Determination of the Influence of Wind on the Keweenaw Current in the Lake Superior Basin as Identified by Advanced Very High Resolution Radiometer (AVHRR) Imagery

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ABSTRACT. The Keweenaw Current is a warm coastal current in Lake Superior that flows northeastward along the northern shore of Michigan’s Keweenaw Peninsula. This study focuses on the fate of the current at the tip of the Keweenaw Peninsula. Results of this study suggest that the path of the current beyond the peninsula is primarily controlled by wind.

In this study, eleven surface temperature maps derived from Advanced Very High Resolution Radiometric (AVHRR) data using computer assisted image processing techniques were used to identify the Keweenaw Current. Wind data from two moored data buoys, a Coastal Marine Automated Network (CMAN) fixed buoy, and three airport weather stations, collected on the same day as each of the images and for the two days preceding the image date, are used to determine whether wind direction and speed influence the path of the Keweenaw Current past the tip of the peninsula. In nine images the current’s path is similar to the surface Ekman transport direction predicted from wind data. All eleven images show a similarity between the current’s actual path and a path calculated when net Ekman transport is assumed. Results of this study also show that there may be a possible lag time of one day between a change in wind direction and the current’s adjustment to that change.

INDEX WORDS: Keweenaw current, AVHRR, water temperature, wind, Lake Superior.

INTRODUCTION

Wind and Temperature in Lake Superior

Lake Superior is positioned in the mid-latitude zone of westerly winds. While the water circulation of Lake Superior is primarily driven by wind and differential heating (Pond and Pickard 1983), other factors influencing the circulation pattern are inflow from rivers, precipitation, variations in atmospheric pressure, and vertical motions, such as upwelling and seasonal overturns (Jipping 1991).

Lake Superior experiences a cycle of mixing and thermal stratification annually. In the early spring, the waters are mixed, the lake is nearly isothermal, and water temperatures are usually 2 to 4°C. Differential heating occurs when the nearshore waters, especially along the southern shoreline, warm more quickly than the central lake water. The water column separates into layers with less dense water near the surface and cold dense water near the bottom. The upper and lower layers are separated by a steep vertical temperature gradient (thermocline). A thermal bar marked by 4°C water also forms in restricted bays and along the shoreline between the warmer nearshore water and cooler offshore water (Green and Terrell 1978). Because freshwater reaches maximum density at 4°C, the thermal bar is a barrier to horizontal water movement and spring runoff is trapped on the onshore side of the bar (Hubbard and Spain 1973). During the winter months lake water reaches temperatures of less than or equal to 4°C so that as the water warms it may become more dense and sink. The thermal bar is a linear, approximately shore-parallel feature that is characterized by downward flow of 4°C water (Hubbard and Spain 1973). With continued warm-
ing and increased mixing, the thermal bar moves offshore and eventually disappears when the water temperature on the offshore side of the bar increases to greater than 4°C. In late summer (usually near the end of July), the most stable vertical stratification occurs and permits wind-driven mixing to take place only in the upper part of the lake. Maximum surface temperatures occur in mid-August.

Wind influence on surface currents is dependent on the wind direction, wind speed, and the persistence of the wind speed and/or wind direction (Phillips 1978). Phillips (1978) determined that strong northwesterly winds blow about 40% of the time, with an average speed of 8 to 15 meters per second. Wind speeds greater than 30 meters per second occur during storms but are infrequent on Lake Superior. Light winds, less than 4 meters per second, are also unusual and occur much less frequently over the lake than the land (Phillips 1978). During the summer, predominant winds blow from the lake to the land during the daytime, and at night, surface winds blow from the land to the lake (Phillips 1978). This alternating wind direction is due to large fluctuations in land temperatures and the difference between land and water temperatures.

Overall, surface wind directions over the lake, as recorded by data buoys, correlate rather well to surface winds recorded at airport weather stations. Phillips (1978) found an agreement between over-lake surface wind direction measurements and wind direction recordings taken at airports in Sault Ste. Marie and Thunder Bay, Ontario. Green and Terrell (1978) also found good correlations of wind direction measurements between the Houghton County Airport, Michigan and over-lake conditions for their study. However, Phillips (1978) noted that light winds are strongly affected by the presence of lakes and streams, urban areas, and landforms.

Wind curl, that is the mathematically defined curl of the vector field representing the wind, is probably important in maintaining counterclockwise circulation in Lake Superior. The wind curl is nonzero when the wind changes magnitude or direction across a region. Scott et al. (1971) determined that wind-driven coastal currents are formed when the wind curl is large or the wind has a dominant component parallel to the coastline. LeDrew and Franklin (1985) suggested that a wind curl must be present for wind-driven circulation to occur in a basin that is smaller than an existing weather pattern.

Although wind is the primary cause of daily changes in coastal currents, the Coriolis force influences the path of currents. The Coriolis force is an apparent force that acts on bodies moving relative to the earth and is caused by the rotation of the earth. The Coriolis force is directed 90° to the water movement induced by wind or another force. In wind-driven circulation, the surface flow reaches a balanced adjustment at 45° to the right of the wind direction in response to the Coriolis force in the northern hemisphere (Pickard and Emery 1990).

The adjustment of a surface current to the Coriolis force results in surface Ekman transport (Duxbury and Duxbury 1993, Pickard and Emery 1990, Pond and Pickard 1983). Beneath the surface, the water collects less energy from the wind stress, travels more slowly, and turns further to the right (in the northern hemisphere) than the water at the surface. At the maximum depth where water is affected by the wind stress, water moves in the opposite direction to the surface water, creating the “Ekman spiral.” The average flow of water set in motion by the wind, termed Ekman or net transport, is at 90° to the right of the surface wind in the northern hemisphere (Duxbury and Duxbury 1993).

