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Further studies of a lake breeze : Part I—Observational study*

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सार — इस लेख में ओन्टारियो सरोवर से विशेष रूप से चुनी गई 24 घंटे की अवधि में उठी सरोवर–स्थलीय समीर चक्र प्रणाली की त्रिआयामी संरचना तथा व्यवहार प्रस्तुत किया गया है। संरचना की परिकल्पना बड़ें सरोवरों के अन्तर्राष्ट्रीय फील्ड वर्ष के दौरान किए गए प्रेक्षणों के आधार पर की गई है। जिस प्रकरण का अध्ययन किया गया है यह उस समय घटित हुआ जब भारी मात्रा में अधिभावी प्रवाह दक्षिण दिशा से अपेक्षाकृत कम गति से बह रहा था। इस अध्ययन से पता चलता है कि दोपहर बाद तथा शाम के पहले पहर में सरोवर से पुरवाई पवनों का बहुत बड़ा झोंका उठता है। इससे यह भी संकेत मिलते हैं कि दक्षिणपूर्वी तटीय क्षेत्र की तुलना में दक्षिणपश्चिम तटीय क्षेत्र में सरोवर समीर ज्यादा उठती हैं। प्रातः आरंभिक पहर में स्थलीय समीर अभिसरण उत्तरपूर्व तटरेखा पर होता है न कि उत्तरपश्चिम तट रेखा पर।]

ABSTRACT. The three-dimensional structure and behaviour of a lake-land breeze circulation system induced by lake Ontario for a selected 24-hour period is presented. The structure is determined from observations made during the International Field Year of the Great Lakes. The case which has been studied occurred when the large scale prevailing flow was blowing from the south at relatively low speeds. The study shows that the lake induces a broad belt of easterlies over the lake in the afternoon and the early evening. It also indicates that the lake breeze is more likely to occur over the southwestern coastal regions than over the southeastern coastal regions. During the early morning hours, surface wind convergence occurs over the northeastern shoreline but not over the northwestern shoreline.

1. Introduction

The Great Lakes of the United States generate various types of mesoscale disturbances in the lower troposphere. Many of these are driven primarily by the surface temperature contrast between the lake and the surrounding land area. An important example of the lake-induced disturbance is the lake breeze. The lake breeze influences the meteorological conditions over the coastal regions by moderating the temperatures and by exerting a strong control on the atmospheric conditions affecting air pollution. In connection with the latter, Lyons and Olsson (1973) showed that the lake breeze favours the occurrence of high air pollution in shoreline areas. This is due to three factors : (1) formation of low-level temperature inversions as cool lake air moves inland, (2) continuous fumigation of elevated plumes from shoreline pollution sources, and (3) recirculation of pollutants within the lake breeze circulation pattern. All of these factors are a consequence of the unique features of the lake breeze temperature and wind structure. A thorough knowledge of the structure is, therefore, highly desirable.

This paper describes further results of a continuing study on the structure of a lake breeze over Lake Ontario. In an initial investigation (Estoque *et al.* 1976), we studied the structure of the lake breeze on 3 October 1972 with the aid of a limited set of observations. The observations were confined to those which were taken over a narrow rectangular strip (longer side approximately north-south and normal to the shoreline). The strip, which is indicated as the Miami network in Fig. 1, is located over the southern coastal area slightly east of lakeside. Due to the limitations of the observational data, this initial investigation was able to examine only the two-dimensional structure of the lake breeze on a vertical plane normal to the shoreline. With the aid of a more complete set of observations, we have now been able to study the structure of the lake breeze throughout the entire lake and the surrounding coastal regions. The results of this observational study will be described in the succeeding sections. This paper represents the first part of a combined observational and theoretical study. The second part will deal with the use of a numerical model for interpreting the results of the observational study.

2. Observational data and method of analysis

The observations were made in 1972 during the extensive field program of the International Field Year of the Great Lakes (IFYGL). The observational network of stations is shown in Fig. 1. The surface observational stations for the field program consisted of a network of buoys, towers, automatic meteorological stations, and standard weather stations which were established by the United States and Canada. There were about fifty surface stations, however, data from only about thirty-five stations were available for this study. Nevertheless, the station

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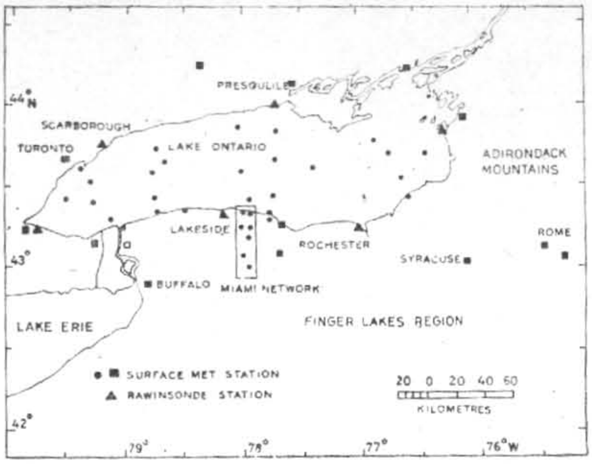

