellite, navigation has an error. In the most extreme examples, the images were misregistered by as much as 14 pixels or 19 km. Without the adjustment procedure, the high variation between images would have precluded comparisons at the pixel level (for the purposes of regression of in situ water quality parameters against MCSSTs). Pixels with channel 2 albedos that exceeded a threshold value were flagged as clouds or land and masked (Stumpf 1992). This procedure provided a highly accurate overlay of the shoreline, given the coarse spatial resolution of the images.

**TABLE 1. Channel characteristics of the AVHRR sensor (from Kidwell 1991).**

<table>
<thead>
<tr>
<th>Channel</th>
<th>Wavelength (µm)</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.58–0.68 (red)</td>
<td>reflected solar energy; clouds, coastlines, and vegetation</td>
</tr>
<tr>
<td>2</td>
<td>0.72–1.00 (near-infrared)</td>
<td>reflected solar energy; clouds, coastlines, and vegetation</td>
</tr>
<tr>
<td>3</td>
<td>3.55–3.93 (mid-infrared)</td>
<td>reflected solar energy; thermal emission; clouds and sea surface temperature</td>
</tr>
<tr>
<td>4</td>
<td>10.3–11.3 (thermal infrared)</td>
<td>thermal emission; clouds and sea surface temperature</td>
</tr>
<tr>
<td>5</td>
<td>11.5–12.5 (thermal infrared)</td>
<td>thermal emission; clouds and sea surface temperature</td>
</tr>
</tbody>
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**Lake Surface Temperature Data**

There is a distinction between skin surface and bulk temperatures. Thermal infrared remote sensors detect radiation emitted from the first 50 nm of the surface or skin of the lake and the intervening atmosphere. Lake skin temperatures are generally several tenths of a degree colder than the lower water strata due to evaporative cooling at the air-water interface (Saunders 1967, Grassl 1976, Paulson and Simpson 1981). Bulk temperature, a variable usually measured by shipboard or buoy instrumentation, measures temperature in the upper 0.5 to 2.0 m of the water column. Understanding and quantifying the relationship between bulk and satellite-derived sea surface temperatures (SST) has occupied two decades of research (McMillin 1975, McMillin and Crosby 1984, McClain et al. 1985a, Minnet 1990, Schlussel et al. 1990, Walton et al. 1990, Wick and Emery 1992). SST algorithms relate the black body temperature detected by the satellite to buoy bulk temperature. The thermal infrared radiation detected in bands 4 and 5 originates from the surface skin of the water, whereas the coefficients for the SST equations are found from regression of skin temperatures against bulk water temperatures (0.5 to 2 m) of buoys. The equations are designed to reduce water vapor effects on temperature (Walton et al. 1990), as the relationship between skin and bulk temperature is presumed to be constant. Different equations are used for daytime and nighttime images, assuring that the skin/bulk
relationship is maintained, which allows for analysis of diurnal variations of surface bulk temperature (Walton et al. 1998, applications for CoastWatch images, Pichel et al. 1995, Leshkevich et al. 1993). Only one of the three daytime algorithms pertain to this study, i.e., OCNMAP, a linear algorithm for daytime images and a nonlinear procedure that incorporates improved atmospheric corrections for nighttime images (Leshkevich et al. 1993).

A primary source of in situ data allowed SST values in the CoastWatch imagery to be compared against bulk temperatures: NOAA National Data Buoy Center (NDBC) buoys. Seasonal differences between AVHRR SST values and buoy bulk temperatures were investigated over the 1993 season. Of 72 images obtained for study, twenty relatively “cloud free” scenes were selected to illustrate a typical yearly cycle. The original and processed images are on file with the Lake Superior Ecosystem Research Center, Michigan Technological University.