In the northern hemisphere, Ekman dynamics will produce a buildup of warm surface water to the right of the wind and an upwelling of colder water to the left. As a result of pressure differences, there will be a relatively high velocity surface flow to the right of the wind and a lower velocity flow of deeper water to the left of the wind direction.

The Keweenaw Current

The Keweenaw Current is a warm coastal current found in Lake Superior that originates at the base of the Keweenaw Peninsula (Fig. 1) and travels north-eastward along the coastline at maximum speeds of 1 meter per second (Viekman and Wimbush 1993, Green and Terrell 1978). Field studies have indicated that the outer boundary of the Keweenaw Current is characterized by a steep temperature gradient that parallels the bathymetric gradient in the lake and extends 3 to 10 kilometers from the Keweenaw Peninsula shoreline. The steep-sloping bathymetry offshore of Eagle Harbor may cause the current to be more well-defined than a typical coastal current. From Eagle Harbor to Copper Harbor the bottom contours plummet down to a 200 meter depth only 2 kilometers from the shoreline, making this slope one of the steepest descents in the lake (Green and Terrell 1978). At the tip of the Keweenaw Peninsula bottom contours become more gradual, thus reducing bathymetric influences on the current.
Ragotzkie (1966) initiated studies of the Keweenaw Current by relating the current’s cross-sections to airborne infrared temperature records during the summer of 1965. He calculated the current’s velocity to be between 0.5 and 1 meter per second, and recorded nearshore surface water temperatures up to 8°C warmer than water in the central lake. His work verified that isothermal surfaces tilted distinctly downward toward the coast. This confirmed that pressure gradients were present, and that the pressure at any particular depth along the path of the current increased offshore. Ragotzkie suggested that in order for the current to persist, an opposing force (the Coriolis force) must be active and that the flow must be geostrophic. Smith and Ragotzkie (1970) found that geostrophic flow, determined by direct dynamic height calculations, did not fully account for the Keweenaw Current. Smith (1972) verified this interpretation using progressive vector diagrams and volume transport computations.

In 1972, Yeske et al. flew six transects in August and September that identified the Keweenaw Current between 5.5 and 10 kilometers from the Keweenaw Peninsula’s shore. Near Eagle Harbor, the current’s velocity was estimated at 50 centimeters per second. In 1978, Green and Terrell used wind speed and direction from Eagle Harbor, Houghton County Airport, and an over-lake site north of Eagle Harbor to determine if wind influenced the Keweenaw Current. They found that west winds usually confine the current to the shoreline and magnify its outer thermal front, while east winds mostly broaden the current and destroy the thermal front.

Although Green and Terrell (1978) determined that wind had an effect on the Keweenaw Current along the Keweenaw Peninsula, there has been little focus on the fate of the current upon reaching the tip of the Keweenaw Peninsula, where it becomes largely unrestricted by shoreline orientation and bathymetry. Drift studies (Harrington 1895, Hughes et al. 1967) demonstrate that the current generally travels southeastward, following the counterclockwise circulation that characterizes all of Lake Superior. Occasional shifts in the current’s path are documented, however (Harrington 1895).

Because the Keweenaw Current is significantly warmer than the central part of the lake, the thermal bands of Advanced Very High Resolution Radiometer (AVHRR) data can be used to identify the path of the Keweenaw Current after it reaches the tip of Lake Superior.
the Keweenaw Peninsula. Although the AVHRR dataset used in this study does not permit observation and analysis of the current on consecutive days, the temperature contrast between the current’s warm water and the cold central lake water makes it possible to identify the path of the current throughout the summer months. It is difficult to obtain useful AVHRR data for the Lake Superior region for consecutive days because the area is commonly cloud covered. Green and Terrell (1978) demonstrated that the outer margin of the current is characterized by surface temperature gradients that can be greater than 1°C per 20 meters during the summer. In addition, the absolute change in temperature across the outer margin of the current may reach 6°C (Green and Terrell 1978). This type of temperature variation is a dominant feature of the Keweenaw Current and has previously been used to successfully monitor the path of the current (Green and Terrell 1978). AVHRR data are capable of discriminating temperature variations of the magnitude encountered across the outer margin of the current, and it is the large magnitude of the temperature variations that makes it possible to identify the path of the Keweenaw Current even in the absence of data from consecutive days.

Image processing and the interpretation of remotely sensed thermal infrared imagery can supply a reliable synoptic description of temperature differences over the surface of a lake, which is not usually possible with conventional sampling. Surface temperature variations provide data that constrain lake circulatory features such as currents, areas of upwelling and downwelling, thermal fronts and bars, and discharge plumes (Malm and Jonsson 1993, Jipping and Maclean 1992, LeDrew and Franklin 1985). In 1987, Cornillon et al. analyzed AVHRR imagery to locate the position of the Gulf Stream by identifying a marked separation between warmer and colder surface water. NOAA satellite imagery of the Great Lakes has been previously used to map and examine surface temperatures and other features (Bolgrein and Brooks 1992, Schwab et al. 1992, Jipping 1991, Strong 1974).

Considering the forces driving the Keweenaw Current, it is hypothesized that upon reaching the tip of the Keweenaw peninsula, the path of the current is primarily influenced by the wind. Therefore, Ekman transport should accurately describe the fate of the current as it rounds the tip of the peninsula. When southerly to easterly winds prevail, the Keweenaw Current should broaden and travel in a north to east-northeastward path into the central lake and the Caribou Basin. Northerly and westerly winds should produce a narrow current, which will travel primarily in a southeast to southwestward direction upon rounding the tip of the Keweenaw Peninsula.

