NOTES AND CORRESPONDENCE

A Simulation of Lake Michigan's Winter Land Breeze on 7 November 1978

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ABSTRACT

A two-dimensional mesometeorological model was originally constructed by Alpert *et al.* to simulate the summer air circulation in the area between the eastern Mediterranean waters and the Golan Heights involving en route Lake Kinneret (the Sea of Galilee). In this study the same model is applied to the case of the nocturnal circulation across southern Lake Michigan. The case simulated is for a wintry day in November 1978, the data for which were documented in a recent article by Passarelli and Braham.

The results of the simulation are very encouraging. Particular mention should be made of the fact that the predicted location of the maximum upward velocities close to the Wisconsin shore of Lake Michigan and the associated lake-breeze front at the convergence zone of the lake breezes of the opposite shores are well predicted by the model. The observed land-breeze front was accompanied by the development of snow bands. The main purpose of this study is to demonstrate that a computationally inexpensive two-dimensional model can adequately simulate coastal flows like that of Lake Michigan in the present study, making it a potentially useful forecasting and diagnostic tool. It was our intention as well to test the same model (physics and numerics) with a different lake-circulation problem. Despite the great differences in the physical characteristics of topography, size and meteorological conditions of the two lakes to which the model was applied (in the Lake Kinneret case, it is the lake which is cooler than the surrounding hot summer air of the Jordan Valley while in the Lake Michigan case it is the relatively warm lake which contrasts the polar air mass). However, in both cases the forcing is similar (10–15°C); it was found to do reasonably well. On the more theoretical side, this numerical study presents the first example of a strongly developed land-breeze front.

1. Introduction

During the past decade a considerable number of models were constructed to represent quantitative aspects of mesometeorological circulation systems. The systems represented by these models were such flow situations as sea and land breezes (e.g., Neumann and Mahrer, 1971; Pielke, 1974; Anthes and Warner, 1978), flow over complex terrain (e.g., Mahrer and Pielke, 1975; Klemp and Lilly, 1978; Nickerson, 1979), air circulation over lakes (Neumann and Mahrer, 1975; Estoque and Gross, 1981) as well as problems of pollution, formation of clouds, thunderstorms, etc.

The models were developed usually with a specific flow situation in mind, such as sea and land breezes along a straight coast or over a peninsula. An important question arising from the multiplicity of models is how well these models describe flow situations which differ greatly from the specific flow problem for which the model has been designed. This question is all the more pressing as in most cases there is no escape from a small or large measure of empiricism, especially in the formulation of the subgrid physics, in order to make the model simulate the mesometeorological circulation contemplated as well as possible.

In a recent paper the present authors and two colleagues of theirs (Alpert *et al.*, 1982) constructed a mesometeorological model designed to simulate the summer circulation from the eastern Mediterranean past Lake Kinneret in the Jordan Valley. The same model is applied here to study the land breezes of Lake Michigan, or to be more precise, to simulate the convergent land breezes of the southern basin of this lake on a particular day described in a recent paper by Passarelli and Braham (1981). An especially interesting feature of the case is a marked land-breeze front on the west side of the lake. This case is all the more interesting as land-breeze fronts hitherto described in the literature are underdeveloped compared with sea-breeze fronts.

The complex topography about Lake Kinneret was

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described in Alpert *et al.*; the land in the vicinity of Lake Michigan can be approximately considered to be level. (This approximation is discussed intensively in Section 3.) However, the differences between the two lakes go far beyond. Over and above the differences in size (and latitude), the seasons and temperature levels involved, both the air and lake waters differ considerably. In the case of Lake Kinneret we have simulated summer conditions with the lake-surface temperature about 27°C and air temperatures of the Jordan Valley up to about 39°C; in the case of Lake Michigan, we deal with a wintry day in November where the lake surface temperature was about 10°C while the air temperatures of the surrounding land vary between about −5 to 5°C (see Fig. 1).

