Seasonal and Interannual Variability in Chlorophyll and Seston Abundances in the Laurentian Great Lakes

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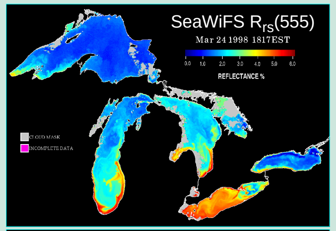
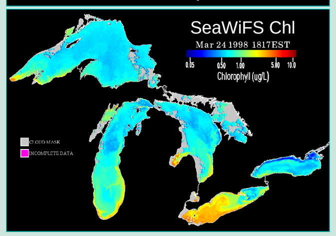
ABSTRACT

The Great Lakes hold 20% of the world's available freshwater supply, making the region increasingly important on a global scale during climatic change. Despite their significance and areal extent, the physical, hydrologic, and biogeochemical properties of the Great Lakes have not been examined to the full extent possible by modern oceanographic and remote sensing techniques. Newly available ocean color imagery derived from SeaWiFS (Sea-viewing Wide-Field- of-View Sensor) is providing the first ever daily estimates of chlorophyll a concentrations (Chl) in the Great Lakes. SeaWiFS data is analyzed using case 2 atmospheric correction scheme and OC2v2 chlorophyll algorithm. Validation with in situ measurements from southern Lake Michigan and central Lake Superior have shown that OC2 performs reasonably well for Lake Michigan, but overestimates chlorophyll by a factor of three for Lake Superior. Differences in optical properties of the two systems suggest that regional chlorophyll algorithms may be necessary for the Great Lakes.

Analysis of time series images of Lakes Michigan and Superior in 1998 and 1999 showed seasonal and interannual differences in seston and chlorophyll abundances. Seston (as Rrs(555)) and Chl concentrations were highest in the coastal margins of the lakes during fall and winter (unstratified), compared to summer (stratified) conditions. Wind-induced cross-margin transport was observed in both lakes on numerous occasions. In Lake Superior, SeaWiFS imagery highlight the effects of wind on particle transport dynamics. A large spring sediment plume near the Ontonagon River that extended 75 km offshore was observed in both years for a period of 6-8 weeks. Episodic resuspension of sedimentary materials in southern Lake Michigan in spring was also correlated with wind, although the relatively more shallow morphometry and differences in the timing and magnitude of storm events resulted in great interannual variability in the spatial extent and mass of suspended materials. A previously unidentified donut-shaped chlorophyll ring was observed in the offshore of Lake Michigan in winter, where investigations are underway to quantify differences in community composition of nearshore versus offshore plankton populations.





Comparison of Ship and Satellite Parameters

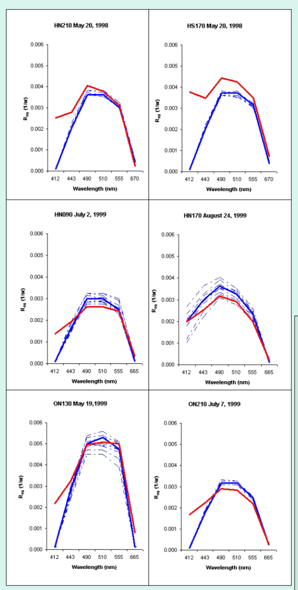
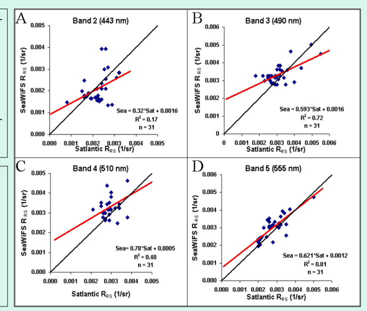


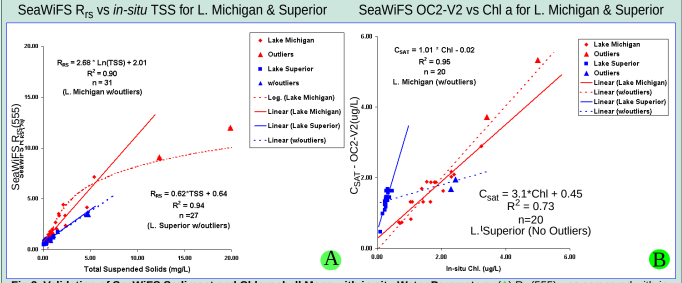
Fig. 1 (left). Satlantic vs. SeaWiFS R_{rs}. A Satlantic optical profiler was used to compute *in situ* R_{rs} in the form R_{rs} = (Lu*Q/Ed)*100 where Q is a percentage approximated by 4.5 with over 80 samples in our initial comparison. Results for Satlantic R_{rs} are shown in red and SeaWiFS R_{rs} from pixels within 2 km of the stations are shown in blue. While the shapes of the curves are similar for SeaWiFS and Satlantic R_{rs}, it appears that nearshore R_{rs} may be overestimated by SeaWiFS (bottom panels), with better overall results from more homogenous offshore waters (top four panels).