**METHODS**

**Data Sources**

In this study, the surface temperature maps of Lake Superior generated from AVHRR satellite images (Fig. 2) were used to identify the path of the Keweenaw Current for dates from June through September during the years of 1987 to 1990. Images for this study were obtained from the NOAA-9, 10, and 11 satellites that provide multispectral imagery of the surface of the earth. These spaceborne sensors are polar orbiting and sun synchronous with spatial and temporal resolutions of 1.1 kilometers and 12 hours, respectively. The AVHRR sensor contains five spectral channels that sense visible, reflective infrared, and emitted thermal infrared radiation. Surface water temperature maps for Lake Superior are derived from the infrared radiation detected by band 4 (10.5–11.5 micrometers). Lillesand and Kiefer (1994) provide an overview of the AVHRR satellite characteristics. Table 1 summarizes the dates and scene characteristics for the 11 images used in this study.

Wind speed and direction for the image dates and the preceding 2 days were acquired from the National Data Buoy Center (NDBC), a division of the National Weather Service. Two moored weather buoys, #45006 and #45001, and a CMAN fixed buoy, STDM4, were chosen as sources of wind data. These buoys record air temperature, water surface temperature, sea-level pressure, wind direction and speed, and wave height on an hourly basis. Wind direction and speed were also obtained from three airport weather stations located at Ashland, Wisconsin, and Houghton and Marquette, Michigan (Fig. 1).

**Computer-Assisted Image Processing**

The AVHRR scenes were initially preprocessed by the EROS Data Center (EDC) to correct for systematic, radiometric, and geometric errors. The EDC also performed basic modifications to improve the quality of the image data including the conversion of digital numbers to albedo values for


FIG. 5. Surface water temperatures in Lake Superior on 22 July 1988.
Influence of Wind on the Keweenaw Current

The procedure developed by Jipping and Maclean (1992) was used to produce surface water temperature maps for this study. The procedure utilized AVHRR band 4 images of the Great Lakes and in situ lake surface temperatures from NDBC buoys to generate and validate surface water temperatures using linear regression. An error of 1.3°K is associated with this method of temperature determination. Atmospheric variability, noise in radiometric satellite measurements, data buoy measurement errors, discrepancies between bulk and skin temperatures, and spatial and temporal variability are interpreted to be responsible for this error (Jipping and Maclean 1992). The images used in this study are a subset of those used by Jipping and Maclean to develop the processing procedure. Due to the synoptic nature of AVHRR data, AVHRR-based surface temperature maps appear to be superior to maps derived from airborne radiation thermometer (ART) surveys and ship reports (Jipping 1991).

Wind Data Processing

The raw wind data consists of wind directions measured clockwise from north in degrees, and wind speeds in knots or meters per second. Data were recorded approximately every hour. For some dates, wind direction and speed were not available from the Ashland, Wisconsin weather station. The wind speed data are averaged for each date, and converted to meters per second if necessary. The vector mean of the wind directions for each date was calculated using the program PlotMe (Landsparger and Huntoon 1995). PlotMe generates a graphical display of the daily wind directions and speeds for each date in the form of a rose diagram (Van Luven 1995). Once the daily averages of wind speed and direction for an image were calculated, they were plotted on the corresponding processed subset image of Lake Superior (Fig. 3). On each subset image, wind direction at each station is depicted by arrows that show the direction the wind is blowing toward. Table 2 summarizes the wind speed and direction from all data buoys and airport locations. Note that in Table 2, wind direction is listed as the direction the wind is coming from, while the subset images (Fig. 3) display the arrows in the direction the wind is blowing toward.

Ekman Dynamics in Shallow Water

Discussions of Ekman dynamics generally assume that currents are present in deep open waters, where the depth affected by Ekman dynamics, or “Ekman depth,” is smaller than the total water depth (Pickard and Emery 1990). In areas close to the shoreline of the Keweenaw Peninsula, the Ekman depth may exceed the total water depth, and therefore, the effect of friction from the bottom of Lake Superior must be considered. Bottom friction causes the current to decrease in speed, which reduces the magnitude of the effect of the Coriolis force. The current then appears to rotate to the left in the northern hemisphere due to the balance between the Coriolis force and frictional forces. The opposing right (due to the Coriolis force) and left (due to bottom friction) turning effects tend to cancel each other as the water depth decreases (Pickard and Emery 1990). Thus, surface and net Ekman transports are deflected by a smaller angle toward the right of the wind direction (in the northern

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**TABLE 1. AVHRR images, including scene descriptions.**

<table>
<thead>
<tr>
<th>Date</th>
<th>Description of Cloud Cover</th>
</tr>
</thead>
<tbody>
<tr>
<td>17 June 1987</td>
<td>Clouds in western Lake Superior, along the Keweenaw Peninsula, and a few in eastern Lake Superior</td>
</tr>
<tr>
<td>5 June 1988</td>
<td>Clouds present in northeastern Lake Superior</td>
</tr>
<tr>
<td>4 July 1988</td>
<td>Cloud free</td>
</tr>
<tr>
<td>12 July 1988</td>
<td>Cloud free</td>
</tr>
<tr>
<td>22 July 1988</td>
<td>Small cloud in western Lake Superior</td>
</tr>
<tr>
<td>10 August 1988</td>
<td>Many clouds in central and eastern Lake Superior with a scattering throughout the lake</td>
</tr>
<tr>
<td>7 September 1988</td>
<td>Clouds in western Lake Superior</td>
</tr>
<tr>
<td>23 September 1988</td>
<td>Small clouds present throughout Lake Superior</td>
</tr>
<tr>
<td>3 September 1989</td>
<td>Clouds mostly in the western portion of Lake Superior</td>
</tr>
<tr>
<td>18 September 1989</td>
<td>Clouds present in western, north central, and eastern Lake Superior</td>
</tr>
<tr>
<td>25 July 1990</td>
<td>Small clouds in central Lake Superior</td>
</tr>
</tbody>
</table>
### TABLE 2. Wind direction data collected by the NDBC and CMAN buoys.