For reasons of limitations on computer time the model is two-dimensional and involves the sigma-coordinate system. Moreover, it simulates a dry flow. The vertical turbulent transports are calculated through a high-resolution boundary-layer formulation due to Blackadar (1978). Turning to the numerical side, a very accurate advection scheme by upstream cubic spline interpolation is adopted as shown, for example, in a paper by Mahrer and Pielke (1978). Explicit horizontal diffusion has been replaced by a highly selective low-pass filter proposed by Long *et al.* (1978). Marchuk's (1974) method of splitting was applied to enable us to use an efficient implicit method for the vertical diffusion terms. The numerical grid consists of 65 points in the horizontal with a constant spacing of about 8 or 4 km and 10 levels in the vertical at altitudes of about 10, 20, 40 and up to 2500 m above the surface.

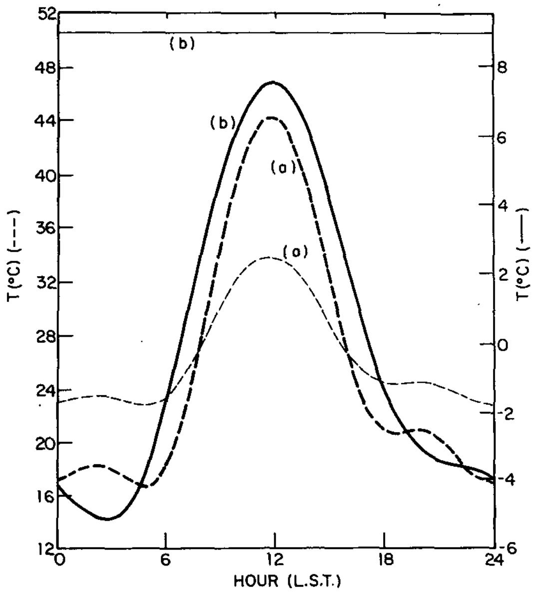

FIG. 1. Diurnal variation of the input surface-temperature (°C) for land and lake. a) Lake Kinneret case; b) Lake Michigan case. Thick and thin lines correspond to land and lake respectively. The scale to the right is for case (a), whereas the scale to the left is for case (b). The secondary maxima correspond to the 4th harmonic which has been included in case (a).

Thus, the goal of this study is to test the capability of our two-dimensional model which was constructed for the Lake Kinneret simulation to simulate in a realistic manner a different lake-circulation problem—the winter land breeze of Lake Michigan. A particularly interesting case on 7 November 1978 is described in the following section. In Section 3 the simulation for that case and the results are discussed in view of the observations. In the last section we compare the input parameters for the two different lake-circulation problems for which the model was applied and discuss the usefulness of the two-dimensional model.

2. Lake Michigan's winter land breezes

Recently Passarelli and Braham (1981) described some cases of snow bands over Lake Michigan, exploiting radar and aircraft data. They concluded that the winter land breezes from one or from both shores of the lake have an important role in organizing low-level convergence and convective motions leading to precipitation. Hsu (1981) has studied the influence of the large-scale pressure gradients on the lake-snow formation by initialization with idealized winter conditions. He, as well as Ballentine (1981), applied a full three-dimensional model including moisture to learn how the boundary-layer processes and the large-scale gradients drive the circulation resulting in snow-band formation.

Motivated by the Passarelli and Braham's (hereafter PB) well-documented study and by their suggestion that a simple land-breeze model is an excellent aid for forecasting the occurrence of shore-parallel snow bands, we have decided to apply our two-dimensional model to their case study of 7 November, 1978. In Fig. 2 (Fig. 1 in PB) which is the surface synoptic map for that day, a high-pressure ridge extends from Lake Michigan to Texas. Reported lake-surface temperatures were ~10°C while land air temperatures were 0 to −6°C at 1200 GMT (0700 LST). This ~10 to 15°C lake-land temperature difference, coupled with the weak northeasterly to northwesterly winds at the surface, made this morning ideal for studying the land breezes. The higher level flow, represented by that at 850 mb at 1200 GMT, is shown in Fig. 3. The charts indicate that the Lake Michigan region is characterized by northwesterly winds associated with a polar outbreak of cold air. Fig. 4 (Fig. 2 in PB) is a cross section of wind and temperature along the aircraft flight track in the early hours of the morning (~0500 LST). The figure shows the wind and temperature fields which resulted from two land breezes that were formed during the night—one from each of the two opposing shores—subject to the large-scale pressure gradient. As noted