### TABLE 2. IP procedure for temperature contour maps.

<table>
<thead>
<tr>
<th>PRELIMINARY IMAGE PROCESSING:</th>
<th>NCAAS</th>
<th>Retrieve NOAA CoastWatch images.</th>
</tr>
</thead>
<tbody>
<tr>
<td>DECON</td>
<td>Shareware program provided by NOAA that strips off header information and converts data from 11-bit to 8-bit format.</td>
<td></td>
</tr>
</tbody>
</table>

**ERDAS IMAGE PROCESSING:**

*Step 1. Import AVHRR imagery.*

- **LDDATA:** Import AVHRR image.
- **BSTATS:** Generate simple statistics.

*Step 2. Image Georeferencing.*

- **CLASOVR:** Adjust image to CoastWatch base map.
- **FIXHED:** Repeat steps A-C with adjustments.

*Step 3. Isolating the Water Signature.*

- **RECODE:** Use visible channels 1-2 reflectance data to create land and cloud mask.
- **GISEDIT:** Edit out inland lakes and rivers.
- **MASK:** Overlay mask on georeferenced image.

*Step 4. SST Verification*

- **DATATAB:** Select data points that match in situ data.

*Step 5. Convert 8-bit satellite data to IDL format (FORTRAN program).*

- **ERDTORAW:** Converts ERDAS binary datasets to ASCII datasets.

*Step 6. Run IDL software to create contoured temperature maps.*

- **.RUN TEMP:** IDL is a command language image presentation software program. A special program within IDL was written to produce false gray-scale and color composites of AVHRR thermal data.

**SPOT-HRV, TM, and RADARSAT ScanSAR Images**

The High Resolution Visible (HRV) sensors of SPOT-1 offer high spatial resolution (10 m panchromatic, 20 m multispectral), but contain bands only in the green, red, and near infrared wavelengths. However, the images are useful for detecting and mapping distinct water masses and turbidity (Vande Castle et al. 1988). Bands 1 and 2 (green and red wavelengths) generally are excellent for picking up turbidity patterns. The Landsat Thematic Mapper (TM) sensor has 30 m pixels and 7 spectral bands, capable of differentiating biotic (Chlorophyll a) and sediment signatures.

For imaging ice packs, RADARSAT-1 ScanSAR data were acquired from the Alaska SAR Facility and the NOAA Satellite Active Archive. Nominal image characteristics are a 500 km swath width, 50 or 100 m pixel size, and 8 bit quantization of backscatter intensity. Because ScanSAR imagery is constructed from multiple narrow beam modes, the
data are as yet uncalibrated. Hence, backscatter is represented as 8-bit digital numbers between 0 and 255, rather than the more usual form of calibrated backscatter expressed as a backscattering coefficient, sigma naught. Image processing consisted of interactive contrast enhancement and speckle reduction (image smoothing) using a 3 × 3 median filter.

Reflectance Spectra for Ontonagon Clays and Stamp Sand Fine Fractions

Sediment reflectance methods followed Bhargava and Mariam (1991). Samples of kaolinite clay (Sigma) and sieved fractions of both Ontonagon River bank clays and stamp sand samples were suspended in a large aquarium. The walls of the 50-gallon aquarium were spray-painted black to minimize internal reflectance. A 1,000 watt tungsten halogen lamp, suspended overhead at a 45° angle to the water surface, provided illumination. A hand-held narrow-slit (10°) spectroradiometer (Analytical Spectral Devices, Boulder, Co.; model Personal Radiometer) was held 1 meter above the water surface, reading reflectance over a 16 cm diameter circle (202 cm²) on the surface of the slurry. Original amygdaloidal stamp sand tailing material was obtained from the Isle Royale piles and sieved into particle size fractions. Kaolinite clay (control), Ontonagon clay, and stamp sand fine particle fractions were introduced in concentrations that ranged between 0 mg/L (control, background water spectra) to 1,280 mg/L. Readings were made for selected size fractions of Ontonagon clay (< 53, 53–63, 63–75, 75–90 µm) and stamp sand (125–150, 150–180 µm). Clearly, further spectral work is required, as iron oxides act in a size-specific fashion, making very fine fractions of stamp sands (so-called slime fraction) more reddish (amygdaloid) or purplish (conglomerate). Here results from the < 53 µm Ontonagon clay and the 125 to 150 µm stamp sand fractions are reported.

