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Inter-basin exchange flows in Lake Erie

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Abstract

Exchange processes between the three basins of Lake Erie relevant to water quality during summer stratified season are discussed in this paper. Currents, water temperature, winds, radiation and waves were recorded at fixed moorings in Lake Erie during 2004 and 2005. Circulation within and between the basins are studied. The thermal structure and exchange processes during summer stratification and early fall indicates that both barotropic and baroclinic processes influence the exchange flows.

1. Introduction

Lake Erie is located between the US and Canada. By volume it is the smallest, and by surface area it is the second smallest, lake in the Great Lake system. As the shallowest of the Great Lakes, it warms quickly in the spring and summer and cools quickly in the fall. The shallowness of the lake also makes it the most biologically productive of the Great Lakes. Eighty percent of Lake Erie's total inflow of water comes through the Detroit River into the western basin. The remaining comes from precipitation and other tributaries flowing directly into the lake. The Niagara River is the main outflow from the lake.

The lake is composed of three distinct basins separated by subsurface ridges. The western basin is very shallow, with an average depth of 7.4 m. The central basin is quite uniform in depth, with an average depth being 18.3 m and maximum depth of 25 m. The eastern basin is the deepest of the three with an average depth of 25 m and a maximum depth of 64 m. These physical characteristics cause the lake to function as virtually three separate lakes. The central and eastern basins thermally stratify every year, but stratification in the shallow western basin is rare and very brief. Stratification impacts the internal dynamics of the lake, physically, biologically and chemically. Water exchanges among the basins have both local and basin-wide effects over both short and long time intervals. The physical characteristics of Lake Erie directly influence the functioning of the lake ecosystem to various stressors.

2. The Field Experiments

Eulerian measurements of currents, winds, and temperatures were made during the spring and summer of 2004 and 2005. Acoustic Doppler Current Profilers (ADCP), meteorological, and thermistor moorings were deployed at several locations in the lake from April to October, 2004 (Fig. 1).

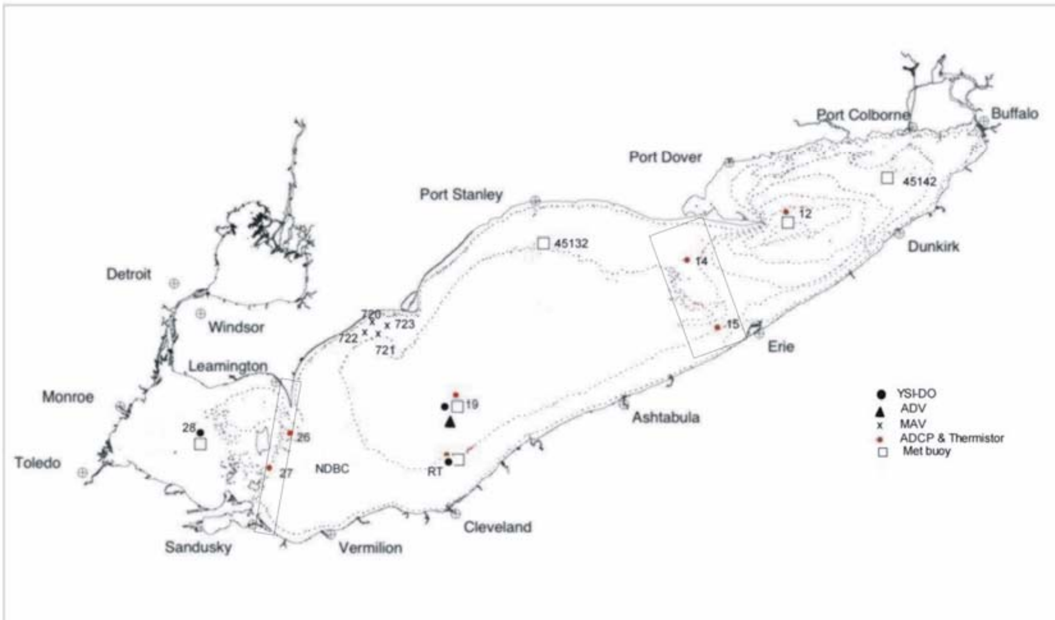

Fig 1: Map of Lake Erie with mooring details in 2004. The boxes show the boundaries between the three basins.