<table>
<thead>
<tr>
<th>Date</th>
<th>Data Buoy #45006</th>
<th>Data Buoy #45001</th>
<th>CMAN STDM4</th>
<th>Ashland, WI</th>
<th>Houghton, MI</th>
<th>Marquette MI</th>
</tr>
</thead>
<tbody>
<tr>
<td>15 Jun/87</td>
<td>3.9 WNW</td>
<td>3.9 W</td>
<td>4.9 NNW</td>
<td>—</td>
<td>3.1 W</td>
<td>2.9 NNW</td>
</tr>
<tr>
<td>16 Jun/87</td>
<td>4.4 SW</td>
<td>3.9 SW</td>
<td>7.6 W</td>
<td>5.5 SSW</td>
<td>3.4 NW</td>
<td>3.7 SW</td>
</tr>
<tr>
<td>17 Jun/87</td>
<td>4.4 E</td>
<td>3.8 ESE</td>
<td>7.9 SSE</td>
<td>—</td>
<td>2.9 E</td>
<td>2.9 NNW</td>
</tr>
<tr>
<td>3 Jun/88</td>
<td>2.7 NE</td>
<td>3.3 N</td>
<td>4.4 N</td>
<td>5.1 NNE</td>
<td>2.6 ENE</td>
<td>1.9 NNW</td>
</tr>
<tr>
<td>4 Jun/88</td>
<td>2.6 SW</td>
<td>3.4 SW</td>
<td>2.6 WSW</td>
<td>—</td>
<td>2.2 WNW</td>
<td>27. NW</td>
</tr>
<tr>
<td>5 Jun/88</td>
<td>2.8 SW</td>
<td>3.4 WNW</td>
<td>4.4 WNW</td>
<td>5.1 SSW</td>
<td>4.0 WNW</td>
<td>2.5 WNW</td>
</tr>
<tr>
<td>2 Jul/88</td>
<td>5.8 SW</td>
<td>3.9 WSW</td>
<td>3.7 WSW</td>
<td>—</td>
<td>2.8 WNW</td>
<td>2.2 NW</td>
</tr>
<tr>
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<td>—</td>
<td>2.6 WNW</td>
<td>2.0 N</td>
</tr>
<tr>
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<td>4.0 S</td>
<td>6.4 S</td>
<td>10.3 SSW</td>
<td>3.2 SSS</td>
<td>2.6 WSW</td>
</tr>
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<td>4.7 SW</td>
<td>6.3 WSW</td>
<td>—</td>
<td>3.9 NW</td>
<td>2.3 NW</td>
</tr>
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<td>11 Jul/88</td>
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<td>7.3 N</td>
<td>—</td>
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<td>3.3 WNW</td>
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<td>2.2 N</td>
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<td>2.5 NNW</td>
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<td>2.3 NNW</td>
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<td>8 Aug/88</td>
<td>14.8 NW</td>
<td>13.3 NW</td>
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<td>—</td>
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<tr>
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<td>16.1 W</td>
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<td>4.5 NNW</td>
<td>—</td>
<td>3.7 WNW</td>
<td>3.0 NW</td>
</tr>
<tr>
<td>10 Aug/88</td>
<td>16.7 SSW</td>
<td>14.1 SW</td>
<td>7.2 SSW</td>
<td>—</td>
<td>4.2 SW</td>
<td>2.8 SW</td>
</tr>
<tr>
<td>5 Sep/88</td>
<td>13.6 NNW</td>
<td>— N</td>
<td>9.9 N</td>
<td>6.4 NNW</td>
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<td>4.2 NNW</td>
</tr>
<tr>
<td>6 Sep/88</td>
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<td>— WNW</td>
<td>8.2 WNW</td>
<td>—</td>
<td>4.3 W</td>
<td>3.9 W</td>
</tr>
<tr>
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<td>— SSW</td>
<td>6.6 SSW</td>
<td>6.8 SSS</td>
<td>4.7 SSS</td>
<td>4.6 SW</td>
</tr>
<tr>
<td>21 Sep/88</td>
<td>13.1 NE</td>
<td>— NNW</td>
<td>6.5 N</td>
<td>—</td>
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</tr>
<tr>
<td>22 Sep/88</td>
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<td>8.0 SSE</td>
<td>—</td>
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<td>3.2 S</td>
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<td>— W</td>
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<td>4.8 W</td>
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<td>6.6 NNW</td>
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<td>11.6 SW</td>
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<td>3.3 ESE</td>
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<td>11.3 SE</td>
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<td>4.7 SSS</td>
<td>—</td>
<td>3.2 ESE</td>
<td>2.6 SW</td>
</tr>
<tr>
<td>18 Sep/89</td>
<td>11.3 SE</td>
<td>6.2 SSE</td>
<td>9.2 S</td>
<td>—</td>
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<td>3.7 SSS</td>
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<tr>
<td>23 Jul/90</td>
<td>— SW</td>
<td>1.8 SW</td>
<td>1.4 SW</td>
<td>—</td>
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<td>2.7 E</td>
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<tr>
<td>24 Jul/90</td>
<td>— SSE</td>
<td>2.3 SSE</td>
<td>2.5 S</td>
<td>—</td>
<td>2.8 W</td>
<td>2.6 NE</td>
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<tr>
<td>25 Jul/90</td>
<td>— SSE</td>
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<td>4.6 SSS</td>
<td>—</td>
<td>3.5 SE</td>
<td>4.5 ESE</td>
</tr>
</tbody>
</table>