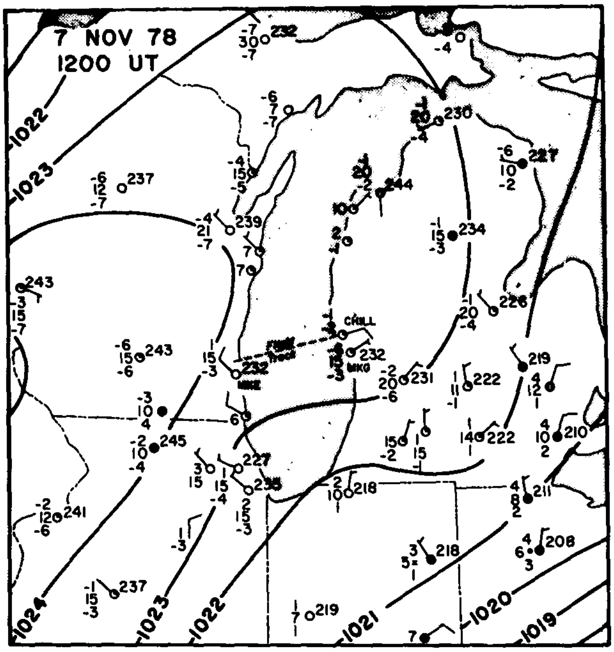

FIG. 2. 7 Nov. 1978 surface observations at 1200 GMT for the Lake Michigan region, North America. Wind barbs in all figures are in 5 kt increments. All temperatures are in degrees centigrade and pressures are contoured in millibars. The dashed line indicates the location of the aircraft passes. From PB—Fig. 1.

by PB, the Michigan land breeze is nearly easterly and reaches a maximum velocity of 7.5–10 m s^{-1} whereas the Wisconsin land breeze, opposed by the large-scale pressure gradient, turns to a weak northwesterly wind. These breezes moved offshore, and ultimately collided to form a relatively strong convergence zone near the Wisconsin shore. Note the upper-level divergence above the low-level convergence. Other interesting features are 1) the modification by the lake of the very cold air mass from the land, a modification that is indicated by a large slope of the potential temperature from east to west, and 2) the relatively stable layer near the lake surface on the Wisconsin side. These are some of the key observational features that should be simulated by the model. Of course the model can provide, at least in this case, a more complete temporal description of the circulation than can be obtained from observation. It is important to note that the simulation of the dry fields preceding the formation of the snow bands are, in fact, the interest of this study. The convergence associated with those fields should certainly lead to cloud formation if allowance is made for sufficiently moist conditions. We believe, however, that it is only at the latter stages that the role of moisture and the latent heat release associated with it become essential. Of course, the moisture and latent heat release have an important influence especially with respect to heat fluxes, water-surface temperature and low-level stability, but we believe that at the first stage (no clouds) their exclusion will not affect the main results in a significant manner.