The experiment also included several surveillance cruises that measured water quality parameters from research vessels during the deployment period..

2. Results

Currents in the lake are determined mainly by the prevailing winds over the lake. A climatological analysis of winds speeds measured at shore stations was reported earlier in a special issue of the Journal of Great Lakes Research devoted to Lake Erie (Boyce et al. 1987). The winds are in general south westerly and have peak variability at periods from 7 to 10 days. As an example, the wind measurements at station 19 from day 211 to 280 in 2004 are presented as an approximation of the meteorological forcing during this period (Fig. 2a). The wind stress was obtained from the quadratic law given as $\tau = \rho_a C_d |W| W$, where $\rho_a = 1.2$ kg m^{-3} is the air density, W is wind velocity. The drag coefficient C_d increases with the wind speed and is estimated as $C_d = (0.8 + 0.065\ W)X10^{-3}$ for W >1 m s^{-1} . A low-pass filter, using a 24-h period for the cut-off, was used to remove the high frequency information in the wind stress. The filtered time series has peaks of over 0.2 N m^{-2} during some episodes, usually associated with easterly storms towards the end of the summer and early fall. The wind field was dominated by two easterly storms: the first from day 252 to 253, and the second on day 263. These easterly winds were responsible for a difference in water level between Buffalo and Toledo of 1.2 m on day 253 and over 75 cm on day 262 (Fig2b).

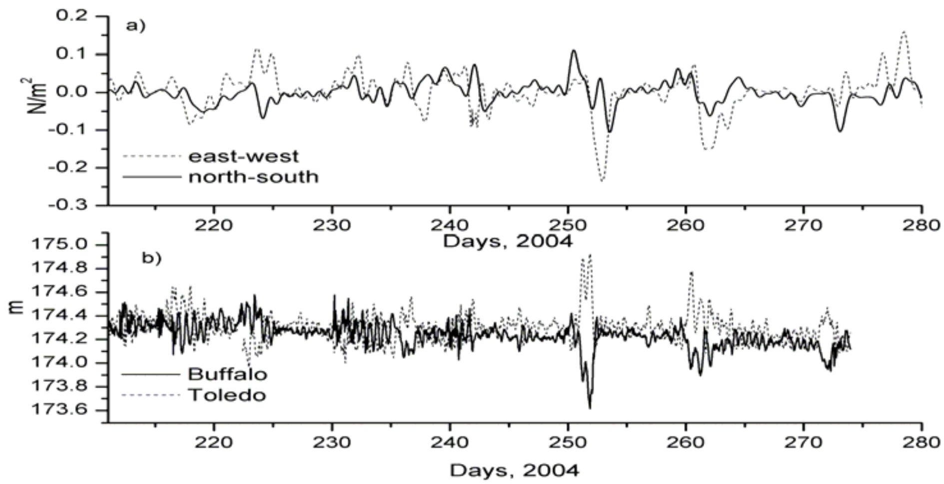

Figure 2: Time series of wind stress at station 19 and water levels at Toledo and Buffalo

Figures 3a-c show the time series of vertically averaged water temperature from the thermistor moorings and currents at stations 14, 26 and 27. During this period stratification at these stations is negligible; therefore we present only the vertically averaged temperatures and currents at these stations. Both stations 26 and 27 are located in the passages between the western and central basins; station 26 is located in the Pelee passage and station 27 is in the passage between Kellys Island and the south shore. Saylor and Miller (1987) indicated that most of the water exchange between the western and central basins takes place in these passages. The cooler waters at these stations are associated with the incursion of water from the central basin and subsequent mixing with the western basin waters due to the presence of westward winds (fig 3b). In the Pelee passage the mean flow was towards the southeast and the mean transport during this deployment period was 3213 m^3/s, whereas at station 27 the mean flow was towards the southern shore with a mean transport of 815 m^3/s. The flow through the Pelee passage roughly equals the inflow from the Detroit River. Bartish (1987) found that the wind influence on the transport is negligible between the western and central basins, but, as shown here, the mean currents at both stations indicate that significant exchange takes place mainly because of pressure gradient force set up due to easterly winds. We will further explore these aspects and the influence of seiches using both years of data. The water temperature at stations 26 and 27 (western-central) are in general warmer by ~1^oC than the water temperature at the Pennsylvania Ridge (station 14).