Fig. 1. Map of Lake Ontario and the observational network. Surface meteorological stations are indicated by rectangles and circles, rawinsonde stations are indicated by triangles

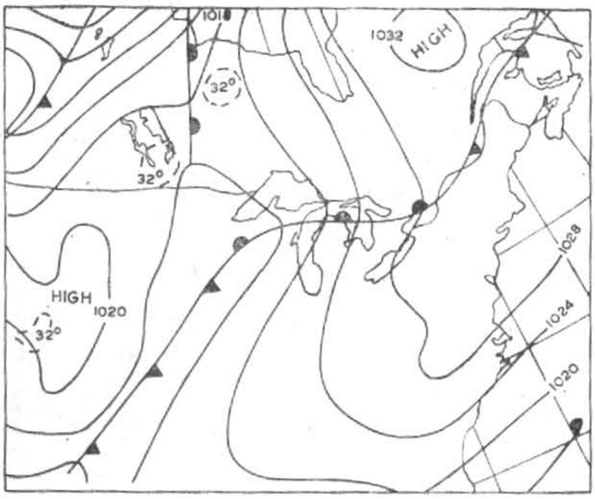

Fig. 2. The surface pressure map on 3 October 1972 at 8 A.M.

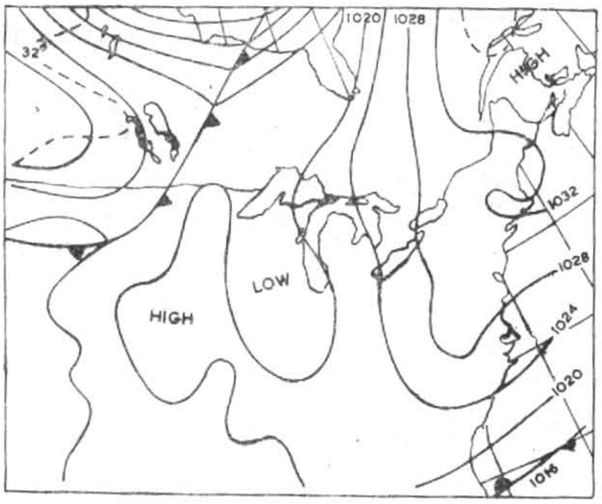

Fig. 3. The surface pressure map on 4 October 1972 at 8 A.M.

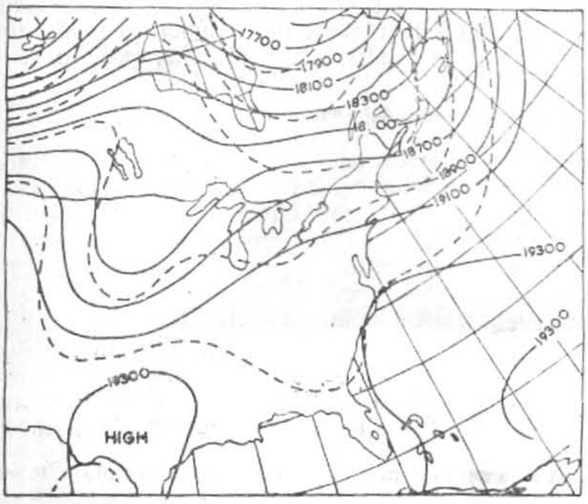

Fig. 4. The 500 mb map on 3 October 1972 at 8 A.M. Isobaric contours are indicated by full lines and isotherms are indicated by dashed line

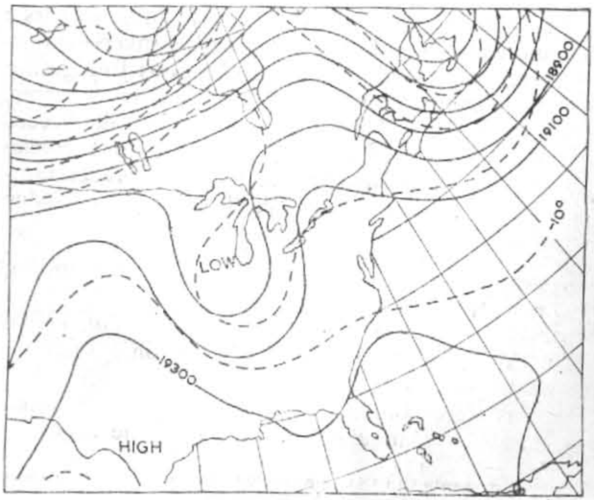

Fig. 5. The 500 mb map on 4 October 1972 at 8 A.M. Isobaric contours are indicated by full lines and isotherms are indicated by dashed lines

density is fairly adequate in resolving the surface mesoscale scale circulation patterns over most sections of the lake region. The important exception to this is the southeastern coastal region where there are relatively fewer observational stations.