RESULTS

Seasonal Patterns At Buoy Stations

Data from NDBC buoys illustrate some general characteristics of Lake Superior thermal patterns. Because of its vast size and depth, the mean temperature of Lake Superior lags behind the cyclical variation of both air and surface water temperature (Phillips 1978). Although its more northern latitude has some influence, relative to the other Laurentian Great Lakes, Superior warms and cools much more slowly, attaining maximum surface temperatures much later than other smaller, regional lakes, Lake Michigan, and especially the much shallower Lake Erie (Fig. 3a).

The thermal inertia of Lake Superior is very evident in the seasonal air temperature versus bulk surface temperature trends. Figures 3b and 3c show the daily mean temperature trends for air temperature and bulk surface temperature at an open-water buoy station in Lake Superior (buoy 45006; Chefs wet Basin, off the Apostle Islands) and at a fixed shoreline station (ROAM4, Rock of Ages Lighthouse, Isle Royale). The curves are hourly water surface temperatures averaged during the interval from 1984 through 1989. Heat storage lags in fall and spring are influenced by two factors: 1) large quantities of stored heat during summer, carrying over into the fall, and 2) the formation and thawing of ice. Each acts to moderate air and surface temperature cycles. The minimum surface water temperature of less than 0.5°C occurs over a 6-week period from late February through early April, whereas the maximum surface water temperature is reached between late July and early September, depending upon the site. In open waters, the surface temperature is lower than the mean lake temperature from mid-December through early May (Phillips 1978). With the onset of spring warming, the surface temperature of open water rises slowly from the end of March to about 3 to 5°C in mid-June.

Serving as an introduction to the spatial heterogeneity characteristic of seasonal warming, Figure 4 compares warming and cooling trends at the three offshore buoys during a single season (1993). The shallower western basin station (45006, Chefs wet) shows more rapid spring warming, early (late July/early August) and high maximum temperature, and relatively early decline of temperature in the fall. In contrast, the central, deepwater station (45001, Central) exhibits a delay in spring warming through July, a low and late maximum temperature and late fall cooling. After attaining surface maxima, temperature decreases rapidly during September and October at all stations, reaching 4°C by early November. The deep offshore (45001, Central) station cools more slowly during November and December than the shallower, nearshore stations, again related to the heat storage effects. However, Buoy 45004 (Stannard Rock, Keweenaw Bay), shows a curious pattern of early warming and temperature irregularities, despite being in one of the deeper basins.
Correspondence Between Buoy And AVHRR Data Sets

It was found that the 1993 AVHRR SST temperatures reproduce the buoy surface bulk temperatures closely (Fig. 5a; r = 0.971) with only a slight negative bias (< 1°C) at low temperatures. Seasonal plots of AVHRR MCSST temperatures versus NDBC buoy bulk temperatures (Fig. 5b) illustrate the very close absolute agreement between values.

Coastal Spatial Thermal Patterns (AVHRR)

The spatial pattern of seasonal warming and cooling for Lake Superior in 1993, created from processed AVHRR imagery, is shown in the two Figure 6 panels. Cooler temperatures are toward the blue, whereas warmer are toward the red. Land is masked as black, while clouds are masked as white. Although the processed pixels are ca. 1.1 km square (1.34 km² area), the resolution is more than adequate for resolving broad-scale patterns of surface skin temperatures, since the lake surface area is over 82,000 km². For example, large-scale eddies from the Keweenaw Current are evident in summer scenes, curling off the tip of the Peninsula, often as far as Stannard Rock. For purposes of discussion, the temperature contour maps illustrate a typical seasonal cycle that passes through six stages:

Mid-Winter Cooling Phase: Ice Maximum

From January to early March, surface temperatures are everywhere below 4°C. Freezing starts from the shallow and wind-protected margins and episodically progresses lakeward. Ice cover reaches its maximum from February to early April (peaked
Central upwelling (IJC 1977) keeps large areas ice-free most years, particularly in the eastern basin.