*Wind direction represents the direction the wind is coming from.
Influence of Wind on the Keweenaw Current

To determine if the areas near the coastline of the Keweenaw Peninsula are shallow enough to affect the surface and net Ekman transports of the Keweenaw Current, Ekman depths and total water depths must be compared. When the only force driving the current is wind stress at the surface, the ratio \( h/D_E \), where \( h \) is the total water depth and \( D_E \) is the Ekman depth, is calculated and used to determine the effect of depth on surface and net transport directions.

Total depth is estimated from a bathymetry map of Lake Superior, while the Ekman depth is calculated with the relation \( D_E = (W/(\sin f)^{1/2}) \), where \( W \) is the wind speed and \( f \) is the latitude. Ekman depth is calculated using estimated maximum and average "real" wind speeds recorded from data buoy #45001. These Ekman depth calculations are based on the assumption that wind is the only force driving the Keweenaw Current. In addition, a second set of Ekman depths is calculated, based on the assumption that wind is not the only force driving the Keweenaw Current. Green and Terrell (1978), Smith and Ragotzkie (1970), and Ragotzkie (1966) suggest that other forces, such as bathymetry, density differences, and geostrophy, probably influence the Keweenaw Current. Due to these additional influences acting on the current, a "pseudo" wind speed, encompassing all of these driving forces, is calculated using an empirical relationship that relates surface current velocity to wind speed (in this case, the pseudo wind speed).

Several studies have determined that the Keweenaw Current flows with maximum and average current speeds of 1 meter per second and 30 centimeters per second, respectively (Smith and Ragotzkie 1970). Because the speed of the current is the result of the sum of all driving forces acting on it, these average and maximum current speeds are used to determine the "pseudo" wind speeds, and thus the second set of Ekman depths. By calculating two sets of Ekman depths, one set assuming that wind is the only driving force, and one set assuming that many driving forces influence the current, the possible range of adjustments in surface Ekman transport and net Ekman transport near the coastline of the Keweenaw Peninsula is considered.

Based on field observations, Ekman determined that the surface current \( (V_s) \) and wind speed \( (W) \) are related as \( V_s/W = 0.0127/((\sin f)^{1/2}) \) for latitudes above 10° (Pond and Pickard 1983). From this relationship, the pseudo wind speed (such that wind speed will represent the cumulative influences of geostrophy, density differences, bathymetry, and wind) is determined to be 67.6 meters per second for a 1 meter per second current, and 20.3 meters per second for the average 30 centimeter per second current. In comparison, the maximum wind speed and average wind speed recorded at the data buoys during the period of the study are 17.0 meters per second and 5.3 meters per second, respectively. The very high calculated pseudo wind speeds support previous interpretations that influences other than wind are controlling the Keweenaw Current as it travels along the northern shoreline of the Keweenaw Peninsula.

Using the pseudo wind speeds, depths of Ekman influence are calculated to be 124 meters for a maximum current speed, and 37 meters for an average Keweenaw Current speed. In contrast, Ekman depths of 31 meters and 9.8 meters are computed when incorporating real maximum and average wind speeds measured during the study period. By evaluating the bathymetry of Lake Superior, isobaths were chosen periodically and evaluated using the ratio of total depth to Ekman depth, \( h/D_E \), to determine the necessary adjustments to surface and net Ekman transport directions.

From these calculations, it is suggested that for average current speeds assumed to be produced by pseudo winds, no alteration is needed for surface transport near the coastline. However, net Ekman transport from pseudo winds should be adjusted to 60° to the right of the wind direction at depths of less than 40 meters (instead of the typical 90° adjustment to the right of the wind direction). For maximum current speeds, the surface transport should be adjusted for depths less than 40 meters, and net Ekman transport should be altered for depths less than 120 meters. Using the real wind speeds of 17.0 meters per second and 5.3 meters per second, it is determined that \( h/D_E \) is greater than 1 even at the shallow 40 meter bottom contour, and thus for real wind speeds, no adjustment in surface or net Ekman transport is required. Because the interest of this study involves analyzing the path of the current at and past the tip of the peninsula, where the bathymetry drops below 40 meters within 2 to 10 kilometers of the shoreline, it is assumed that no alteration for surface or total Ekman transport is required.
SURFACE TEMPERATURE MAP DESCRIPTIONS

Figure 3 is an example of the surface temperature maps constructed for the study area for selected dates during June through September, 1987 to 1990. The observed wind directions at the airport stations and data buoys were incorporated into the maps so that the arrows indicate the direction that the wind was blowing toward. The wind direction at Ashland, Wisconsin is also posted even though it is located to the west of the study area.

The Keweenaw Current is identifiable on the maps because of its relatively warm temperatures (Table 3). The width of the current can be estimated by noting the location of a steep temperature gradient where the warm current abuts against the cold central lake water. Table 4 lists the approximate width of the current at Freda, Eagle Harbor, Copper Harbor, and Keweenaw Point, Michigan for each image. The distances were measured perpendicular to the coastline.