In addition to the surface observations, there were six upper air (rawinsonde) stations which measured wind, temperature, and moisture. The stations were located along the shoreline and were more or less evenly distributed around the lake (*see* Fig. 1). There was no rawinsonde station over the lake itself. The number of upper air observations is much less than that of surface observations. Consequently, it is not possible to describe the structure of the atmosphere at upper levels with as much detail as that at the surface. The lack of upper air observations over the lake is certainly a great handicap in doing the study.

The analysis of the observational data consisted of drawing streamline maps for the surface and for three other levels (100 m 450 m, and 2000 m) above the surface. The maps were drawn at three-hour intervals. Surface isotherm maps were also drawn. However, upper level isotherm maps were not constructed because there were not enough temperature observations to justify the drawing of meaningful isotherm patterns at these levels. In doing the streamline analysis, we exercised great care in maintaining the continuity of patterns, both in time and along the vertical. Continuity along the vertical was useful especially in constructing the streamlines at the 100-metre level (where data were sparse) with the aid of the surface streamline patterns.

3. Synoptic conditions

In order to provide some background for interpreting the results of our analysis, we will first describe the large-scale flow pattern which prevailed during the period of the lake breeze occurrence. The general characteristics of the flow pattern are indicated by the sequence of 24-hourly surface and 500 mb maps (shown in Figs. 2 to 5). It may be seen that the Lake Ontario region is dominated during most of the period by a surface anticyclone with its concomitant weak winds and clear skies. On 3 October, there was a very weak front to the west of Lake Ontario. Subsequently, the front started moving eastward and approached the northern edge of the lake within the next 24 hours. However, it was rapidly dissipating at the same time; by 4 October, the front had entirely dissipated. Consequently, the front did not have any adverse effect on the weather conditions over Lake Ontario. During most of the period of analysis, the wind was generally weak and from the southwest. On the other hand, the 500 mb wind was westerly over Lake Ontario and vicinity at the beginning of the period. The wind backed rapidly with time as an intensifying trough approached from the west. At the end of the period, the 500 mb wind had become primarily southerly.

4. Description of the surface temperature field

The thermal contrast between the lake and the surrounding land areas is the fundamental cause of lake-induced perturbations on the prevailing atmospheric flow pattern. Therefore, it would be logical to describe the characteristics of the surface temperature field before those of the wind field. Fig. 6 shows the surface isotherm maps at three-hourly intervals, starting at 1 A.M. on 3 October 1972. Examination of the set of maps indicates that the isotherm patterns may be classified roughly into two different regimes—a morning regime and an afternoon regime. These two regimes are mainly a result of infra-red cooling and the short wave warming of the land surface in the morning and the afternoon, respectively. The characteristics of the morning regime are exemplified by the isotherm patterns for 4 A.M. (0400 LST). As expected for this time of day, the lake is warm relative to the surrounding land areas. The warmest surface temperature of 16° C is located over the lake near the northern shoreline, slightly northeast of the lake centre. There are strong horizontal temperature gradients in the vicinity of the northern shorelines. These strong temperature gradients are presumably due to the combined effects of radiative cooling of the land and horizontal temperature advection. In connection with the latter, one expects that a land breeze would develop over the northern coastal regions and advect cold land air toward the warm lake. At the same time, the prevailing southerly flow tends to advect warm lake air toward the same regions. The net effect of these two opposite advective processes is to produce strong horizontal temperature gradients over the northern coastal regions. The circumstances over the southern coastal regions are somewhat different. In these regions, both the land breeze and the large-scale wind blow toward the same general direction, *i.e.,* northward. Therefore, there is no significant confluence in the wind flow; consequently, no strong temperature gradients develop over the southern shorelines. Instead, there is a strong advection of cold land air over the warm lake. This process tends to shift the maximum temperatures from the centre of the lake towards the northern shore.

The afternoon temperature regime is typified by the isotherm map for 4 P.M. (1600 LST). In contrast with the temperature field for the morning regime, the lake at this time is relatively cold with respect to the surrounding land areas. The coldest temperature (14° C) is located over the western end of the lake. On the other hand, the warmest temperature is 24°C and is located at the southwestern coastal region near the northeastern end of Lake Erie. The occurrence of the maximum temperature in this particular location is somewhat surprising because it was expected that the entire southern inland region would be more or less uniformly warm with only minor horizontal variations in temperature. There appears to be no clear reason for the occurrence of this localized maximum temperature; it may be due to the fact that this region is relatively more urbanized than the areas to the east. North of this region of maximum temperature, we note a zone of strong temperature gradients which are primarily due to differential horizontal advection. Another region of relatively strong temperature gradients is located over the western coastal region, about 50 km northwest of the western tip of the lake. The weakest temperature gradients are located over the northeastern coasts of the lake.