3. The Lake Michigan simulation—7 November 1978

For the initial temperature profile of that day, the Green Bay, Wisconsin sounding for 1200 GMT was

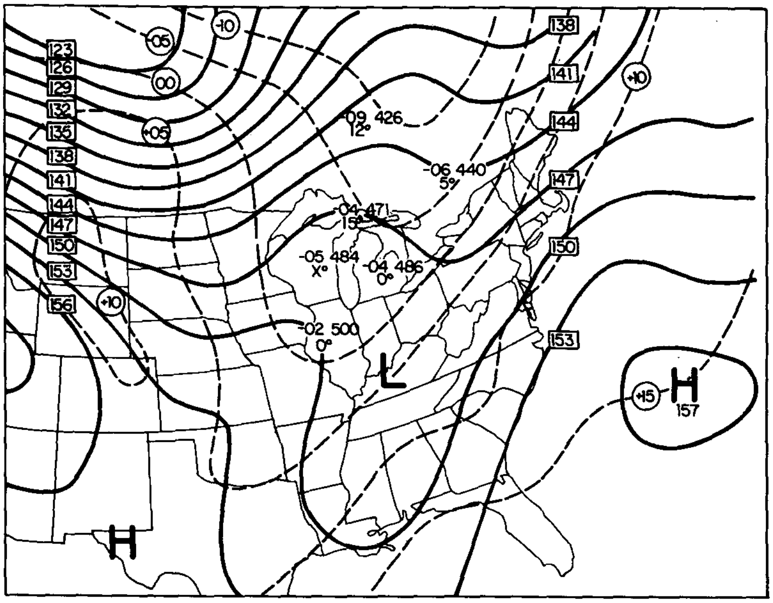

FIG. 3. 850 millibar chart for 7 Nov. 1978 1200 GMT from the NMC analysis.

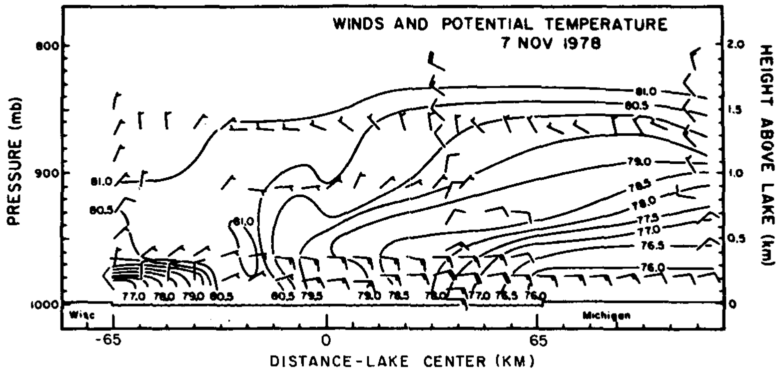

FIG. 4. East–west cross section of horizontal wind and potential temperature (K) along the flight track of 7 November 1978. The leading digit in 2XX.X is deleted in all potential temperature labels. The terrain and lake are schematic. The flights were performed between 1000 and 1200 GMT (0500 and 0700 LST). From PB—Fig. 2.

chosen (see PB Fig. 3), while the wind distribution is that reported upwind of Lake Michigan. For surface temperature we adopted the same curve as in Alpert *et al.* (1982) where only the amplitudes and phases of the harmonics were modified to fit temperatures for the Lake Michigan region. For the detailed winds as-

TABLE 1. Comparison of input parameters for the two lakes.