**Initial Stages of the Spring Warming Phase**

During early March to April, the whole lake is still below 4°C and portions remain covered with floating ice (see RADARSAT ScanSAR section) during characteristic inverse stratification of the water column. Ice lies along the periphery, particularly in the Apostle Islands, Thunder Bay, Keweenaw Bay, Whitefish Bay, and smaller embayments along the southern shoreline, keeping temperatures near freezing. Warmer water (1.3°C) is located both in the mid-lake and along the northwest coast. By early April, the lake water column is essentially isothermal with a temperature of approximately 2°C (Jipping 1991). At the end of this period, the land responds more quickly to increased insolation and the warming of the atmosphere. Especially along the warmer southern margin, rivers and streams discharge large volumes of warmer waters during the spring snow-melt period.

**Thermal Bar Formation Stage of Warming Phase**

During the initial stages of the warming phase, water along the shoreline heats faster than offshore waters and also receives warmer river discharges. Along the southern shoreline, this phenomenon is especially pronounced in shallow embayments (Duluth basin, Chequamegon Bay, Keweenaw Bay, Whitefish Bay). Temperatures start to move above 4°C in bay regions, whereas the middle portion of the lake remains below 4°C (5/25 to 6/28 scenes, Fig. 6).

Later June scenes (6/10 to 6/28 scenes, Fig. 6) show a definite temperature gradient developing along the south shore. The average surface temperature of the main body of the lake at that time is approximately 2 to 3°C. Along the southern coastal margins and the western arm of the lake, surface temperatures range from 5 to 11°C. Again the rise is pronounced in bays. The boundary between the inshore warm region and the isothermal offshore waters is termed the “thermal bar” (Huang 1972, Ullman et al. 1998). The thermal bar position is easily determined by the location of the 4°C isotherm. The thermal bar acts to confine shoreline discharges along the coast. This isotherm marks a predominately vertical boundary between waters from different sources, near the temperature of

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**FIG. 5.** Verification of surface temperature data in Lake Superior: a) regression of 1993 AVHRR MCSST skin surface temperatures against NDBC buoy bulk surface temperatures. See Methods section for discussion of procedures. Fit regression equation and $R^2$ values given in insert. b) Comparison of 1993 AVHRR MCSST temperatures with NDBC buoy bulk surface temperatures at the three open-water buoy sites, plotted through time.
maximum density. The density causes a sinking motion along the offshore edge of the 4°C isotherm, and a type of isolation of flows on either side of the 4°C isotherm. Waters of different color, marked differences in phytoplankton populations, and different flow patterns are commonly observed along the 4°C isotherm (Ullman et al. 1998).

Sinking along the 4°C isotherm causes surface convergence. The convergence at the thermal bar is thought to result in an upwelling in the middle portion of the lake during this period of time (Ragotzkie and Bratnick 1965, IJC 1977, Bennett 1978). The upwelling to the surface of the offshore basin provides water colder than the temperature of maximum density (4°C) until the disappearance of the thermal bar. The spring thermal bar period usually lasts for 4 to 6 weeks. The shallow nearshore water gradually warms toward the deeper offshore areas during the course of summer.

During May to early July the horizontal temperature difference between the edges of the lake and the middle portion increases several fold. Shoreline waters become much warmer than offshore waters and coalesce to form a continuous southern corridor. Under the influence of prevailing westerlies associated with barometric highs (Niebauer 1976), coastal waters form a major counterclockwise coastal current along the western shoreline of the Keweenaw Peninsula. The Keweenaw Current (Ragotzkie 1966, Smith 1972, Smith and Ragotzkie 1970) compresses near the tip of the peninsula, then jets with obvious eddy patterns into the Caribou Basin (6/28 to 7/11 scenes, Fig. 6). SPOT and TM images capture coastal sediments becoming entrained in the Keweenaw Current (Figs. 7a–b). These sediments are a mixture of Ontonagon clays from the Ontonagon River discharge, sandy beach sediments from weathering shoreline rock formations (Freda Sandstone, Copper Harbor Conglomerate), and stamp sand material broadcast along the shoreline from stamp mills. From the Freda and Redridge shorelines north for 23 km, waves and longshore currents work the dark sand beaches (stamp sands), suspending particles that are entrained offshore into the Keweenaw Current (Fig. 7b).

