Satellite-based Chlorophyll and Turbidity Estimates Using SeaWiFS Imagery of Lake Superior

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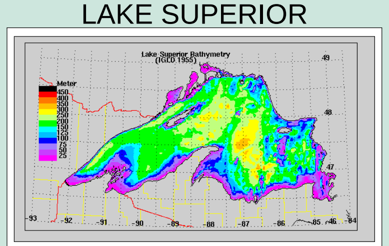
Abstract

Cross-margin transport processes in the coastal margins of Lake Superior were studied using satellite-based chlorophyll and turbidity maps from the Sea-Viewing Wide Field-of-View Sensor (SeaWiFS). We used remote sensing reflectance at 555 nm to estimate suspended solids concentrations, while chlorophyll concentrations were obtained from an empirical algorithm that is a ratio of bands 3 (490 nm) and 5 (555 nm). Analysis of Advanced Very High Resolution Radiometer (AVHRR) lake surface temperature (LST) imagery provided ancillary information about the location of physical fronts in relation to sediment concentrations and chlorophyll biomass. Validation of SeaWiFS chlorophyll indicate a linear fit of the data with R^2 values of 0.90 in Lake Superior; however, satellite-based chlorophyll was overestimated by a factor of 3 in Lake Superior, indicating that regional chlorophyll algorithms may be necessary for the Great Lakes. Work is ongoing to develop a chlorophyll bio-optical retrieval algorithm for Lake Superior (see poster by Li et al., 2002). Time series satellite images of Lake Superior in 1998 and 1999, indicate a productive southern coastal corridor from Duluth Harbor to the tip of the Keweenaw Peninsula during spring and summer months (May to August). Images obtained during the unstratified period from November to mid-April revealed a persistent sediment plume in the Ontonagon River region during both years. Cross-margin transport of materials at the tip of the Keweenaw Peninsula was dependent on wind direction, with evidence of materials being broadcast northward, eastward and southeastward depending on prevailing winds.

KITES STUDY SITE

LAKE SUPERIOR



- Lake Superior is the largest and most pristine of the Laurentian Great Lakes.
- The bathymetry along its coasts varies from very shallow to extremely steep slopes with the effect of intensifying circulation features.
- In mid-summer, Lake Superior's Keweenaw Current (found on the western shore of the Keweenaw Peninsula, carries water at approximately the same flow rate as the Mississippi River (30,000 m^3, Smith and Ragotzkie 1970)

Smith, J.P. and R.A. Ragotzkie. 1970. A comparison of computed and measured currents in Lake Superior. Proceedings 13th Conf. GL Res. pp. 969-977.

KITES REMOTE SENSING STUDIES

Impact of the Keweenaw Current on Cross-Margin Transport in L. Superior: Physical Processes, Chemical Gradients, and Biological Communities

S. A. Green and thirteen others

Thermal Fronts: The thermal bar can be monitored with remotely-sensed temperature data and its timing and duration can be determined by easily measurable climate variables (e.g., air temperatures, prevailing winds, duration of ice cover).

Particle Remote Sensing: Sedimentary materials and river discharges carried by the Keweenaw Current can be detected in remotely-sensed imagery.

SeaWiFS Sensor Characteristics and Image Processing

SeaWiFS is sensitive to the wavelengths at 410, 440, 490, 510, 555, 670, 760, and 860 nm. The first six visible channels are used to derive biogeochemical variables (chlorophyll a and sediment concentrations) and the two near infrared channels (760 and 860 nm) are used to remove atmospheric contamination. The ratio of the R_{rs} at 490 nm and 555 nm is used to estimate chlorophyll, while R_{rs} at 555 nm is used to estimate sediment concentration.

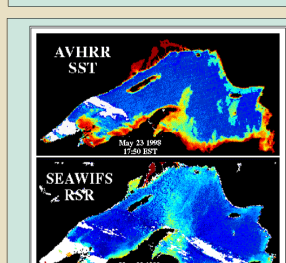
SeaWiFS imagery are received from NASA Goddard Distributed Active Archive Center (DAAC) and AVHRR imagery are received from NOAA Satellite Active Archive. Automated image processing is done in-house at Michigan Tech. We use a coastal atmospheric correction algorithm because the standard case 1 atmospheric correction routine produces negative radiances and overestimates chlorophyll in the Great Lakes. The modified correction developed for coastal waters (see Stumpf et al. 1998) removes negative radiances and provides more stable and valid results for chlorophyll. We use the OC-2 V4 chlorophyll algorithm. T

Stumpf, R.P. and others. 1998. Ocean Color Algorithms for Remote Sensing Coastal Waters of the U.S. Southeast and Easter Gulf of Mexico. EOS, Transactions, American Geophysical Union, 13:1559-1569.