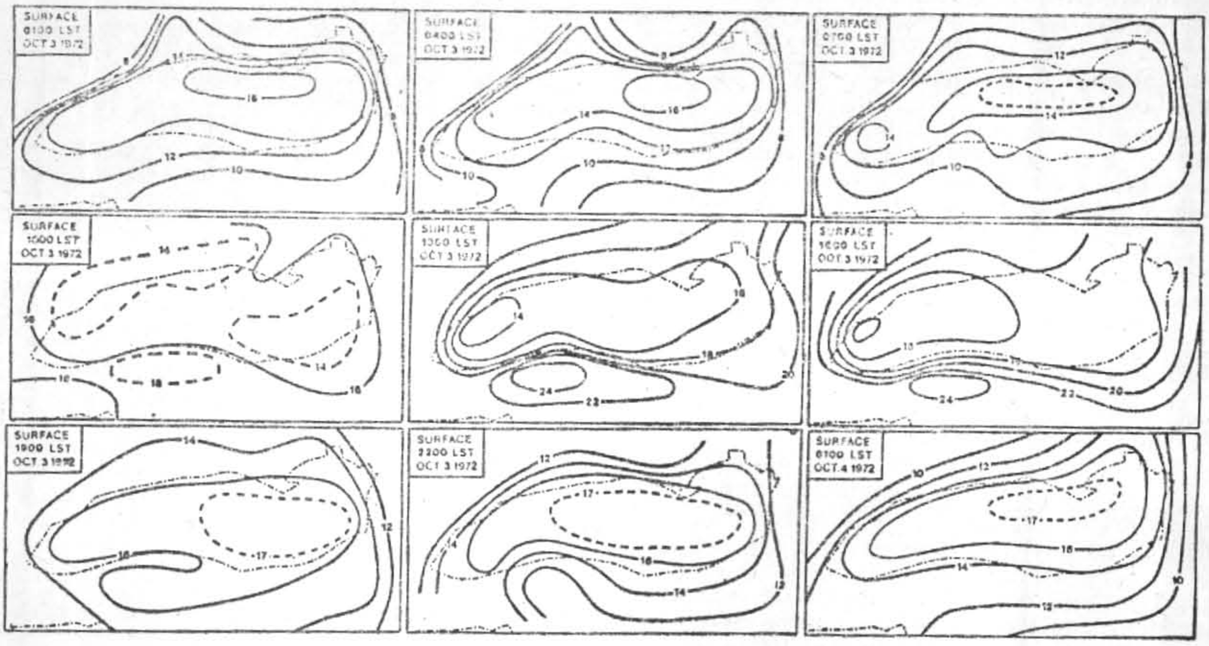

Fig. 6. The surface temperature (°C) distribution. Contour interval is 2°C

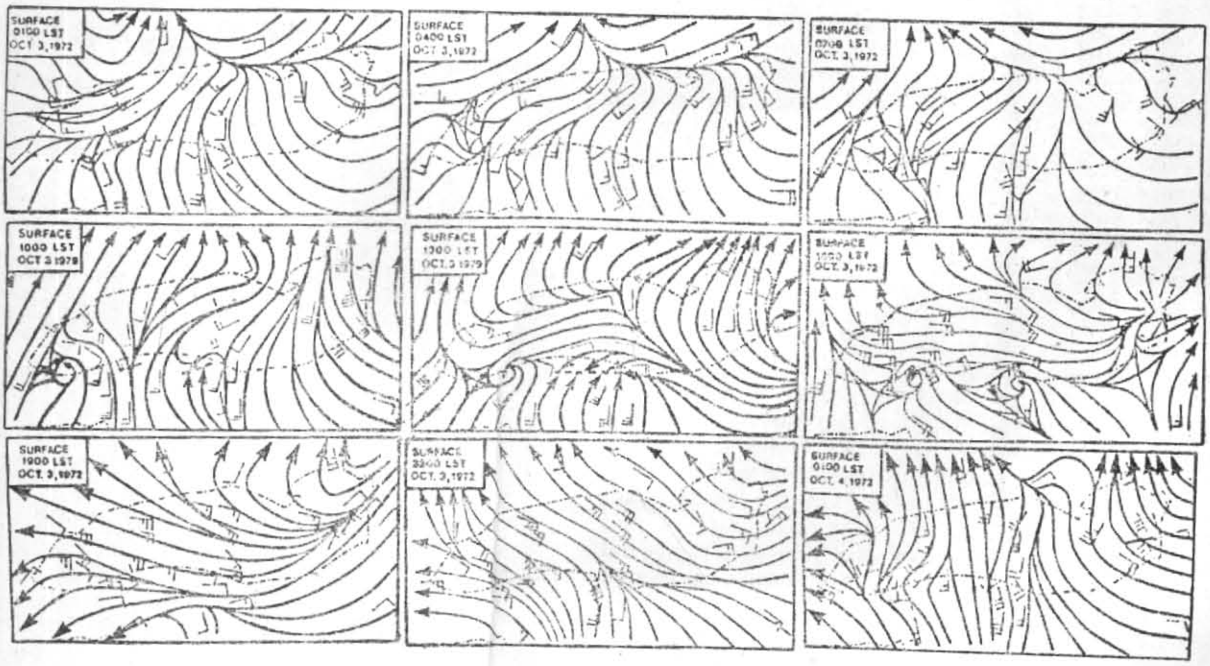

Fig. 7. Surface streanlines. Units : one full barb is 2 m s^{-1}

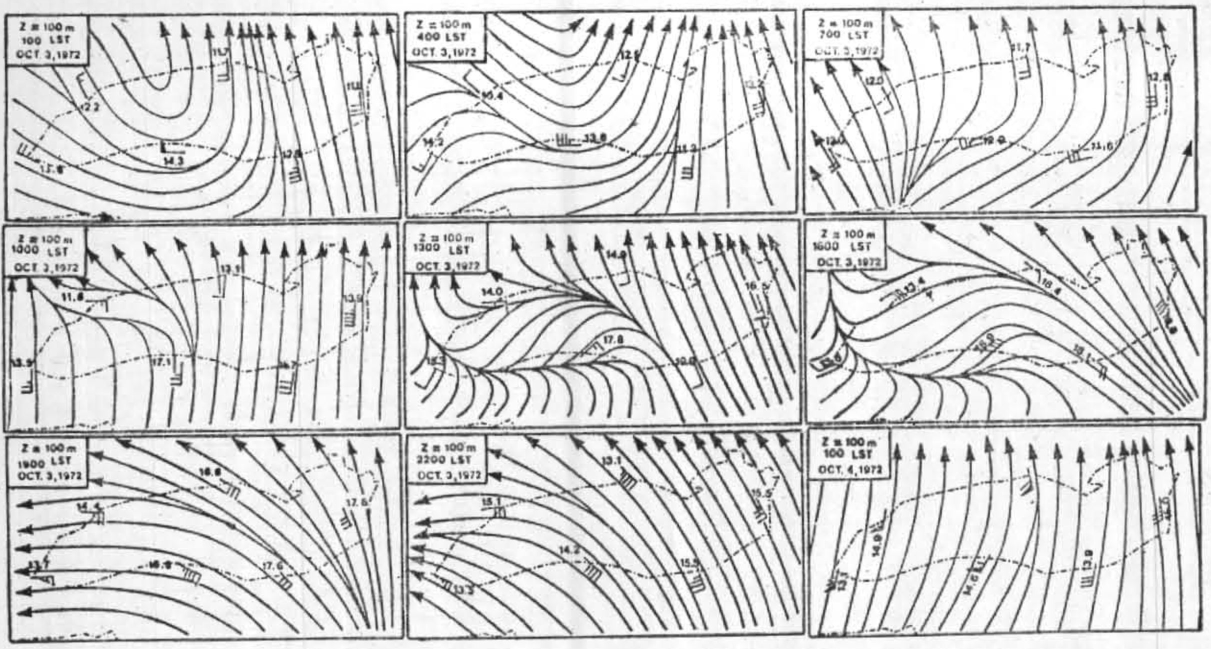

Fig. 8. Streamlines at 100 metres above the surface. Units : one full barb is 2 m s^{-1}. One flag is equal to 10 m s^{-1}

The period of transition between the two temperature regimes described above occurs just before 10 A.M. and before 7 P.M. Note that the temperature fields for these two times are characterized by relatively weak thermal contrasts between the lake and the land.

As mentioned previously, temperature observations were made also at upper levels by rawinsonde soundings. However, there were only six rawinsonde stations over the entire area. Since the number of observations is rather limited, isotherm maps were not drawn for levels above the surface. In order to give a general idea about the temperature variations at upper levels, we have plotted the observed temperatures on the appropriate streamline maps which are presented in the next section.

5. Description of the windfield

The results of the streamline analysis are shown in Figs. 7 to 10. The streamline maps are shown at three hourly intervals for the surface and for the next level above (100 m). For the rest of the upper levels (450 m and 2 km), the maps are presented only at six-hour intervals because the winds at these two levels are relatively less variable with time.