Fig. 2 (Right). Evaluation of Atmospheric Correction. The standard marine atmospheric correction produces non-physical, negative radiances in many scenes in the Great Lakes, as well as extremely high and variable chlorophyll concentrations in areas that have low and stable concentrations. Here, we used a case 2 atmospheric correction scheme in the validation. We expected a slope of 1 and intercept near 0. The results indicate a linear relationship for channel 3 and 5 with r^2 values of 0.72 and 0.81, respectively, which is noteworthy since these channels are used in the derivation of SeaWiFs chl.



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

SeaWiFS OC2-V2 vs Chl a for L. Michigan & Superior



SAMPLING LOCATIONS

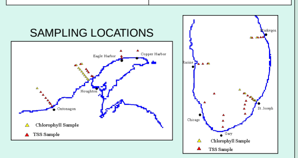


Fig 3. Validation of SeaWiFS Sediment and Chlorophyll Maps with in situ Water Parameters. (A) $R_{rs}(555)$ was compared with *in-situ* TSS collected in 1998 and 1999 for southern Lake Michigan and Lake Superior. Station locations are shown on map insets (left). The results show a linear fit of the data 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 ratio 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 significantly different 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.

LakeBAM: A Starting Point

Table 1: Data Sources and Characteristics of LakeBAM Data Set

Data Set	Location	Date	n	f_{chla}	Wavelength
KITES	Central Lake Superior	Monthly 1999	162	162	412,443,490,510,555,665

f_{chla} = fluorometric chlorophyll a.

After **O'Reilly, J.E.**, S. Maritorena, B.G. Mitchell, D.A. Siegel, K.L. Carder, S.A. Garver, M. Kahru, C. McClain. 1998. Ocean color algorithms for SeaWiFS. **JGR 103(C11): 24,937-24,953**.

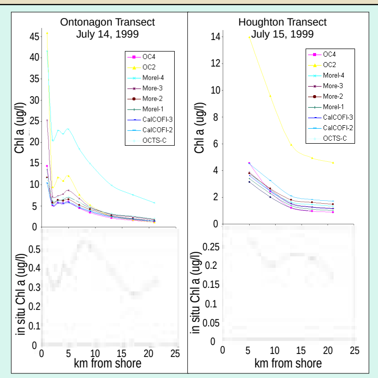


Fig. 4. Model estimates of chl using marine algorithms applied to Lake Superior at two transects in mid-summer. All of the algorithms overestimate in situ chlorophyll, particularly nearshore where absorption by CDOM may complicate the optics.