Table 1: **Sensor Characteristics of the AVHRR and SeaWiFS instruments.**

Satellite Sensor	Limnologic Phenomena	Channel	Wavelength (ug)	Spatial Resolution (km^2)	Temporal Resolution
AVHRR	Reflected solar energy; suspended sediment, coastlines, and clouds	1	0.58-0.68 (red)	1.1 km^2	4-6/day
	Reflected solar energy; coastlines, and clouds	2	0.72-1.00 (near-IR)	1.1 km^2	4-6/day
	Reflected solar energy; thermal emission; clouds and sea surface temperature	3	3.55-3.93 (mid-IR)	1.1 km^2	6-10/day
	Thermal emission; clouds and sea surface temperature	4	10.3-11.3 (thermal IR)	1.1 km^2	6-10/day
	Thermal emission; clouds and sea surface temperature	5	11.5-12.5 (thermal IR)	1.1 km^2	6-10/day
SeaWiFS	Reflected solar energy; gelbstoffe	1	0.412 (violet)	1.0 km^2	1/day
	Reflected solar energy; chlorophyll absorption	2	0.443 (blue)	1.0 km^2	1/day
	Reflected solar energy; pigment absorption	3	0.490 (blue-green)	1.0 km^2	1/day
	Reflected solar energy; chlorophyll absorption	4	0.510 (blue-green)	1.0 km^2	1/day
	Reflected solar energy; pigments, optical properties, sediments	5	0.555 (green)	1.0 km^2	1/day
	Reflected solar energy; atmospheric correction (CZCS heritage)	6	0.670 (red)	1.0 km^2	1/day
	Reflected solar energy; atmospheric correction, aerosol radiance	7	0.765 (near-IR)	1.0 km^2	1/day
	Reflected solar energy; atmospheric correction, aerosol radiance	8	0.865 (near IR)	1.0 km^2	1/day

CROSS MARGIN TRANSPORT

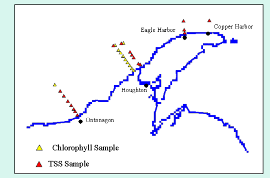


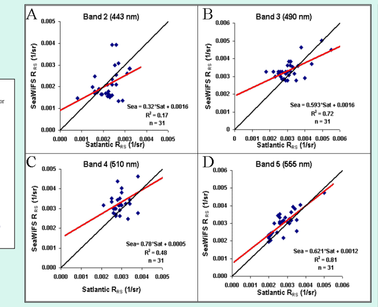
This AVHRR lake surface temperature (SST) image from May 23, 1998 indicates an offshore eddy current at the tip of the Keweenaw Peninsula. The SeaWiFS papapokip

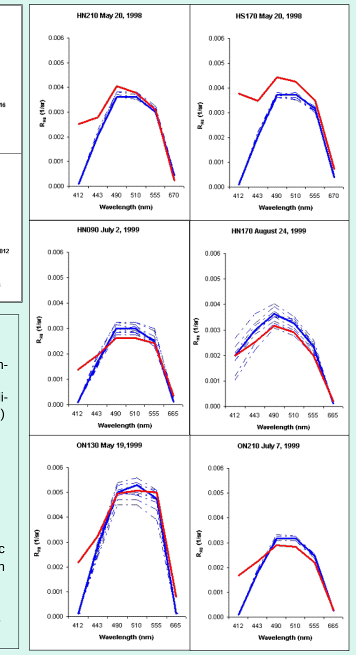
sediment map acquired within hours of the AVHRR image, provides the

Coastal Atmospheric Correction Algorithm

SAMPLING LOCATIONS







Coastal Atmospheric Correction Algorithm. The standard case 1 marine atmospheric correction produces non-physical, negative radiances in many scenes of the Great Lakes, as well as extremely high and variable chlorophyll concentrations in areas that have low and stable concentrations. Ship-based measurements from a Satlantic optical profiler were analyzed to determine how well the case 2 (coastal) atmospheric correction worked for Lake Superior. SeaWiFS and Satlantic radiometric band widths are identical (Table 1). The remote sensing reflectance at each wavelength ($R_{rs}(\lambda)$) was calculated in the form $R_{rs}(\lambda) = (Lu*Q/Ed)*100$ where Q is a percentage approximated by 4.5.