Station 14 was located on the Pennsylvania Ridge between the central and eastern basins. The mean flow was towards the east basin., but the horizontal resolution on the ridge was not sufficient to estimate the transport during this year. Boyce et al. (1980) observed a westward flow in the hypolimnion of Pennsylvania channel between the eastern and central basins, The transport of cold, oxygenated hypolimnion water from the eastern to the central basin has been considered as a possible oxygen renewal mechanism for the central basin bottom waters (Burns and Ross, 1972; Boyce et al., 1987). However, their observations did not resolve the epilimnion and they assumed that most of the time the transport in the epilimnion was towards the east basin. The current measurements from ADCPs in 2004 and 2005 provide an opportunity to explore the flow between these basins in more detail.. Figures 3d-f show the time series of layer averaged water temperature from the thermistor moorings and currents at station 15 between days 224 and 280 in 2004.. During this period stratification is confined to the 23.2 m deep Pennsylvania channel. A hypolimnion of 2-3 m thick was observed between 220 and 242, and again from day 250 to 252. The mean epilimnion, mesolimnion and hypolimnion temperatures were 20.6, 14.6 and 8.9 ^{o}C, respectively. In general the currents were towards the central basin in all three layers with higher values in the hypolimnion. In the channel the mean epilimnetic flow was -3150 m^3/s (negative sign indicates flow towards the west), which is 60% more than the combined westward transport in the hypolimnion (-720 m^3/s) and mesolimnion (-1478 m^3/s)..

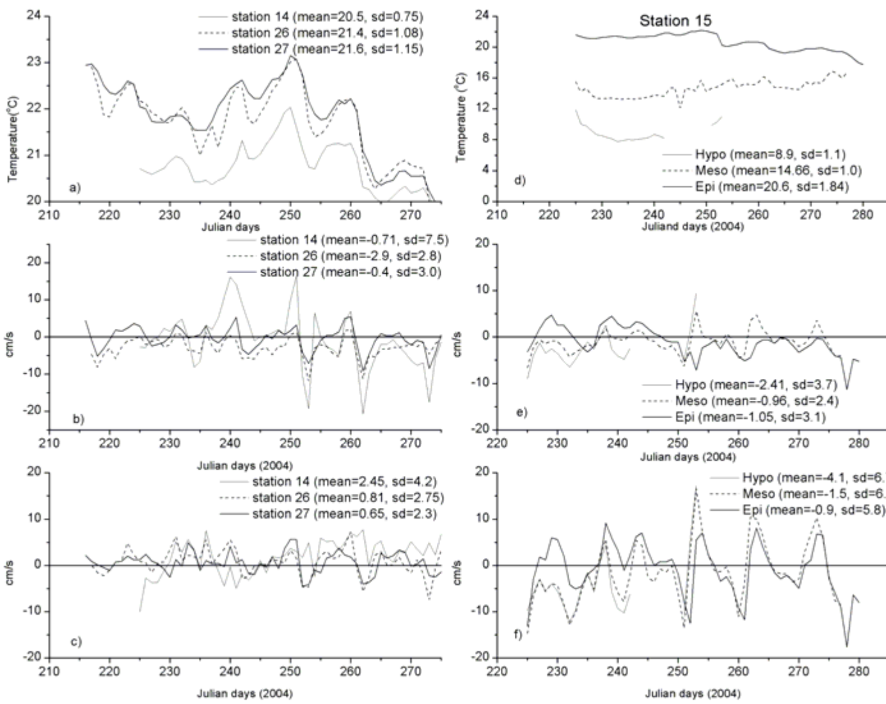

Figure 3: (a) to (c) Time series of vertically averaged temperature and currents at three stations and (d) to (e) layer averaged temperature, cross channel flow and along channel flow in the Pennsylvania channel.