	Kinneret Summer circulation	Michigan 7 Nov. 1978—case study	
	Average summer sounding	*Green Bay sounding*	
Lapse-rate	$\Gamma = -6.5°\text{C km}^{-1}$	-8.5 to $-7.5°\text{C km}^{-1}$	
Inversion thickness	$\Delta p = 930\text{–}900$ mb	880–850 mb or none	
	Surface temperatures (°C)		
Lake-land maximum difference	$\Delta T \simeq 13$ *by day*	$\simeq 16$ *by night*	
Lake surface temp.	$T = 27 \pm 4$	$\simeq 8.5$	
Temperature amplitude (inland)	$\Delta T = 28°\text{C}$	$\simeq 15$	
Lake's width	$L \approx 3\Delta X$	$\approx 25\Delta X$	
	Average summer conditions	*Upwind Lake Michigan (m s^{-1})*	
Wind associated with large-scale pressure-gradient	$(u_g, v_g) = (3, -1)\ \text{m s}^{-1}$	Exp. 1 and 2	Exp. 3
		(−2, 0)	(−2, 0) at ∼10 m above lake
		(−3, 0)	(−3, 0) at ∼18 m above lake
		(−5, 0)	(−5, 0) at ∼30 m above lake
		(−5, 0)	(−5, 0) at ∼56 m above lake
		(−6, 0)	(−6, 0) at ∼100 m above lake
		(−5, −1)	(−5, 0) at ∼180 m above lake
		(−3, −3)	(−3, 0) at ∼330 m above lake
		(−1, −3)	(0, 0) at ∼580 m above lake
		(+1, −3)	(0, 0) at ∼1050 m above lake
		(+2, −5)	(1, −3) at ∼1900 m above lake
	Topography		
Maximum slopes	α = up to 4°	= 0.03°	
Horizontal grid distance	$\Delta X = 4000$ m	Exp. 1, 2 = 8160 m ≈ 0.1° longitude Exp. 3, 4 = 4080 m	
Coriolis parameter	$f = 0.73 \times 10^{-4}\ \text{s}^{-1}$	$= 0.98 \times 10^{-4}\ \text{s}^{-1}$	
Filter* parameter	$\delta = 0.05$	= 0.03	

* The parameter δ is defined through the following implicit filter $(1-\delta)\bar{\Phi}_{i-1} + 2(1+\delta)\bar{\Phi}_i + (1-\delta)\bar{\Phi}_{i+1} = \phi_{i-1} + 2\phi_i + \phi_{i+1}$ where $\bar{\Phi}_i$ and ϕ_i are the filtered and unfiltered fields respectively at the i-th point.

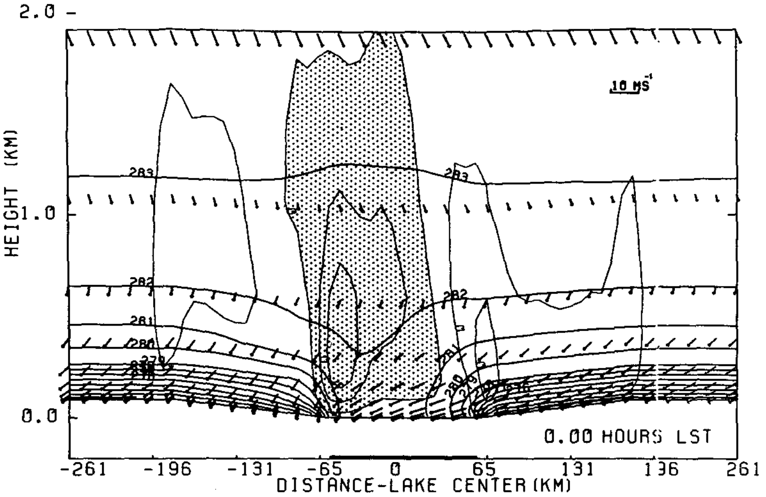

FIG. 5. Horizontal winds (m s^{-1}, arrows), vertical winds (cm s^{-1}) and potential temperatures at 0000 LST (8 hours of simulation). Arrow bases are fixed at the level which they represent. Directions of arrows to the right represent pure westerly winds, whereas the upward direction indicates southerly winds. Location of Lake Michigan is illustrated by the wider lower line. Horizontal wind scale is introduced in the upper corner on the right. Contour interval for vertical velocity is 0.5 cm s^{-1}. Horizontal grid spacing is 8160 m (~0.1° of longitude). Upward motion areas larger than 0.25 cm s^{-1} have been shaded.

sociated with the large-scale pressure gradient and the surface temperatures. See Table 1 and Fig. 1.