We turn our attention first to the surface wind variations which are shown in Fig. 7. As in the case of the surface temperature field, it is possible to classify the surface wind field into two general types — a morning regime and an afternoon regime. The former prevails roughly from 1 A.M. to 7 A.M. Since the lake is relatively warm during this period of the day, there should be a tendency for the flow to converge toward the lake, *i.e.,* a land breeze occurrence. Looking at the morning streamline maps and bearing in mind that the prevailing flow is southerly, we see some indications of this tendency. Thus, at the western and the eastern ends of the lake, the winds tend to have westerly and easterly components, respectively. Over the northeastern coastal regions, this tendency for land breeze development has resulted in the generation of a line of convergence between the prevailing southerly flow and the eastnortheasterly lake-induced flow. Over the northwestern shorelines, a distinct line of convergence does not develop. This is probably due in part to the occurrence of a mesoscale trough which appears to dominate the flow pattern over this section of the lake. This trough, a perturbation which is not induced by Lake Ontario, is well-defined on the 1 A.M. map at the 100 metre level. Over the southern coastal regions, both the land breeze and the southerly prevailing flow tend to blow from the south. The result is a relatively strong southerly flow over those regions and also over the middle of the lake.

After 7 A.M., the morning flow regime begins to break down as the sun heats the surrounding land areas and the land-lake temperature contrast disappears. At 10 A.M., the initial indications of lake breeze development are shown by a northeasterly wind at the shoreline east of lakeside and easterly winds near the western end of the lake. Further development of the lake breeze leads to the afternoon flow regime which prevails from 1 P.M. to 7 P.M. The streamline pattern for 1 P.M. shows the fully-developed lake breeze circulation. The flow is from lake to land over most of the shorelines. The most important exception is the southeastern shoreline where the lake breeze appears to be absent. There are no shoreline surface wind observations to confirm definitely the absence of a lake breeze. However,

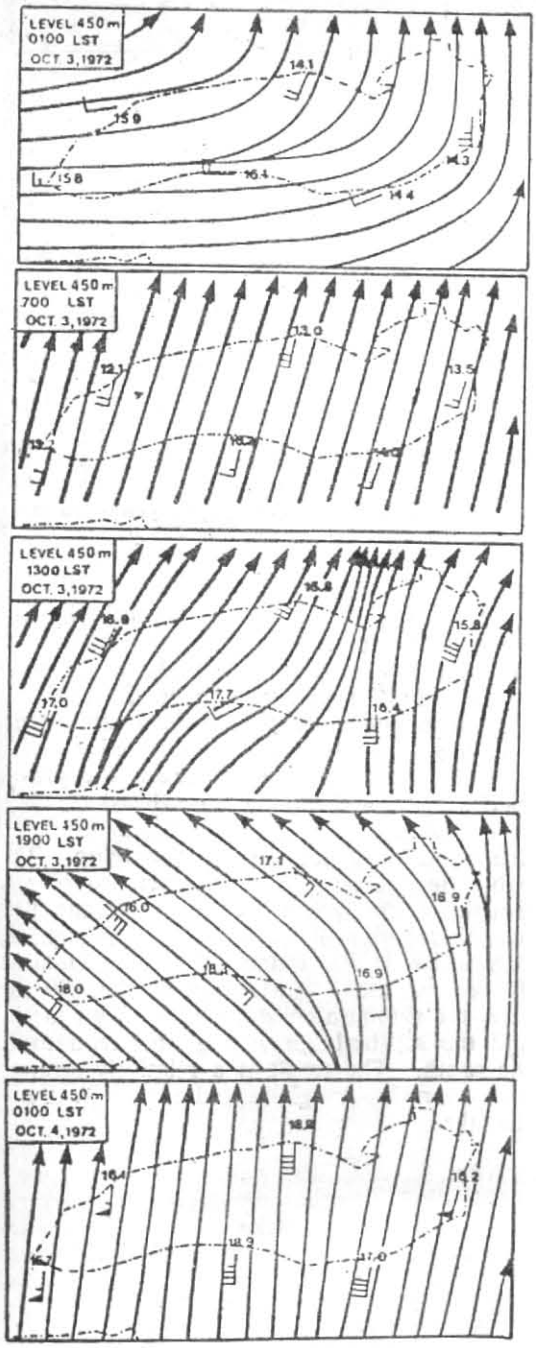

Fig. 9. Streamlines at 450 metre above the surface. Units : one full barb is 2 ms^{-1}; one flag is equal to 10 ms^{-1}. Numbers are temperatures in °C