Fig. 1 (left) Linear regression of Satlantic vs. SeaWiFS $R_{rs}(\lambda)$. In the comparison of Satlantic vs. SeaWiFS $R_{rs}(\lambda)$, we expected a slope of one and intercept near zero. The results indicate a linear relationship for channel 3 and 5 with r^2 values of 0.72 and 0.81, respectively. These two channels are used in the derivation of SeaWiFs [chl].

Fig. 2 (right). Station comparisons of Satlantic vs. SeaWiFS $R_{rs}(\lambda)$. Results for the Satlantic $R_{rs}(\lambda)$ are shown in red. SeaWiFS $R_{rs}(\lambda)$ from pixels within 2 km of the sampling locations are shown in blue. Stations were analyzed spatially (i.e., nearshore vs. offshore) and temporally (i.e., seasonally). While here were no distinct temporal and spatial trends in the data, it appeared that nearshore $R_{rs}(\lambda)$ may be overestimated by SeaWiFS, with better overall results from more homogenous offshore waters.

Validation of Biogeochemical Parameters

SeaWiFS R_{rs}(555) vs. *in-situ* TSS for L. Michigan & L. Superior

SeaWiFS OC2-V4 vs. Chl a for L. Michigan & L. Superior

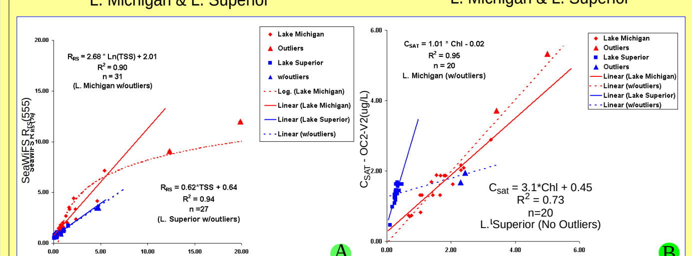


Fig 3. (A) Linear regressions of SeaWiFS R_{rs}(555) vs. *in-situ* TSS collected in 1998 and 1999 for L. Michigan and L. Superior. The results show a linear fit of the data for Lake Superior and log fit for L. Michigan with R^2 values of 0.94 and 0.90, respectively.
(B) Satellite-based chlorophyll was obtained from OC2-v2, an empirical band ratioing algorithm that uses SeaWiFS R_{rs}(490) and R_{rs}(555). We expected the regression slopes to equal one and intercepts near zero. For Lake Michigan, the results were as expected; whereas, for Lake Superior, in situ chl was overestimated by a factor of 3 and the bias (0.45 ug/l chl) was greater than zero. In Lake Superior, relatively low concentrations of the three major absorbing species (i.e., sediment, chlorophyll and CDOM) make it difficult to separate and quantify the species individually, suggesting that development of regional chlorophyll and CDOM retrieval algorithms may be necessary for the Great Lakes.

Lake Superior Thermal Inertia: Interannual Differences in the Timing of Thermal Stratification

LAKE SUPERIOR BUOY LOCATIONS

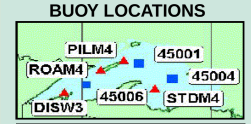


FIG. 8. The National Weather Service (NWS), under the auspices of the NOAA/ National Data Buoy Center (NDBC) operates automated weather stations from moored buoys and fixed monitoring sites throughout the Great Lakes. The location of the three open lake buoys in Lake Superior are shown above (Isle Royale Basin, Buoy 45001, Lat 48.0 N and Lon 87.6 W; Caribou Basin, buoy 45004 47.2N 86.5W; and Chefswet Basin Buoy 45006 47.3N 90.0W).