The experiment was started at 1600 LST for which time we could reasonably assume that the land and lake surface temperatures are equal. The horizontal grid spacing is 8.16 km (equivalent to ~0.1 longitude). Figs. 5 and 6 show the two-dimensional cross-sections of potential temperature, horizontal wind and vertical velocity at 0000 and 0400 LST (8 and 12 hours of simulation). At midnight, Fig. 5, the land breezes are relatively weak. They can be observed in the form of weak northerly winds near the Wisconsin coast but quite easterly on the Michigan coast and even far offshore. This is probably due to the weak easterly large-scale pressure-gradient near the surface which supports the Michigan land-breeze but opposes the Wisconsin land-breeze. The maximum easterly offshore winds on the Michigan coast are ~5 m s^{-1}, yet the upward cell of vertical velocities near the Wisconsin coast can already be noted with the maximum value being about 1 cm s^{-1}. Four hours later the convergence zone is more intense as can be seen

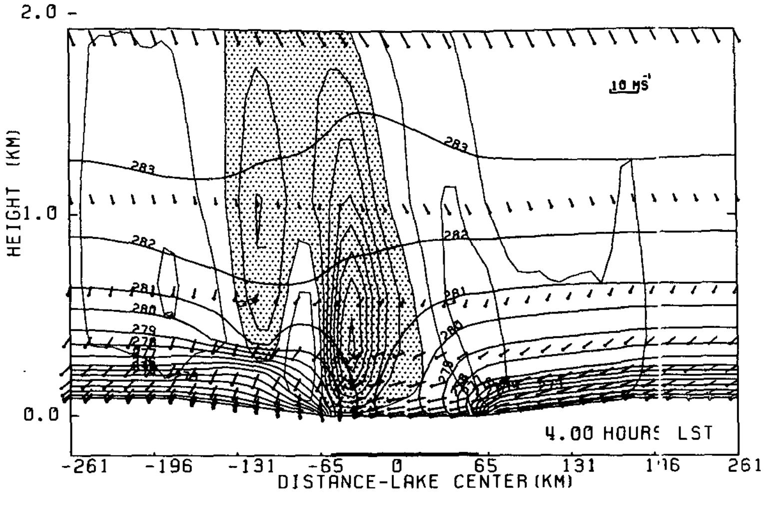

FIG. 6. Same as Fig. 5 at 0400 LST (12 hours of simulation).

in Fig. 6. The easterly offshore Michigan land breeze advanced towards the lake center and is now 6–7 m s^{-1}; light northwesterly winds developed near the Wisconsin coast where the vertical velocities are now 3 cm s^{-1}. Another feature of the circulation is the tilt of the upward motion cell which is probably the result of the large-scale wind shear. That tilt is already noticed at 0000 LST and becomes stronger at 0400 LST when, in fact, a secondary cell of upward velocities appears above the Wisconsin shore. It is the higher level return current of the Wisconsin land breeze interacting with the large-scale wind which probably leads to the formation of this secondary cell. Of course, the same cannot happen on the Michigan shore since the return current there joins the large-scale wind; compare the wind at the level of ~1 km in Fig. 6. The large-scale is also the reason for the asymmetry of the downward cells. The eastern cell is partly above the lake while the western cell is thoroughly above the Wisconsin shore.

In this experiment we made allowance for the gentle slope of the terrain, viz. up to 90 m elevation at a distance of 100 km from the lake, as noted in Fig. 5 and 6. But in repeating this experiment without topography only small changes were noticed—see Fig. 7. First, the maximum upward velocities above the lake decreased by 10–15%. However, the downward cell on the Michigan coast became slightly stronger and, also, it shrank to a horizontal scale comparable to the lake's width—around 100 km. The larger horizontal scale of this downward cell found in the previous experiment—see Fig. 6 as compared to Fig. 7—is explained by the enhanced horizontal velocities downslope. The stronger downslope wind strengthens the subsidence above the slope, the downward cell expands and reaches the top of the eastern slope. There is also some weakening of the downward cell on the Wisconsin (western) shore and a small movement towards the west of the secondary upward cell in the case topography is present. The presence of the slope strengthened the horizontal velocity far onshore and gave rise to an enhanced secondary convergence zone at some higher altitude where the return current was established. These small changes are also reflected in the thermal structure and particularly in the 281°K curve on the western coast. In the next higher resolution experiments level topography was assumed. That was primarily because with the higher resolution the slopes hit the lateral boundaries unless the horizontal region is increased. And, this increase was avoided from reasons of limited computation time.