Summer Warming Phase: Keweenaw Current and Offshore Upwelling Followed by Thermocline Period

After the disappearance of the thermal bar, the lake surface warms above 4°C. During this time, the central and eastern basins are characterized by a relatively cool, central upwelling region that is characteristic of Lake Superior. Along the shoreline, coastal upwelling regions may result from shifts in prevailing wind patterns, as barometric highs are followed by lows. Strong barometric lows can lead to prevailing southeasterly winds, causing upwelling along the western coastline of the peninsula (Niebauer 1976). By late June or early July, offshore waters in the western basin are much more homogeneous and a weak thermocline begins to grow.

The July scenes (7/11 to 7/30) show that as the heat content increases in summer, the surface temperature gradient becomes stronger, ranging from 15 to 19°C along the shoreline and from 4 to 7°C in the central eastern basin. During this time, there is very little change in the central part of the eastern basin, due to strong water density differences restricting mixing and to the development of mid-lake upwelling.

Mid- to late-August (8/07 to 8/24) shows a major increase in central, offshore surface temperatures. By late August (8/20 to 8/24), the temperature ranges from 14°C at the central portion of the lake to 20°C toward the shoreline. The early to late August scenes capture the transformation of the large isothermal midlake zone into a stratified region. By early August through mid-September, the lake becomes strongly thermally stratified. That is, there is a sharply defined vertical temperature gradient everywhere across the lake. The nearly homogeneous epilimnion is isolated from the cold hypolimnion.

The thermal maximum occurs in the first two weeks of September. By mid- to late September (9/15 to 9/23 scenes), surface temperatures rapidly decline. The average surface temperature of the main body of the lake is approximately 11°C. Upwelling is evident along the western coastline of the Keweenaw Peninsula on the September 15 image.

Early Fall Cooling Period

The lake begins to cool in late October to November over its entire surface (Feit and Goldenberg 1976, Assel 1985, 1986). By December, the waters become nearly homogeneous again, as the surface waters are above 4°C, but the edges are cooler than the center.

Late Fall/Early Winter Cooling Period: Inverted Stratification

During this final stage, shoreline waters cool to 4°C, then below 4°C. Rapid cooling in embayments
FIG. 6. Seasonal development of the Lake Superior coastal zone as illustrated by AVHRR images. Scenes illustrate the thermal bar interval in May and subsequent development of a strong Keweenaw Current by late June to early July. Note changes in temperature scale through the sequence of images.
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to 4°C leads to profile-bound density currents, as the denser waters sink toward deeper portions of the basin. Once below 4°C, ribbons of low-density, cool waters ring the shoreline (Smith 1973). Whereas inverted temperature regimes should lead to formation of an autumn thermal bar, the phenomenon is not as pronounced as its spring counterpart largely due to great disturbance by early winter storms. The temperature difference between the edges and the main body of water is only 4°C, much smaller than the gradient during the spring warming phase, and sometimes barely recognizable. Soon ice formation begins along certain (shallow, protected) shorelines.

Full winter coverage of Lake Superior by AVHRR imagery is extremely difficult to obtain because of extensive cloud cover. However, RADARSAT ScanSAR uses 5.6 cm wavelengths that can penetrate through cloud cover and darkness to reveal drifting ice and open water regions. Maximum ice cover does not occur until mid-March (Phillips 1978).

Reflectance Spectra for Ontonagon Clays and Stamp Sands

SPOT and TM imagery permits zooming in on coastal Keweenaw waters to check for suspended particles. Entrained particles seen in SPOT and TM images are a mixture of particles from various source materials: clay and silt-sized particles discharged from the Ontonagon River, which erodes previous lake-bed deposits along its banks, re-worked clay, silt, and sand from weathering shoreline rock outcrops (Freda Sandstone, Copper Harbor Conglomerate) and reworked stamp sands. The stamp sands were discharged from five large mills at Freda and Redridge, plus smaller mills between Eagle River and Eagle Harbor. In this high-energy environment, silt-sized and clay-sized particles are frequently seen during spring river high-discharge periods, after storms, and in the fall high-wave period.