The flow observations presented above shows that the mean transport in all the layers was towards the central basin. However, the variability in the vertical structure indicates a two-layer flow between days 224 to 242. Figures 4a to 4c show the variations of low-pass filtered currents and temperature at station 15 in the Pennsylvania channel. The currents are rotated in the direction of the major principal axis. Comparison of east-west wind stress and the along-channel currents show that there is a good correlation during strong wind episodes. Current reversals associated with winds and surface pressure gradient set up (fig 2b) were common during the summer regime, with each episode on average lasting for 4-6 days. The along-channel currents in the mesolimnion and hypolimnion were opposite the wind direction on a few occasions, supporting earlier observations that transport is towards the central basin due to the baroclinic part of the pressure gradient force. For example, the along-channel currents in the epilimnion from day 225.5 to 231 flowed towards the east under the influence of eastward winds, however the currents did not change direction in the mesolimnion and the hypolimnion, and flowed towards the west. The internal pressure gradients were calculated from the mean thermocline positions (Figures 5a and 5b) measured on both sides of the ridge during the surveillance cruises . The thermocline position in the eastern basin was 1 to 2 m deeper than the central basin thermocline position in July and September. Eastern basin profiles in

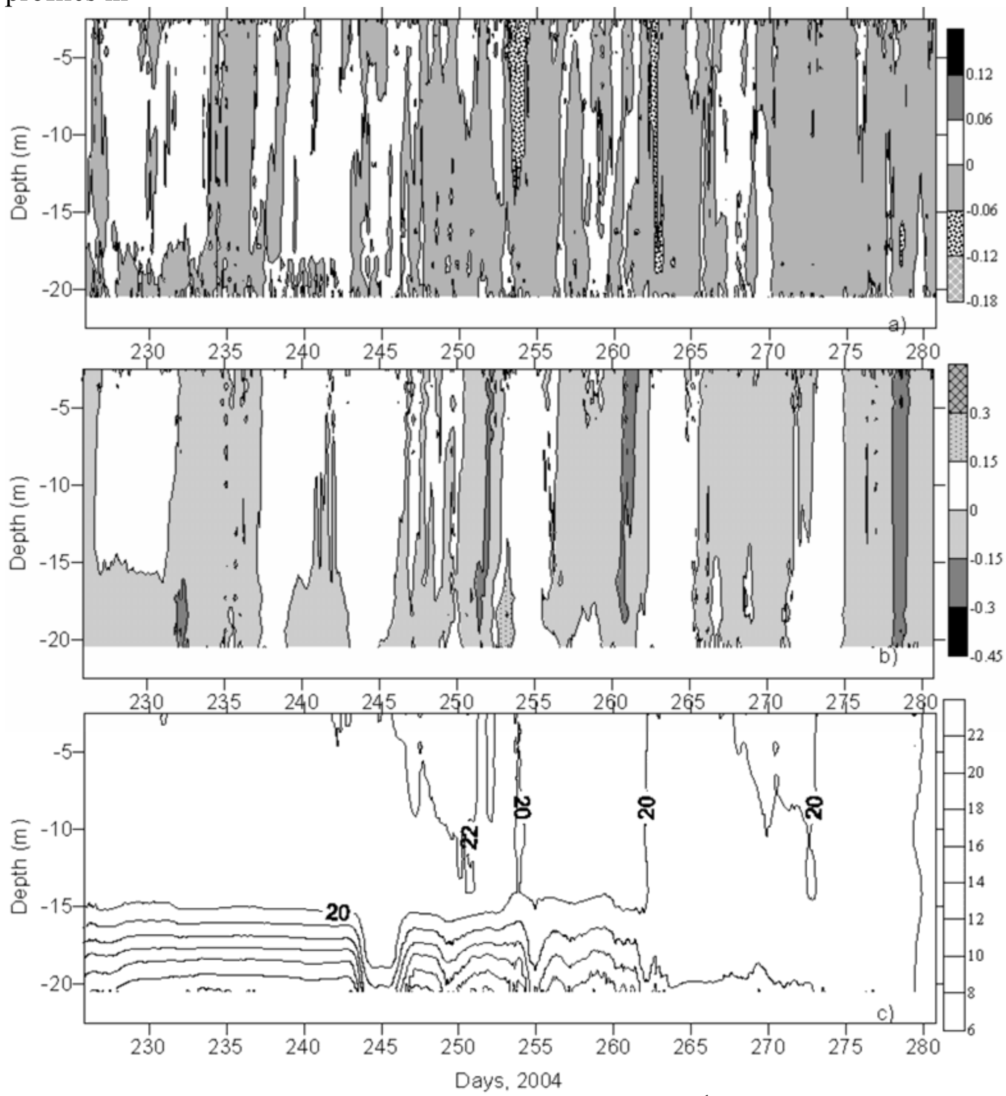

Figure 4: Vertical structure low-pass filtered currents in m s^{-1} in a) cross-channel b) along channel directions and c) thermal structure at station 15.