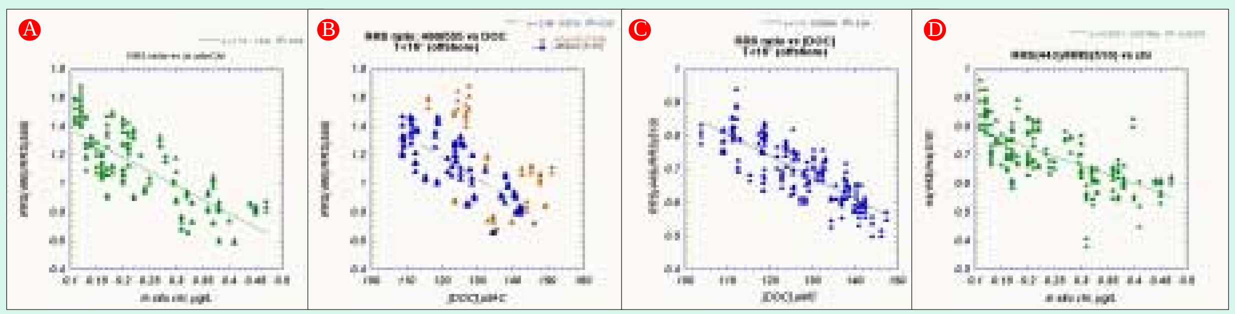


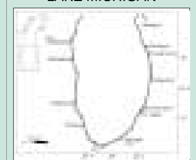
Fig. 5. Plot of $R_{rs}(490)/R_{rs}(555)$ (A) shows a reasonable correlation with in situ measured chlorophyll (R^2=0.6). DOC also contributes to this signal (B); for offshore stations (selected as those with surface T<16 degrees) the correlation of DOC with this ratio is equally strong. In this system, there is no correlation between DOC and chl, thus they are contributing independently to the signal. For offshore waters, the ratio $R_{rs}(443)/R_{rs}(510)$ provides a good fit to DOC (C), but a poorer correlation to chl (D). The combination of 443, 490, 510, and 555 nm bands may resolve the relative contributions of chl and DOC to the signals.

ACKNOWLEDGMENTS

We wish to thank the National Science Foundation (NSF), the National Oceanic and Atmospheric Administration (NOAA), and the Michigan Space Grant Consortium, the crew of the *R/V Lake Guardian,* Bridger Deville, Ken Thiemann for their generous contributions to and support of this project.

STUDY SITES IN LAKE SUPERIOR AND MICHIGAN

LAKE MICHIGAN



- o Lake Michigan is the sixth largest lake in the world.
- o Its hydraulic residence time is 62 years (Quinn 1992). For particle-reactive constituents, internal removal through sedimentation is much more rapid.
- o The distribution of post-glacial sediment in s. Lake MI is asymmetric with the greatest accumulations within 20 km from the eastern shore and decreasing towards the deepest sounding in the basin.

Quinn, F.H. 1992. Hydraulic residence times for the Laurentian Great Lakes. *J. Great Lakes Res.*

LAKE SUPERIOR

- o Lake Superior is the largest and most pristine of the Laurentian Great Lakes.
- o The bathymetry along its coasts varies from very shallow to extremely steep slopes with the effect of intensifying circulation features.
- o 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, 1972)

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

EEGLE REMOTE SENSING STUDIES

Retrospective Analysis: Measuring the Historical Magnitude of Turbidity Plumes Using Remotely Sensed Imagery

J.W. Budd, W.C. Kerfoot, and R.P. Stumpf

Episodic Nature: How dramatic are southern Lake Michigan resuspension events and how much do they depart from ten year average conditions? Quantifying the historical magnitude of turbidity plumes provides valuable information for numerous historical comparisons. Dependency Hypothesis: Several contingencies influence turbidity plume development and cross margin transport. How important are ice pack surges and ice scour along the shoreline in mediating cross margin transport? What is the relationship of thermal bar formation to coastal plume development in the southern basin? How do other coastal phenomena (e.g., impact of river plumes) influence cross margin transport on a seasonal and interannual basis?

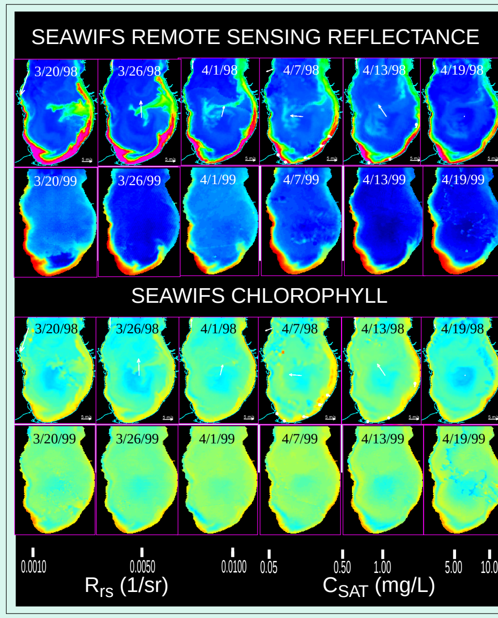
KITES REMOTE SENSING STUDIES

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

S. A. Green, J. W. Budd and twelve others

Large-scale Dynamics: Large-scale features and dynamics of the Keweenaw Current associated with seasonal and interannual differences in warming of surface waters, the formation, location and movement of the thermal bar, and coastal upwellings can be described in easily measurable climate variables (e.g., water temperatures, prevailing winds, duration of ice cover). Particle Remote Sensing: Turbidity and chlorophyll concentrations will be elevated in the extreme nearshore regions of southern Lake Superior. Time series imagery provide useful information for understanding magnitude of episodic events, frequency and duration of cross margin transport and water mass circulation.