Reflectance spectra for pure kaolinite clay, Ontonagon clay, and stamp sands are shown in Figure 8. The different spectra suggest that Ontonagon and stamp sand components may be separated from each other by use of multi-band satellites such as Landsat TM or the Sea-viewing Wide Field-of-View Sensor (SeaWiFS), potentially allowing estimates of suspended solids for each type of source material.
RADARSAT ScanSAR Images of Ice Rafting

The Keweenaw Current is not the only transport option operating along the Keweenaw Peninsula. Ground studies and aerial observations of Lake Superior and other Great Lakes show that nearshore ice may incorporate large sediment loads (primarily shoreline sand, with subordinate pebbles, cobbles, but also organic-rich deeper sediments). The sediments are concentrated in nearshore ice facies by a variety of mechanisms, principally because nearshore regions are most directly exposed to sediment supply and entrainment (Barnes et al. 1994).

Sediments are subsequently transported to midlake areas via ice rafting. Here ground-based and remote sensing studies were used to document sediment entrainment mechanisms around the Keweenaw Peninsula. A combination of ground photos and aerial photos show fine details, whereas synthetic aperture radar (SAR) images illustrate large-scale ice pack features.

Those who venture out on the lake during winter know that shoreline ice is “dirty.” A typical nearshore ice complex (NIC) consists of a grounded ice foot, one or more shore-parallel ridges (with coalescent ice-volcanoes), and intervening shore-parallel ice lagoons (Fig. 9). The features of a typical NIC are described in detail by Barnes et al. (1994), O’hara and Ayers (1972), and Marsh et al. (1973). The NIC remains shorefast for much of the winter, although it may become active whenever directly exposed to waves. The outer edge of the NIC is a boundary with mobile ice facies, notably 1) a belt of brash and slush ice, and 2) a band of drifting pack ice. NIC zones form as a shore-parallel grounded ridge of ice constructed through advection of slush ice, water, and sediments, primarily during winter storms. The icefoot is a product of episodic pulses under conditions of high-energy waves and concurrent snowfall that produces copious amounts of slush. Initial growth is an early season phenomenon, prior to the nearshore zone becoming inaccessible to large, deepwater waves. If snow is present in sufficient amounts, a belt of slush floats lakeward of the icefoot edge. Under stormy conditions, large waves churn the water into a turbid brown, due to suspended sediments and lumps of slush ice. Waves incorporate sediment into the floating slush, which in turn provides a mechanism for lifting sediments onto the ice foot. The high surface to volume ratio of slush increases its effectiveness as a sand and pebble lifting agent.

Sediment entrainment mechanisms include the following:

1. Waves entrain sediments into the water column and floating slush;
2. Waves deposit entrained sediments (directly from water or as slush) on top of solid ice (floes and ice foot);
3. Ice keels scour and entrain sediments (divers using SCUBA report that ice keels may reach 20 to 30 m depth);
4. Sediment-laden anchor ice detaches from lake bottom;

FIG. 8. Comparison of reflectance spectra from pure kaolinite, Ontonagon, and stamp sand fine fractions.
5. Sediment-laden river ice enters lake;  
6. Sediment-laden river water flows onto river or lake ice (aufeis);  
7. Cliff/bluff sediments fall onto ice surface;  
8. Wind-blown (eolian) deposition.

Based on our field experience in Lake Superior, the first four mechanisms are probably the most significant in terms of bulk mass of sediments incorporated into NIC zones.

Three main environmental factors facilitate the sediment entrainment-transport process: 1) shallow bathymetry (2 m or greater waves are common in winter storms), 2) abundant source materials (unconsolidated sediments), and 3) strong onshore winds and waves. The Keweenaw coast immediately off McLain State Park, at the North Entry to the Keweenaw Waterway, exemplifies these conditions (Fig. 10). A mixture of natural beach sands and stamp sands coat the melting ice foot in early April, 1997. Sandy layers incorporated into the ice foot are exposed in broken cross sections.

