Multi-Frequency HF Radar Observations of the Thermal Front in the Great Lakes

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In large fresh water lakes in temperate regions, the spring transition from weak to strong stratification is characterized by the formation of a coastal thermal front. This transition is dominated by high gradients in temperature, nutrient and plankton fields. A combination of solar warming, boundary heat flux, coastal bathymetry and surface wind stress causes the frontal system to develop such that a surface convergence forms at the nearly vertical 4°C isotherm (the temperature of maximum density). This isotherm propagates offshore as warming of the nearshore water increases and as storms provide a mechanism by which the two water bodies (warm stratified nearshore waters and cold isothermal offshore waters) mix. As part of the NSF Episodic Events – Great Lakes Experiment (EEGLE), HF Radar observations were obtained during the development and progression of the vernal thermal bar in Southern Lake Michigan in April 1999. Two Multi-Frequency Coastal Radars (MCR's) were utilized to provide observations of near-surface current vectors and vertical current shear adjacent to the Lake Michigan shoreline near St. Joseph, Michigan. MCR measurements of near-surface currents show evidence of theoretical vernal thermal front circulation supported by in-situ measurements of thermal and dynamic structure. A two-week study of surface dynamics in the vicinity of the thermal front is presented and compared with in-situ measurements.

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BACKGROUND

Many large temperate lakes undergo a spring transition, from weakly stratified winter conditions to strongly stratified summer conditions, which is characterized by the formation of a coastal thermal front [1,2]. In spring, initial warming of the nearshore waters is accomplished through spring runoff. Besides the influx of warmer water, this process also provides suspended particulates, dissolved organic matter, dissolved nutrients and seed populations of algae to the nearshore zone and provides a visible manifestation of a frontal boundary. In addition, due to the morphometry of the basin, solar heating occurs from the coast lakeward. As the water temperature increases to 4°C, the temperature of maximum density for fresh water, this water tends to sink and a zone of convergence is observed. If the surface convergence rate exceeds the natural dispersion rate for fluid parcels, the frontal system is sustained. In the Great Lakes, these features persist up to 90 days, migrating offshore at a rate of about 0.5 to 1.0 cm/s.

The water offshore of the 4°C isotherm remains cooler and surface heat flux causes convective mixing which results in a slow temperature increase. Inshore, the water temperature increases to such an extent that a significant cross-shore pressure gradient develops which tends to push the warm water offshore. As this flow develops geostrophic balance, the mean current is directed alongshore in a cyclonic fashion (in the northern hemisphere) at a rate of a few cm/s.

The longshore velocities are generally one order of magnitude larger than the cross-shore velocities in the frontal region. The generalized flow pattern is diagrammed in Fig. 1.

Associated with the vernal thermal front are strong gradients in turbidity, nutrients and biomass, with the warmer nearshore waters enriched. Observations indicate that these gradients coincide most strongly with the 6-7°C isotherms, the center of the spring thermocline [3].

Wind stress plays an important role in the formation and development of the front. Cross-shore winds introduce an asymmetry into the basin-wide circulation pattern with the development of the thermal front enhanced on the downwind boundary of the basin. In Lake Michigan, this is the eastern side of the lake [4]. Strong wind stress serves to induce instabilities along the thermal front enhancing cross-frontal exchange and mixing, which in turn can induce episodes of increased downwelling (due to the formation of 4°C water) [4,5]. Wind blowing with a component along the shoreline will also serve to further modify the frontal region by inducing a surface wind drift current which will either compress or expand the warm inshore water with respect to the coast [6].

THE EEGLE EXPERIMENT

As part of the Episodic Events Great Lakes Experiment (EEGLE), a large in-situ data collection activity was directed at the southern extreme of Lake Michigan. The primary focus of this experiment is to measure cross-shore variation in environmental and ecological parameters before and after strong wind events which induce resuspension plumes. These events typically occur in the early spring when the thermal gradient over the lake is unstable and strong wind events from the north are more common. This time frame is coincident with the development of the thermal front in this region.