S. LAKE MICHIGAN PLUME TIME SERIES



1998 TIME SERIES

A 35-day time series from March 20 to April 23 provided detailed spatial maps of surface sediment and chlorophyll concentrations in southern Lake Michigan. The plume, which originated near Port Washington, Wisconsin (see location map above) can be tracked along the shoreline over 400 km to Ludington, Michigan. Several offshore features are also evident in the imagery originating at Chicago, Illinois, St. Joseph and Muskegon, Michigan. The most pronounced example of cross margin transport was a large gyre near Muskegon, which extended offshore into the center of the lake, a distance of 75 km. This feature contorted over the next three weeks and finally dissipated in the southwestern basin around 4/13/99. Chlorophyll concentrations were enhanced along the plume track consistent with field sampling indicating high phosphorus concentrations in the plume. An intriguing "donut" shaped feature appeared just outside the plume track in late March and persisted for three weeks, that revealed a productive offshore zone; however, we found no evidence of enhanced sediment concentrations at the same locations. Both the R_{rs} and chl images indicate uniformly low concentrations of materials in the central southern basin for the entire period.

1999 TIME SERIES

This series encompassed a slightly longer period from March 6th through May 3rd, 1999. The sediment maps indicate that the areal extent of the plume is somewhat truncated as compared with 1998, particularly in the eastern basin north of Grand Haven. There were two small plumes that developed and moved in a counter-clockwise direction at Chicago and Grand Haven, Michigan. In late March/early April the plumes still exist, but their areal extent is greatly diminished. By late April/early May, the plume is constrained to the southern-most tip of Lake Michigan. The same spatial patterns were detected in the chlorophyll images, with two distinct maxima and two distinct minima, identical to 1998. The maxima occurred along the coast coincident with the sediment plume and then again offshore in the shape of a donut. The central minima is surrounded by the toroidal (donut) shaped off-shore maxima. A second crescent-shaped minima located in the southern basin separates the off-shore maxima from the near-shore maxima. A thread of the crescent-shaped offshore minima continues up the western coast and to a lesser extent along the east coast.

Horizontal Structure

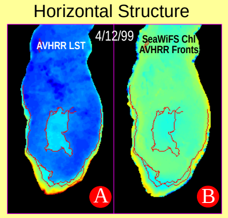


Fig. 6. **Biological and physical fronts.** Horizontal thermal fronts shown in this April AVHRR image (A) indicate the location of the 4°C thermal bar. The spatial patterns of Chl in the SeaWiFS image (B), acquired within one hour of the AVHRR image, are almost identical to the thermal imagery. The discovery of these large scale physical and biological fronts has led to new hypotheses about the structuring of the lower trophic food web in winter and spring.

Vertical Structure

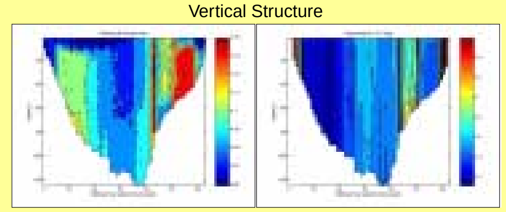


Fig. 7. Community structure in SLM during winter to spring is more complicated than previously thought. Studies are ongoing to quantify differences in the composition of nearshore vs offshore plankton populations.

LAKE SUPERIOR BUOY LOCATIONS

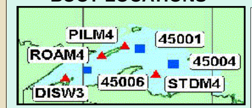


FIG. 8. As part of the NOAA/National Weather Service (NWS), the National Data Buoy Center (NDBC) operates automated data acquisition systems from moored buoys and fixed monitoring stations throughout the Great Lakes. The location of the three open lake NOMAD Buoys in Lake Superior (Isle Royale Basin, Buoy 45001, 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) are shown above.