August are not available, but previous observations show similar characteristics (Boyce et al. 1980). A time series of the daily averaged thermocline positions at the two moorings are shown in Figure 5c. The thermocline in the east basin varied strongly at 7-10 day period between days 220-252 due to the meteorological forcing. Between days 225-228 the east basin thermocline was situated at deeper depths compared to the thermocline position in the channel providing strong baroclinic forcing. As suggested by Boyce et al. (1980), this supports the intrusion of colder eastern basin water into the central basin. However, as these measurements indicate, except for a few episodes like these during weak wind conditions, the transport appears to be mainly uni-directional.during August and early September.

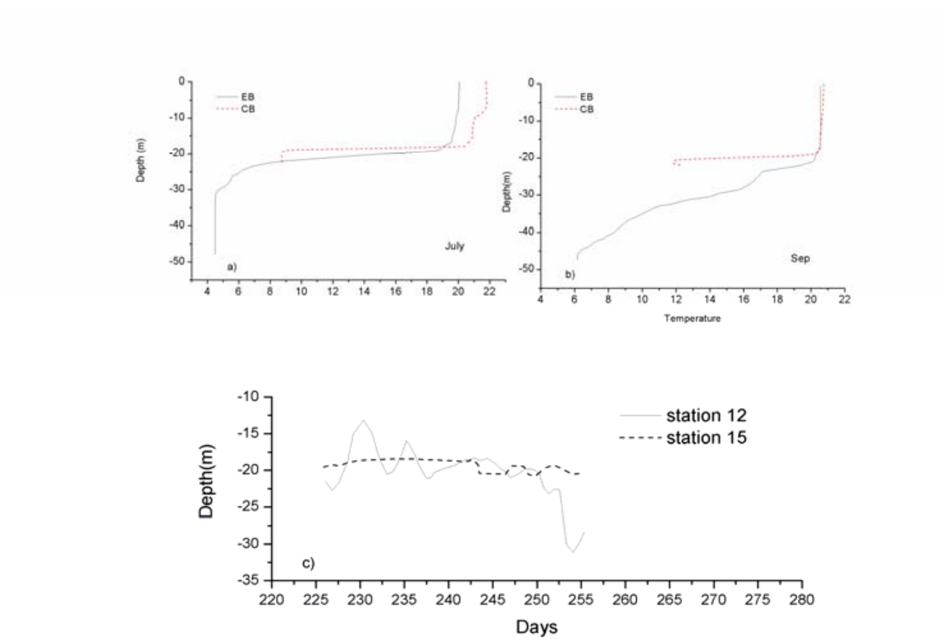

Figure 5: Temperature-depth distributions in the eastern (EB) and central basins (CB) and time series of the thermocline position at two stations.

3. Conclusions

This study presents some observations of inter-basin transport from a large experiment in Lake Erie. Flow and thermal structure in the lake presents a complex scenario during certain episodes and also under mean summer stratified conditions. The time series of vertical structure of along-channel currents and temperature in the Pennsylvania channel showed strong influence of along-the-lake winds, and two-layer structure probably associated with return currents due to surface and internal pressure gradients. Further studies using the complete data base during 2004 and 2005 and non-linear numerical models to investigate the inter-basin exchanges and mixing are in progress.

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