As part of the data collection effort, two Multi-Frequency Coastal Radars (MCR's) were installed to monitor nearshore surface currents in the region of St. Joseph, Michigan. The radar footprint of these systems encompassed the sites of five

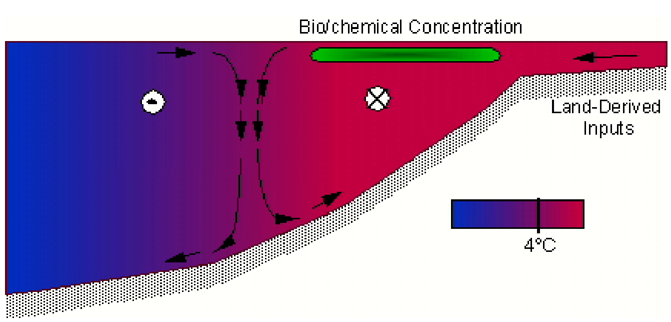

Fig. 1. Schematic diagram of a thermal front showing temperature contours, theoretical circulation pattern, and associated biological gradients.

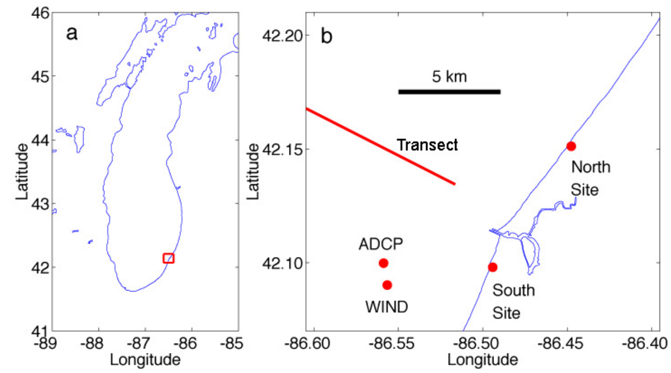

Fig. 2. EEGLE site diagram showing instrumentation locations.

bottom-mounted acoustic doppler current profilers (ADCP's), a meteorological buoy and a shore-perpendicular transect across which vertical and horizontal profiles of ecologically important variables were collected (Fig. 2).

The MCR's, operating at 4 to 21 MHz, obtained reliable near-surface current data during several small wind events which affected thermal front development during the Spring of 1999. The first of these is presented here.

THE 1999 VERNAL THERMAL FRONT

The early spring of 1999 was characterized by relatively low winds with few events from the north. This low energy regime was conducive to the development of an early coastal thermal front in southeastern Lake Michigan. In-situ temperature data is available from a meteorological buoy located at 42° 05.41N 86° 33.40W, approximately 5 km offshore, immediately adjacent to a bottom-mounted ADCP. Fig. 3 shows a timeseries of these two data sets for the period April 1 through April 12. Note the unstable stratification of this region prior to the passage of a strong surface thermal gradient on April 5. Coincident with increasing south winds on the 6^{th}, the surface and bottom water temperatures converge to about 4°C. Presumably this is due to mixing brought about by shoreward propagation of surface water accompanied by a return flow at depth [6].

Huang [5] and Gbah et al [4] suggests that increased winds induce frontal instabilities which serve to enhance exchange across the frontal boundary and induce downwelling as 4°C water is created through a mixing of the two water masses. In support of this theory, current measurements at the mooring locations show strong flows to the northeast (alongshore) throughout the water column accompanied by a downwelling of about 12 hours in duration centered on the 7^{th} at 00UT. Following this event, the wind lightens and the water at the mooring site becomes stably stratified.

A detailed cross-sectional temperature survey conducted offshore of St. Joseph, Michigan, on April 7 showed vertical isobars from 4 to 26 km offshore with the 4° isotherm located approximately 6.5 km from shore.