Analysis of the eleven images (Van Luven 1995) demonstrates that upon reaching the tip of the Ke-
weenaw Peninsula, the Keweenaw Current generally travels southeastward, following the counterclockwise circulation that characterizes all of Lake Superior. In several images, however, a portion of the Keweenaw Current moves north and northeastward into the central part of the lake.

5 June 1988—On this date the study area appears very cold, mostly between 4.5 and 6°C. The Keweenaw Current is beginning to develop at the base of the peninsula. At Freda, where the current is broadest (9 kilometers) a temperature range of 4.9°C across the current can be easily detected. Approaching Eagle Harbor and Copper Harbor, the Keweenaw Current is very confined along the shoreline. At Keweenaw Point, there is evidence of the current widening somewhat, but overall the current remains very narrow as it travels past the tip of the peninsula toward the southwest. A few pockets of warm water can be detected along the southern coastline of the peninsula near Gay. These pockets of warm water appear to have broken away from the southwest directed current and are lineated somewhat in a southeast direction. In general, the Keweenaw Current on 5 June is very narrow as it travels northeastward along the northern shoreline of the peninsula, and upon rounding the tip, remains close to the shoreline and travels southwestward.

17 June 1987—The southern part of Lake Superior is much warmer than the northern part on this date. At Freda, the current is quite broad, approaching 22 kilometers in width. At the tip of the peninsula, the current is also rather wide and is clearly visible. A protrusion of relatively warm water extends toward the center of the lake in a north-northeast to northeast direction at the tip of the peninsula, suggesting a perturbation of the overall south-southeast path of the current. A pocket of warm water, 6.9 to 7.3°C, can be identified above Copper Harbor. It is likely that this pocket of water is detached from water of similar temperature to the west or south, since the water depth is close to 240 meters at this location. As the Keweenaw Current rounds the tip of the peninsula, it remains quite broad and generally flows toward the south to southeast. It is interesting to note that the path of the current, especially along the northern shoreline and at the tip of the Keweenaw Peninsula, along with the protruding north-northeast trending warmer water, approximately follows the isobaths of the lake.

4 July 1988—The western portion of Lake Superior is obviously beginning to warm, but the central and eastern basins are still cold on this date (Fig. 4). Surface temperatures indicate the cold water is at nearly maximum density. The warmest water appears to originate in the Apostle Islands, and it is being transported by the Keweenaw Current along the southern shoreline of the lake. Very warm bodies of water along the Keweenaw Peninsula show north-northeast directed streaks, as though they have been stretched in that direction. Upwelling can be detected at the base of the peninsula where there is a 4°C temperature difference between nearshore cold water and warmer offshore Keweenaw Current water. Along the northern shoreline of the Keweenaw Peninsula, the current generally mimics the bathymetry of the lake. At the base of the peninsula, the current is quite broad, it becomes most narrow at Eagle Harbor, and then it widens at the tip of the peninsula. As in the 17 June 1987 scene, warm water is entering the central lake in a north-northeastward to northeastward direction, and warm pockets of water are present along the north shore of the Keweenaw Peninsula. As the main current rounds the peninsula, it remains quite broad and travels southeastward toward the shoreline of Lake Superior.

12 July 1988—The Keweenaw Current appears quite different on this date (Fig. 2) than on 4 July 1988. On 12 July the current is narrow on the northern and southern shorelines of the Keweenaw Peninsula. It is most confined between Freda and Keweenaw Point on the northern shore. North of the Keweenaw Peninsula, a broad northeastward-trending body of warm water is present. Mixing between warm and cold waters in this area is inferred because of the interfingering between warm and cold waters. The warm water body is interpreted to be cut off from the main current and actively mixing with colder central lake water. Beyond the tip of the peninsula, the current moves south-southeastward to southwestward toward the southern shoreline of Lake Superior. Again, the overall path of the Keweenaw Current generally follows the isobaths of Lake Superior.

22 July 1988—Ten days later (Fig. 5), the entire lake has warmed considerably, leaving two cold pools remaining in the central and eastern basins. Mixing is pronounced along the southern shoreline of Lake Superior. This is particularly evident where a large gyre eastward of the Keweenaw Peninsula partially enters the Caribou Basin. This circular-like pattern is approximately 40 kilometers wide. Large gyres varying from 50 to 100 kilometers wide have previously been identified with AVHRR imagery in
Lake Michigan and Lake Huron (Schwab et al. 1992). Schwab et al. (1992) determined that these circular-like patterns were wind induced and persisted for 3 to 8 days. The width of the Keweenaw Current on 22 July 1988 along the northern shoreline of the Keweenaw Peninsula is hard to measure, due to an unmasked elongated cloud (11.5–12.5°C temperature range) located north of Ontonagon. In general, however, the current appears to have a similar narrow pattern as on 12 July 1988. The current is narrowest at Copper Harbor, and it travels toward the south-southwest after passing around the tip of the peninsula. This south-southwestward flow is identified by a tongue of 14 to 15°C water rounding the tip at Keweenaw Point. The exact path is hard to pinpoint on the southern shoreline, due to the proximity of the gyre and the general warming in Keweenaw Bay.

25 July 1990—The Keweenaw Current in Figure 3 is broad along the northern shoreline of the Keweenaw Peninsula, although minor cloud contamination has caused some interference in its detection. The current is deflected toward the north-northeast to northeast at the tip of the peninsula, and the warmer protruding waters contain lineated north-northeastward to northeastward patches of 12°C water. It is interesting to notice that the north-directed tongue in this image is broader and extends deeper into the central basin than the bodies noted on 17 June 1987 and 4 July 1988. This more pronounced northward penetration of the Keweenaw Current into the central basin may suggest persistence of the current in this direction for an extended period of time. Upon rounding the tip of the peninsula, the main component of the current travels southeastward.