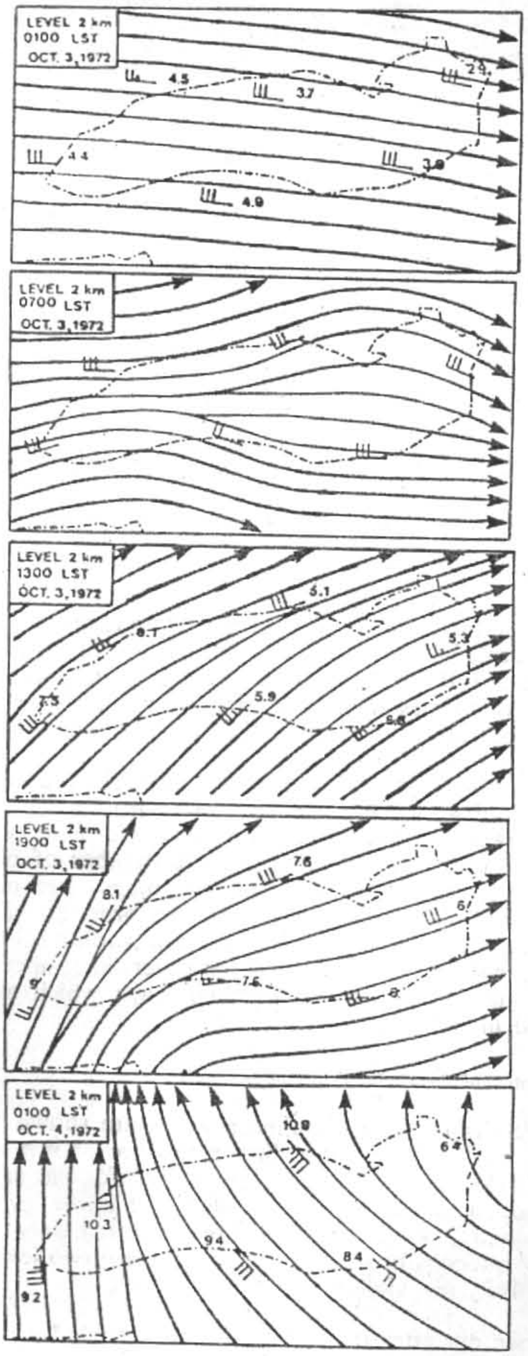

Fig. 10. Streamlines at 2 km above the surface. Units : one full barb is 2 ms^{-1}; one flag is equal to 10 ms^{-1}. Numbers are temperatures in °C

the 100-metre rawinsonde wind observation at Sodus Point at this time shows a southerly component, indicating the absence of a lake breeze. In contrast, the flow pattern over the southwestern shorelines is very different. Here a strong lake breeze convergence line has developed. At the same time, at the opposite (northwestern) side of the lake, a divergence line has formed. This divergence line, together with the convergence line to the south, suggests a vertical circulation with strong ascending and descending motions over the southern and the northern coastal regions, respectively. Another important feature of the afternoon regime is the development of an easterly flow over the lake. The easterlies form initially over a small area at the western end of the lake in the late morning. This area of easterlies gradually expands eastward and southward with time as the lake breeze circulation develops. By early evening (7 P.M.) the easterlies have expanded to such an extent that they prevail over the entire lake as well as over the southern coastal regions. Subsequently, the easterlies veer with time. The most rapid veering occurs over the southern coastal regions; at 10 P.M., the winds over these regions have returned to the prevailing southerly flow. The complete return to the prevailing general flow over the lake occurs about 3 hours later (1 A.M.). Note the striking similarity between the flow pattern at these times with that twenty-four hours earlier (1 A.M. of 3 Oct) despite the large differences between the corresponding flow patterns aloft at the 2-km level. This similarity indicates a high degree of diurnal periodicity in the surface flow pattern which is a result of the diurnal variation in the surface temperature field.

We now consider the flow pattern at the 100-metre level (Fig. 8). The wind field at 1 A.M. for 3 October shows an unusual feature — a mesoscale trough over the western section of the lake. On the basis of its previous history, it appears to be unrelated to the lake-land breeze circulation induced by Lake Ontario. The trough is confined mainly within the first kilometre of the atmosphere. Before this time, it has been moving slowly eastward and weakening in intensity. Six hours later, it has almost entirely dissipated and the flow pattern has become predominantly southerly like the large scale prevailing flow. As it has been noted in the discussion of surface wind distribution, the initial stages of the lake breeze is indicated by turning of the wind from southerly to easterly flow near the western end of the lake. A similar indication is shown at 100-metre level by the wind at Scarborough for 10 A.M. After this time, the general flow pattern changes suddenly as the lake breeze circulation intensifies rapidly. At 1 P.M., the flow pattern at this level has acquired characteristics which are very similar to those of the surface flow pattern. Thus, there is a convergence line over the southern shoreline and divergence over the opposite northern shoreline over the western half of the lake. In addition, the easterlies increase with time, both in intensity and areal coverage. Note the predominantly easterly flow at 7 P.M. The wind subsequently veers with time and by 1 A.M. of 4 October, the flow pattern has reverted to the prevailing southerlies over the entire region.