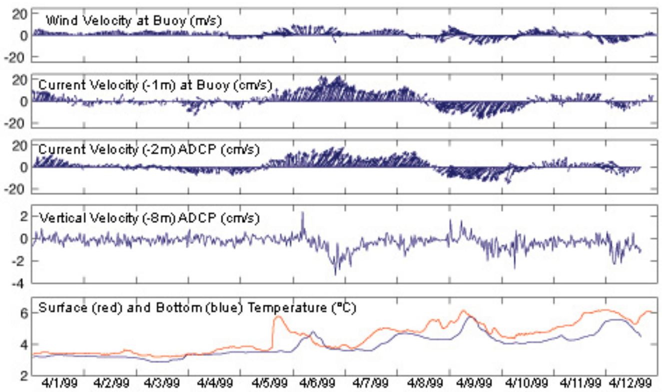

Fig. 3. Wind, current and temperature data as measured by meteorological buoy and bottom-mounted ADCP.

HF RADAR OBSERVATIONS

In order for the MCR to obtain reliable estimates of near surface flow, waves of a particular wavelength and height must be present on the lake surface travelling with a component parallel to the radar look direction [7]. During the first two weeks in April, conditions were favorable for MCR data acquisition during the peak of the alongshore wind event described above.

Each individual MCR site records a spatial distribution of current radial velocities. These two data sets are then combined to form a spatial array of current velocity vectors for each of four radar frequencies. The four radar frequencies produce estimates of current velocities at four "effective depths" [8]. By comparing the current velocities between "effective depths" current shear estimates may be produced.

MCR estimates of current flow for the 10 hour period 1230-2230 UT on April 6, show strong surface flow alongshore accompanied by a small component towards shore which increases with "effective depth." Fig. 4 displays 24 vector current maps superimposed to show the MCR coverage area during this event and the variability in the near surface flow field. In general, the component of flow directed along-shore responds directly to the wind, while the cross-shore flow reaches a maximum of about 0.1 m/s once the cross-shore component of wind exceeds approximately 3 m/s. This cross-shore flow threshold is indicative of the presence of a cross-shore pressure gradient, further supporting the flow pattern suggested by Csanady as the result of long-shore wind stress acting over a thermal front [6].

CONCLUSIONS

The early development of the vernal thermal front in Lake Michigan in 1999 was primarily driven by the input of warm runoff and solar heating under low wind conditions. With the onset of an alongshore wind event, instabilities were introduced into the early flow field and cross-frontal exchange resulted in an episode of downwelling along the front. The flow pattern observed by the MCR's suggests the presence of a cross-shore flow component supporting previous theoretical work on the influence of wind stress on thermal front dynamics.

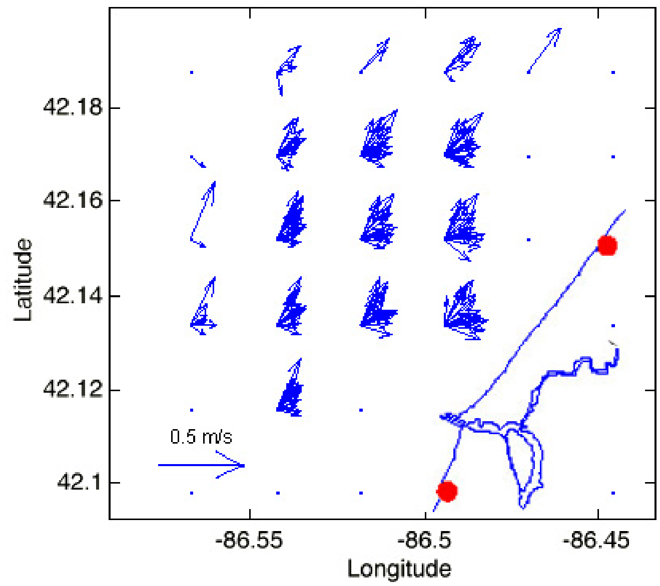

Fig. 4. MCR current vector estimates overlaid for 10 hour time period (1230-2230 UT, April 6) during significant southwest wind event.

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