ONSET OF THERMAL STATIFICATION

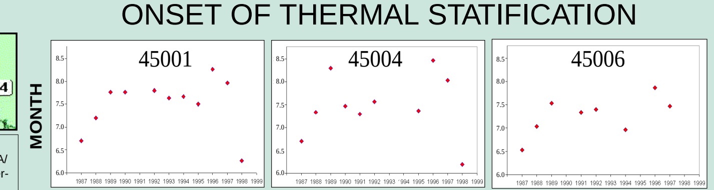


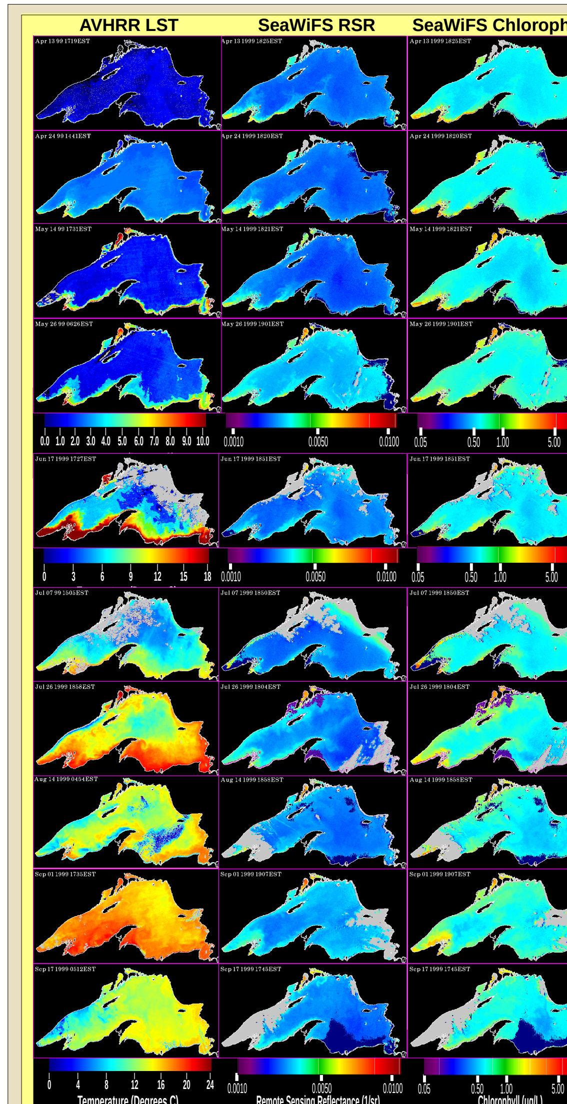
FIG. 9. Data from NDBC buoys illustrate general characteristics of Lake Superior thermal patterns. These graphs indicate the date at which surface temperatures in the open lake were consistently above 4 °C, which signals the onset of thermal stratification. The timing of thermal stratification varied greatly from year to year and between basins. Although the exact timing of stratification varied between basins, warm and cool year trends can be distinguished from these data. For example, open lake waters warmed most quickly in 1988 (a drought year) and 1998 (El Nino), whereas in 1996 and 1997 when Lake Superior froze over, stratification did not occur until late July.

KEWEENAW INTERDISCIPLINARY TRANSPORT EXPERIMENT IN SUPERIOR

ACKNOWLEDGMENTS

This research is supported under the auspices of the KITES (Keweenaw Interdisciplinary Transport Experiment in Superior) and EEGLE (Episodic Events-Great Lakes Experiment) projects, designed to investigate nearshore-offshore transport processes in the Great Lakes. We would like to thank our sponsors, the National Science Foundation (NSF), the National Oceanic and Atmospheric Administration (NOAA), MIchigan Sea Grant, and the Michigan Space Grant Consortium, for their generous support of this project.

AVHRR LST | SeaWiFS RSR | SeaWiFS Chlorophyll



LAKE SUPERIOR SEASONAL TRENDS

1999 AVHRR Lake Surface Temperature Images:

The spatial pattern of seasonal warming and cooling for Lake Superior in 1999 is shown in the panels to the far left. Cooler temperatures are towards the blue, whereas warmer temperatures are towards the red. Land is masked as black while clouds are masked as gray.

The thermal inertia of Lake Superior is very evident from the lake surface temperature trends shown in these images. Heat storage lags in fall and spring are influenced by two factors: 1) large quantities of stored heat during summer, carrying over into fall, and 2) formation and thawing of ice. Each acts to moderate air and surface temperature cycles. The minimum surface water temperature range of 0.5 -4.0 °C occurs over a six to eight week period typically from April to mid-July, whereas the maximum temperature is reached between late July and mid-August. After attaining the thermal maxima, temperature decreases rapidly during September and October at all stations reaching 4 °C by early November.