Next, we present the streamline maps for the 450-*metre* level (Fig. 9). In general, the pattern at this level represents a transition between the southerly flow and the upper level westerly flow. The first map, corresponding to 1 A.M. of 3 October, shows a weak trough which is simply an extension of the mesoscale trough at lower levels. As noted previously, this trough dissipates during the next six hours. At 7 A.M. no trace of the trough is evident and the flow pattern has returned to the prevailing southerly flow. It continues to be relatively unperturbed for the next six hours. After 1 P.M., however, a backing of the wind occurred; six hours later (7 P.M.), the winds are generally from the southeast. This backing is simply a weak extension of similar wind changes associated with the development of the easterlies at lower levels. The flow from the southeast is only short - lived ; six hours later at 1 A.M. of 4 October, the flow has gone back again to the prevailing southerly flow.

Finally, we present the flow pattern at the 2-km level. The flow at this level is relatively unaffected by the lake. Therefore, it represents approximately the large-scale prevailing flow at upper levels as indicated by the 500 mb maps in Figs. 4 and 5. Consistent with Fig.4, the streamline maps show that the winds are generally westerly during the first six hours of the 24-hour period. As the intensifying upper trough approached lake Ontario from the west, the wind gradually backed with time. Near the end of the twenty-four hour period, the wind had acquired southerly components throughout the entire region.

5. Summary and concluding comments

In this section, we will, discuss some of the unusual features of observed lake-induced circulation. The unusual features can be deduced by comparing the observed circulation described above with a corresponding picture which would be expected from previous studies, both observational as well as theoretical. Exemples of some pertinent studies are those by Estoque (1962), Neumann and Mahrer (1974), and Lyons and Olsson (1973). On the basis of these studies and assuming that the prevailing wind is identically zero, we have the the following picture of the diurnal flow variation. During the night time and the early morning when the lake is relatively warm, the solenoidal field will accelerate the surface air toward the lake. Therefore, a land breeze develops. Since this flow is inherently nongeostrophic, the coriolis effect will tend to produce a local veering of the wind with time. Consequently, the overall surface flow pattern around the lake during this period of the day would be roughly elliptically-shaped, convergent, cyclonic. A convergence line will tend to develop offshore, parallel to the coastline. The strongest convergence and cyclonic curvature will develop over the western and the eastern ends of the lake. Near the end of the period, westerlies and easterlies will prevail over the southern and the northern coastal regions, respectively.

During the late morning and afternoon, the solenoidal field is reversed and a lake breeze develops. The circulation over the lake becomes divergent and anticyclonic; a lake breeze front develops inland. At the end of the period, the local veering of the wind due to the coriolis acceleration will produce westerlies and easterlies over the northern and the southern shoreline areas, respectively.

If the prevailing flow is southerly instead of being calm, the lake-induced circulation described above would be modified due to horizontal advective processes. The southerly prevailing flow will tend to displace the circulation patterns northward and also to produce some distortions. For example, during the early morning hours, the land breeze front offshore over the northern portion of the lake would occur inland and would be more intense. On the other hand, during the afternoon the prevailing flow will tend to decrease the inland penetration of the lake breeze over the southern coastal regions. In addition, the prevailing southerlies will intensify the associated lake breeze front. Over the northern coastal regions, the prevailing southerlies will tend to inhibit the development of a strong lake breeze front; moreover it will tend to advect the front northward. Finally, the general displacement of circulation patterns by the prevailing southerlies would displace the easterlies over the southern coastal regions northward toward the lake centre. It is interesting to note that such an occurrence of the easterlies over the lake has been predicted by a two-dimensional model (Estoque *et al.* 1976).

Comparing the expected circulation patterns for the case with southerly prevailing flow described above with the actually observed lake-induced patterns, we note some similarities between the two. Notable among these are the following :

(1) The tendency for development of convergence lines over certain sections of the northern shorelines in the morning and over the southern shorelines in the afternoon,

(2) The occurrence of divergence over the lake in the afternoon, and

(3) The occurrence of easterlies over the lake in the late afternoon.

However, there are also discrepancies. Some of the more important observed features which are rather unexpected are :

(1) The apparent lack of well-defined land breeze convergence line during the early morning hours over the northwestern coastal region,

(2) The non-occurrence of a lake breeze in the afternoon over the southeastern coastal region and the persistence of anticyclonic flow over the same region and over the eastern end of the lake,

(3) The tendency for the development of small vortices along the lake breeze front over the southwestern shorelines,

(4) The initial formation of an area of easterlies over the western end of the lake in the morning and the gradual extension of this area eastward and southward in time.

The above discrepancies are presumably due to the complicated configuration of the coastline and also the horizontal nonuniformities in the orographic features. The two major departures are those which are associated with presence of Lake Erie and the nonuniformity of the terrain elevation. Both of these must produce major distortions in the lake-induced circulation. We have studied these distortions theoretically with the aid of a numerical model. In addition, we have used the model to analyze other physical processes which are important in determining the characteristics of the lake breeze. The results of the theoretical studies are presented in a complimentary article (Estoque and Gross 1980).

Acknowledgements

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