Late winter RADARSAT ScanSAR images of Lake Superior from March and April, 1997, show the NIC as a bright band along the coast from Ontonagon to Keweenaw Point (Fig 11). Pack ice is originally consolidated, then surges back and forth, and drifts past the tip of the peninsula under the influence of strong westerly winds. Images on 11 March 1997 document the pack ice drifting past Copper Harbor and Manitou Island (Fig. 12). Clearly, particle transport via ice rafting is real, yet the mass transport details require further research.

DISCUSSION

If used in isolation, NDBC buoy and CMAN fixed stations provide detailed temporal temperature records at scattered sites, but little information on spatial patterns. However, when verified by the temporal point data, AVHRR spatial imagery allows reconstruction of large-scale Lake Superior surface thermal patterns. The spatial results are striking in their ability to capture large-scale details of the coastal zone. Moreover, the data are truly synoptic and the errors are relatively small.

Satellite imagery has been available for decades in the U.S., yet relatively few individuals and institutions have utilized this source for analysis of surface water temperatures in the Great Lakes. The primary difficulty has been the expense of purchasing scenes and the software necessary for processing satellite imagery. Exceptions include Sabatini’s (1971) use of data from Nimbus 1, 2, and 3, Strong’s (1974) use of data from the NOAA 2 satellite, Lathrop and Lillesand’s (1986, 1987) use of Thematic Mapper (TM) data, and Lathrop et al.’s (1990) use of NOAA 9 infrared data. Vande Castle et al. (1988) strongly advocated use of TM, SPOT-1, and AVHRR in water quality studies. Other investigations not dealing primarily with temperature, but utilizing this information, include Strong and Eadie’s (1978) use of imagery from Landsat, the NOAA polar orbiting satellites, and the Skylab Earth Terrain Camera system to investigate lake surface temperature and calcium precipitation patterns, plus Mortimer’s (1988) use of Coastal Zone Color Scanner (CZCS) data to test a variety of hypotheses about chlorophyll a and upwellings.
FIG. 10. In situ photos of sediments in icefoot: A) sand ablation cones on surface of eroding icefoot, west McLain State Park, MI, April 1997, and B) beach sand/stamp sand mixture in vertical cross-section of icefoot (matchbook for scale). Cone structures form through differential ice ablation.

FIG. 11. RADARSAT ScanSAR image of Lake Superior (April 1, 1997). Nearshore ice on windward coasts is the dominant sediment accumulation facies. Offshore ice facies are less likely to entrain sediments. The NIC appears as a narrow bright band along the coast from Ontonagon to Keweenaw Point. ScanSAR Wide B image, pixel size = 100 m, swath width = 500 km. Copyright Canadian Space Agency, 1997.
In the regression analysis of AVHRR SST versus buoy bulk temperature, errors of a fraction of a degree are not unreasonable. In fact, the global SST has a standard error of estimate about 0.5 to 0.7 degree. The Lake Superior comparison in this study came close to this, except for the bias at low temperature. The errors can be attributed to atmospheric variability (0.1 to 0.2 K; Kidwell 1986), noise in the radiometric satellite measurements (0.12 K; Kidwell 1986), errors in the buoy data (0.1 K; Verity 1988), the difference between bulk and skin temperatures (0.1 to 0.5 K; McClain et al. 1985a,b; Schlussel et al. 1987; Schlussel et al. 1990; Minnett 1990), and cooling or warming effects associated with diurnal variation. Another possible source of error is the uncertainty introduced by spatial and temporal variability (Schlussel et al. 1987, Minnett 1990). That is, the satellite measurement is a near-instantaneous spatial average, whereas the buoy measurement is a temporal average at a given sample location. The error induced by this aspect probably is not very large since the AVHRR surface temperature seldom shows gradients of 0.5°C per pixel (Schlussel et al. 1987).

One possibility for the low bias, suggested by R. Stumpf (personal communication), is that the global analysis is made over the open ocean, where air temperatures are almost certainly higher when the water is below 5°C. The water vapor correction may be over-compensating for consistently lower water vapor content over Lake Superior.