TIMING OF THERMAL STATIFICATION

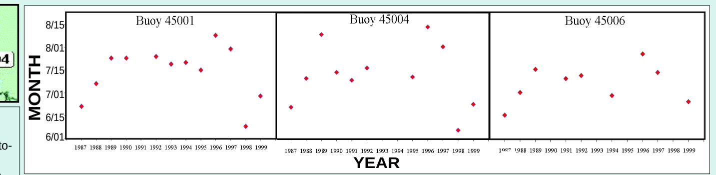
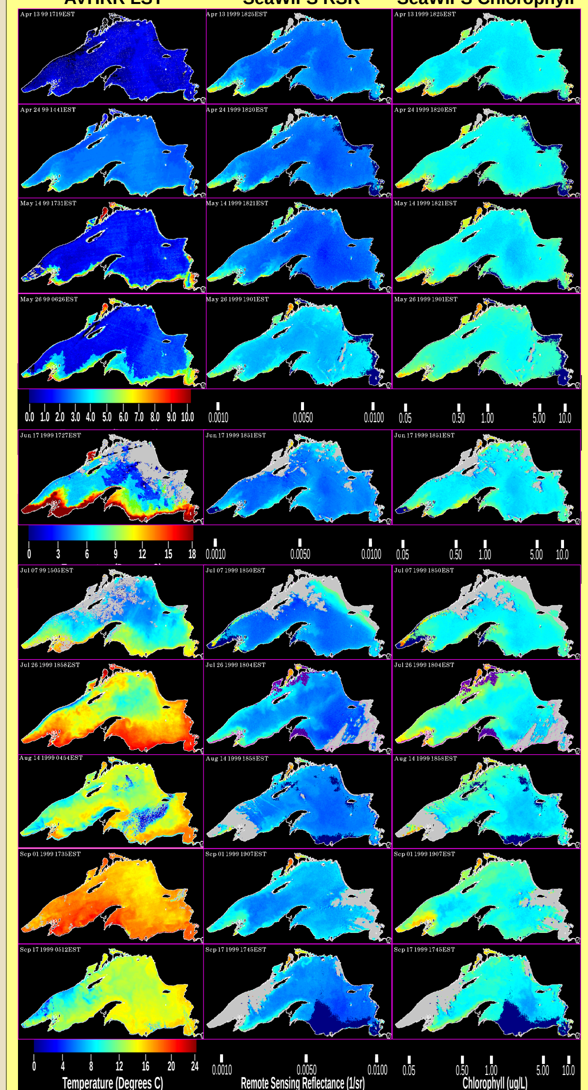


FIG. 7. Data from NDBC buoys illustrate general characteristics of Lake Superior thermal patterns. Onset of thermal stratification, indicated by the date on which surface temperatures at open lake stations were consistently above 4 °C, is shown for thirteen years. The timing of thermal stratification 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. Open lake waters warmed most quickly in 1988 (a drought year) and 1998 (El Nino), whereas stratification did not occur until late July and early August in 1996 and 1997, unusually cold years when Lake Superior froze over.



LAKE SUPERIOR TIME SERIES

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.

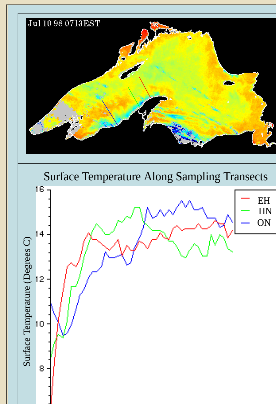
The thermal inertia of Lake Superior is very evident from the lake surface temperature trends shown in these images. Heat storage lags in fall and spring are influenced by two factors: 1) large quantities of stored heat during summer, carrying over into fall, and 2) formation and thawing of ice. Each 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 stages 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:

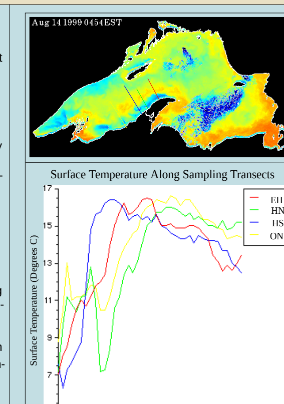
The images shown in column 2 and 3, which were acquired over a six month period between April 13 and September 17, 1999, show the temporal development of a highly productive, nearshore southern coastal corridor in Lake Superior. These shallow regions of Lake Superior warm more quickly than open lake 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.



1998 Upwelling

Fig. 8. Surface temperatures along the north Keweenaw coast on July 10 are cooler indicating 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).

Upwellings occurred earlier and were less pronounced in 1998 (El Nino) compared to 1999 (La Nina). 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 ranged from 6-10 °C, well below surface temperatures 14-16 °C outside the upwelling region.



1999 Upwelling

Fig 9. Satellite reconnaissance revealed several large coastal upwelling upwellings in 1999. One August upwelling period was sustained over a twelve day period from August 14th to the 25th. Houghton North (HN in green) temperatures on the August 14, 4:54 EST image (right) were 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. Temperatures lakeward of 12 km steadily increased to a high of 17 °C.