10 August 1988—The overall temperature range of the whole lake is beginning to decrease in this image, suggesting onset of nearly isothermal conditions (Irbe 1992). This is common in lakes and results from large-scale mixing (Green and Terrell 1978). On the northern shoreline of the Keweenaw Peninsula, cloud contamination prevents the outer boundary of the current from being identified with confidence. Overall, however, the current appears fairly wide. The current is notably broad between Eagle Harbor and Copper Harbor, but no warm water plume can be detected north of the peninsula due to cloud contamination. Rounding the tip of the Keweenaw Peninsula, the current travels toward the south-southeast to southeast. East-southeast to eastward directed meanders on the outer edge of the Keweenaw Current are well displayed. Meanders in the Keweenaw Current have been previously recorded by Ragotzkie (1966) and Green and Terrell (1978). They suggest these meanders are due to instabilities forming along the usual sharp outer edge of the current and have recorded meanders on the outer edge of the Keweenaw Current doubling in size over a 1-day period.

3 September 1989—Intense mixing is taking place on this date throughout the study area. Warm pockets of water are present throughout the generally colder central lake north of the Keweenaw Peninsula. Due to cloud contamination and intense mixing, the Keweenaw Current is difficult to identify along the northern shoreline of the peninsula. However, at the tip of the peninsula, the current is quite wide near Copper Harbor, and upon rounding the tip it flows eastward to east-southeastward. Several small gyre-like bodies composed of 10.5 to 12.5°C water appear to the east-southeast of the tip of the peninsula.

7 September 1988—On this date the Keweenaw Current is broad along most of the northern shoreline, but it is narrowest near Eagle Harbor. Two protrusions of relatively warm water leave the tip of the peninsula and are directed toward the north-northeast and east-northeast. This warmer water, which has moved into relatively cooler water, does not penetrate as far into the central lake as similar protrusions on 17 June 1987, 4 July 1988, and 25 July 1990. This may suggest that the current has not been oriented in this direction for a long time, or that the peak is relict from some preexisting wind pattern. A warm pocket of water north of the main protrusion appears to have become detached from the main body. Past the tip of the peninsula, east-southeastward flow is occurring. A gyre, possibly the remains of the gyre identified on the 22 July 1988 image is identified to the east of the Keweenaw Peninsula.

18 September 1989—Extensive cloud contamination is present on this date making identification of the Keweenaw Current on the northern shoreline of Lake Superior difficult. Near the tip of the peninsula, the current appears broad, and after rounding the tip it moves almost solely in a eastward and then southeastward direction. A possible meander can be identified attached to the outer edge of the current eastward of Keweenaw Point.

23 September 1988—This map shows a relatively narrow current as compared to previous images (excluding 12 July 1988). At the tip of the peninsula, the current travels eastward from Keweenaw Point and then southeastward toward the
Influence of Wind on the Keweenaw Current

The outer edge of the current, especially on the northern shoreline of the peninsula, displays evidence of instability and is characterized by the presence of meanders. It is interesting to notice that meanders have been identified on all images for the study collected after early August in every year.

RESULTS AND DISCUSSION

Observation of the Keweenaw Current on the eleven dates described above suggests that although the general path of the Keweenaw Current is southeastward as it rounds the tip of the Keweenaw Peninsula, the current is occasionally deflected into the central lake. Because wind is the primary cause of daily changes in coastal currents and Ekman dynamics have been determined to explain quite well the flow of the Keweenaw Current (Green and Terrell 1978), Ekman dynamics are considered during investigation of the possible relationship between wind and the changing path of the current. For each of the eleven surface temperature maps wind data for the image date were used to predict the directions in which surface and net Ekman transport should occur if wind were the dominant force controlling the path of the Keweenaw Current beyond the tip of the Keweenaw Peninsula. Wind data for the 2 days preceding the image date were also compiled to determine the duration of the wind pattern for each image.

Wind directions on 5 June 1988 all contain an east-directed component and four of the six wind recordings are east-southeastward. North directed winds are predominant on 4 June, while south directed winds occur on 3 June, showing that wind directions are highly variable for this 3-day period. Weak wind speeds dominate at all of the stations on 5 June 1988 and the preceding 2 days. For winds on 5 June 1988, surface Ekman transport (Fig. 6a) should be directed to the east to south-southeast, while net transport should travel south-southwestward. The current appears to be traveling south-southwestward against the shoreline of the peninsula, correlating well with the predicted net Ekman transport direction. The pockets of warm water extending off the current along the southern shoreline of the peninsula may be an indication of a beginning southeastward flow, which would correlate well to the predicted surface Ekman transport for wind directions on 5 June 1988. The weak winds may not be as effective as high velocity winds in controlling the direction of the current. In a study of Lake Ontario, Scott et al. (1971) found the full current response to a wind direction change took 1 to 2 days. In addition, studies by Mortimer (1988) and Simons and Schertzer (1989) determined that wind speeds less than 2.5 meters per second, and at times ranging from 2 to 4 meters per second, could not be reliably correlated to current directions.