![FIG. 12. ScanSAR image of A) Keweenaw Peninsula region, (March 11, 1997), with close-up B) showing ice drifting from NW to SE past Copper Harbor (CH) and Manitou Island (MI). ScanSAR Wide B image, pixel size = 50 m. Copyright Canadian Space Agency, 1997.](image-url)
Current limitations are primarily the 1 km² resolution of the AVHRR imagery and the fact that AVHRR senses only the surface temperature (not revealing internal structure). True variations on a diurnal basis produce about 0.5 K differences between day and night temperatures (Bernstein 1982). At present, given minimal cloud coverage, satellite monitoring could potentially produce four scenes per day. Buoy data, taken at hourly intervals, could be utilized for general interpolation of diurnal cycles.

Temperature contouring reveals several special features of Lake Superior. The first is the long lag time in summer warming, the second is the thermal bar and Keweenaw Current phase, and the third is the large central upwelling region and other more-localized coastal upwelling zones associated with strong westerlies or southeastern winds. The nearshore coastal features constrain and distribute warm waters. On one hand, offshore waters remain cooler longer than in other Laurentian Great Lakes and smaller regional lakes, whereas the Keweenaw Current is also responsible for broadcasting large volumes of coastal waters and entrained materials across some of the deepest regions in Lake Superior (Caribou Basin).

Computer contouring derived from corrected AVHRR imagery gives a more instantaneous and completely objective view of spatial temperature isolines than previous methods. The general patterns of surface water temperature based on AVHRR data are very similar to those found through ship (Webb 1975) and ART surveys, yet details of thermal gradients and large-scale eddy structure are much more evident in the AVHRR-based isolines. For example, summer surface water circulation patterns are dominated by a steep nearshore-offshore temperature gradient and a counter-clockwise nearshore current system (Adams 1970, Smith and Ragotzkie 1970, Sloss and Saylor 1976). In the AVHRR-derived images, the steep shoreline temperature gradients are very evident and irregularities in contours capture large-scale eddy structure at several locations (off the tip of the Keweenaw Peninsula). Planned studies of the Keweenaw Current using drogues and drifters (NOAA/NSF KITES Project) will help quantify currents off the tip of the Peninsula and across the Caribou Basin.

Determining the amount of sediment transported in this system will be challenging, requiring a combination of current meters, sediment traps, and water sampling. Wind-driven, shore-parallel coastal jets which lie within 10 kilometers of the shoreline have been documented in all of the Great Lakes (Murthy and Dunbar 1981). However, direction reversals, peculiar to closed basins, have not been observed thus far in Lake Superior, presumably because the lake circumference is so large (Vieckman and Wimbush 1993). Maximum current velocities are reached in the summer stratified period when stratification hinders the ability of wind to mix the water column. However, high sediment loads come in the spring and late fall. For example, the Ontonagon River contributes nearly 25% of the total riverborne sediment load to the lake (Kemp et al. 1978). Yet surface transport of clay-sized particles from this source can best be seen in May, when the warmer river waters are so buoyant that the sediment-laden strata move over cooler coastal waters. In mid-summer, when temperatures of river and coastal waters are similar, the clay-laden waters plunge below shoreline strata (Strong 1995).

Estimating the amount of sediment transported by ice rafting will be equally challenging. Although the preliminary observations reported here document substantial sediment loads, the amount and direction of ice transport has not been systematically documented, nor the sediment loads and ice wasting process. A combination of ice coring and ice pack drift tracing by RADARSAT imagery might accomplish this task.

AVHRR imagery, supplemented by higher resolution SPOT-HRV, LANDSAT TM, or RADARSAT scenes, supplies the amount of spatial coverage and real-time detail necessary to monitor dynamic changes associated with many meso-scale lake phenomena. In the future, application of AVHRR and the recently launched SeaWiFS instrument to document thermal bar formation, coastal jet and large-scale eddy mixing, and upwelling events holds exciting promise.

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