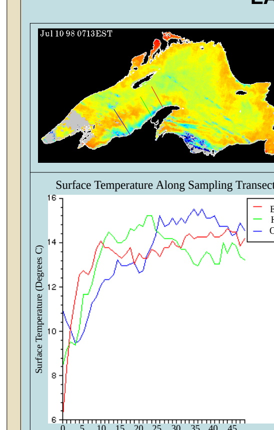
In mid-April 1999, the whole lake is still below 4 °C and in cold years, portions may remain covered with floating ice. During warmer years, such as 1999, temperatures in the nearshore exceeded 4 °C in late April. During the initial states of the spring warming phase, water along the shoreline receives warmer river discharge and heats faster than offshore waters. Along the southern shoreline this phenomenon is especially pronounced in shallow embayments (e.g., Duluth basin, Chequamegon Bay, Keweenaw Bay and Whitefish Bay). Temperatures start to move above 4 °C in bay regions, whereas the middle portion of the lake remains below 4 °C (May images). Late May and June images show a definite temperature gradient developing along the south shore. The boundary between the inshore warm region and the isothermal offshore waters is termed the "thermal bar" (Huang 1972). The thermal bar marks the 4 °C isotherm, which is a predominantly vertical boundary between nearshore warmer and offshore cooler water masses. The spring thermal bar period usually lasts 4-6 weeks.

In late June or early July, the offshore waters in the western basin are more homogenous. Typically, the thermocline appears at this time (defined from the buoy data at top). The July images show that as the heat content increases in summer, the surface temperature gradient becomes stronger, ranging from 15-19 °C along the shoreline to 4-7 °C in the central and eastern basins. Mid- to late-August scenes show a major increase in central, offshore surface temperatures. The temperatures range from 10 °C at the central portion of the lake to 20 °C toward the shoreline. The early to late August scenes catch the transformation of the large isothermal midlake zone into a thermocline region. The thermal maxima occurs in late August to early September. By mid- to late-September, surface temperatures rapidly decline (e.g., 9/17/99)

1999 SeaWiFS Tubidity and Chlorophyll Maps:

The images shown in column 2 and 3, which were acquired over a six month period between April 13 and September 17, 1999, show the temporal development of a highly productive, nearshore southern coastal corridor in Lake Superior. These shallow regions of Lake Superior warm more quickly than open lake waters during spring months (shown in column 1). Nearshore warmer waters are separated from offshore waters by the thermal bar, which may create horizontal gradients in turbidity and chlorophyll. Duluth Harbor and Chequamegon Bay had distinctly higher sediment and chlorophyll concentrations throughout the six month period than other regions of the lake. The shallow Ontonagon river region appears to be the most highly productive in the KITES study area. A distinct sediment plume was observed west of the Ontonagon River in April through May, 1999, indicating cross margin transport. Offshore transport of materials at the tip of the Keweenaw was observed on July 26 and August 14, among other days.

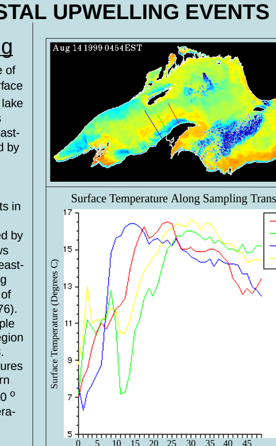
LARGE SCALE COASTAL UPWELLING EVENTS



1998 Upwelling

After the disappearance of the thermal bar, the lake surface warms above 4° C. AVHRR lake surface temperature images reveal that the central and eastern basins are characterized by a relatively cool, central upwelling region. 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).

The most striking example of coastal upwelling in this region occurred on July 7-13, 1998. During this period, temperatures along the entire southwestern shore were ranged from 6-10 °C, well below surface temperatures 14-16 °C outside the upwelling region.



1999 Upwelling

Satellite reconnaissance revealed several upwelling/ downwelling periods in 1999. One August upwelling period was sustained over a twelve day period from August 14th to the 25th. The image from August 14 at 4:54 EST indicates both upwelling and downwelling along the sampling transects. The Houghton North (HN in green) transect indicates temperatures in the range of 7-17 °C. Nearshore temperatures from 0-3 km offshore were 7-11 °C indicating upwelling. Temperatures from 4-10 km offshore hovered around 9-13 °C, then dropped to 7 °C again at 11-12 km offshore indicating downwelling. Temperatures lakeward of 12 km steadily increase to a high of 17 °C.

HIGH RESOLUTION SATELLITE IMAGERY FOR COASTAL PROCESSES

High resolution imagery resolves smaller scale phenomena (e.g., river discharges, dynamics of coastal sediment and mine tailings movement) that are not possible with the AVHRR and SeaWiFS instruments. These examples show false color and gray scale composites of a) Landsat TM imagery of the Keweenaw Peninsula and surrounding waters, b) Landsat TM of lake surface temperature, c) Landsat TM close-up of Eagle Harbor, d) Landsat TM of north entry and Freda stamp sands deposits (light blue), and e) SPOT Panchromatic image of Freda stamp sands.