On 17 June 1987 all wind direction data, with the exclusion of wind direction data from the Marquette weather station, have a westerly component, which opposes the general counterclockwise circulation pattern of Lake Superior. Without consider-
ing the counterclockwise circulation of Lake Superior, winds on 17 June 1987 suggest surface Ekman transport should trend toward the northwest to east-northeast, and net transport should move toward the north to east-southeast. The protrusion of the Keweenaw Current into the central lake basin in a north-northeastward to northeast direction closely correlates to surface Ekman transport calculated from wind data from Marquette and STDM4 (Fig. 6b). A significant southeast component of current flow is also present, and this orientation is consistent with net transport predicted from data collected at buoy #45001, STDM4, and Marquette for 16 June 1987 (the day preceding the image collection date). Because of the counterclockwise flow of Lake Superior, it is not likely to expect a component of the Keweenaw Current to travel northwest off the tip of the peninsula against the general flow. However, the broadness of the current along the northern shoreline of the Keweenaw Peninsula can be attributed to the westward winds (Green and Terrell 1978). Relatively low wind speeds prevailed for the 3-day period prior to the acquisition of the image.

The winds on 4 July 1988 are directed northward, and overlake winds on 3 July 1988 also are traveling toward the north. These winds suggest that northeastward to east-northeastward surface Ekman transport and eastward to southeastward net Ekman transport should occur. At the tip of the peninsula, the Keweenaw Current travels in a distinct northeastward direction (Fig. 4), correlating well with the surface Ekman transport direction calculated for winds at all locations except Marquette (Fig. 6c). The predicted net transport based on winds at Houghton and Marquette correlates well with the direction of the current. Considering the overall northeastward streaking of the current along the shoreline of the peninsula, and the agreement between the observed and predicted current directions, a wind influence on the surface waters of the Keweenaw Current is obviously evident on this date.

On 11 and 12 July 1988 winds at all locations are mostly directed toward the south, varying from southwestward to southeastward, excluding data buoy #45006. Winds on 10 July are north-directed. Surface Ekman transport should occur south to westward (Fig. 6d) and net transport should follow a southwest to northwest path. The observed current direction relates well to the surface Ekman transport direction predicted from the overall wind data at all over lake and land locations except data buoy #45006. Considering that on 3 and 4 July the prevailing winds were north-directed, it is evident that wind directions have rotated at least 180° during this time period. Because the Keweenaw Current on 12 July is very narrow and confined to the shoreline, the protruding warm mass of water north of the peninsula is most likely relict water that moved into the deep lake because of preexisting north-directed winds. The relatively warm and cold pockets of water north of the peninsula are probably remains of the mixing that has resulted from changing wind orientation for the time period of 2 to 12 July. These observations enforce the prediction that wind is a major influence on the Keweenaw Current.

On 21 and 22 July 1988, winds are mostly southward directed, ranging from southwestward to south-southeastward (with the exception of data buoy #45006). These winds suggest surface Ekman transport should be directed west to south-southwest, and net transport should be directed toward the northwest to west-southwest (Fig. 6e). The south-southwestward directed current (Fig. 5) correlates well with the surface Ekman transport direction predicted on the basis of data from buoy #45001, STDM4, and Marquette. Any correlation between wind and net transport cannot be detected, although there may be some relationship. Since the net transport of the current would be traveling toward the shoreline, it could not be detected if present because the prominent warm water would most likely cover up any evidence of net transport.

Of all the dates for this study, 25 July 1990 is one of two which have the same wind orientation on the image date and preceding 2 days. For 23 to 25 July the winds are directed northward, ranging from north-northwest to north-northeastward. These winds lead to a prediction of north-northeastward to east-northeastward directed surface Ekman transport (Fig. 6f), and east-northeast to northeastward directed net Ekman transport. The Keweenaw Current for this date relates well to wind data because a portion of the current is deflected toward the north-northeast to northeast (Fig. 3). Wind persistence of at least 3 days in this northward direction is most likely responsible for the broad, deeply penetrating peak that moves into the central lake waters. Overall, this image suggests a strong correlation between wind and current directions.

Wind directions on 10 August 1988 are mostly northeastward directed, suggesting that east-northeastward to eastward-directed surface Ekman transport should occur (Fig. 6g). East-southeast to southeastward net transport is predicted. The cur-
The results of this study clearly demonstrate the ability of AVHRR satellite imagery to identify the boundary of the Keweenaw Current because of its surface temperature signature. While the Keweenaw Current travels along the northern shoreline of the Keweenaw Peninsula, geostrophy, bathymetry, water density, and shoreline boundaries, in addition to wind stress, are all likely responsible for its strength and persistence. However, upon reaching the tip of the peninsula, wind appears to be the primary influence on the path of the Keweenaw Current. Current directions observed in the images generally related well to predicted surface Ekman transport directions based on wind data. Predictions based solely on data from STDM4 and the data buoy #45001 yielded the best results. Viekman et al. (1992) also determined that winds at data buoy #45001 and STDM4 correlate well to the current direction at a site located 2 kilometers north of Copper Harbor.

Of the 11 images analyzed, the current direction in 9 images is consistent with surface Ekman transport predicted from wind data. Only 2 images, 5 June 1988 and 18 September 1989, did not clearly display the predicted relationship between surface Ekman transport direction and the direction of the
current. In all 11 images the current’s observed pattern is broadly consistent with the predicted net Ekman transport direction. This study also suggests that the Keweenaw Current may take a day to adjust to a change in wind direction. For all image dates in which the preceding date was characterized by the same wind direction as the image date, a strong wind-current relation developed. For all image dates that were preceded by days affected by wind directions different from those on the date of the image, the current most often weakly related to winds on both the image date and the preceding day, appearing to be in a transition period. This apparent lag time may be due to the time at which the image was acquired, as some AVHRR images are sensed in the morning. In this case, the current would have been exposed to only a portion of the 24 hour period of winds for that date. It would make sense in this case that the pattern of the current may then better or partially be consistent with the wind on the preceding day.

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REFERENCES


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