In a third experiment we reduced the horizontal grid to half (about 4 km). We can see the results of the reduction in Fig. 8 for 0400 LST. As anticipated, the vertical velocities are now higher. In this experiment, we also reduced the weak large-scale gradient to zero at the levels of divergence—see Table 1. This was done in order to examine the divergence zone over the surface convergence zone. Of course, these zones of convergence near the surface and the divergence at the level of ~1000 m right above the left half of Lake Michigan are now clearly illustrated. Moreover, it is interesting to note the change in the Michigan land breeze, that is especially noticeable near the lake center. The winds are now nearly easterly as compared with the more northerly direction in the previous figures. This probably suggests that the higher resolution in Fig. 8 must have been responsible for that. It is the higher resolution which enables us to look at points offshore which are numerically far enough from the coast effect. Notice the slightly northerly winds onshore and near the coast which turn to nearly easterly offshore.

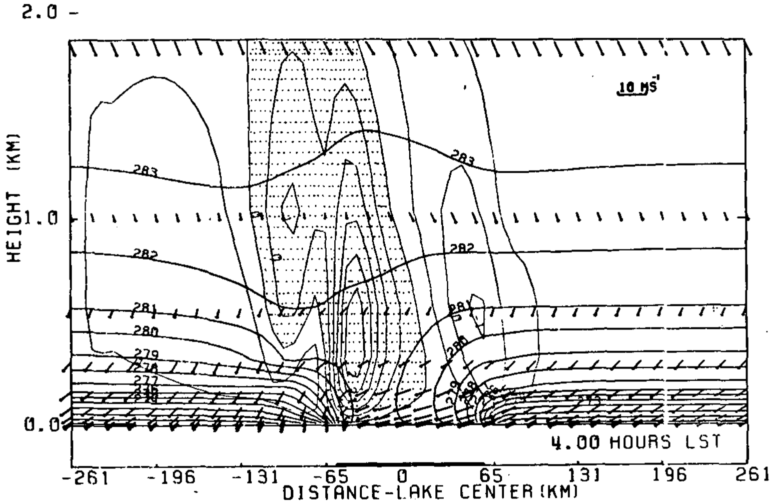

FIG. 7. Same as Fig. 6 but without topography.

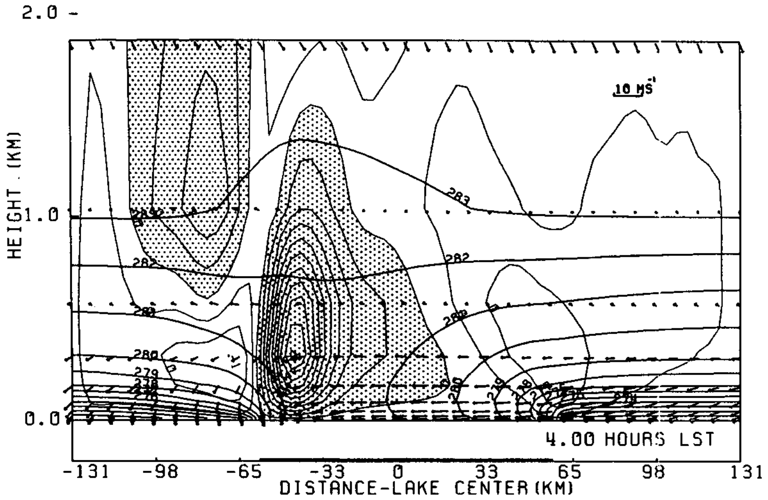

FIG. 8. Same as Fig. 7 except with a grid distance of 4080 m (~0.05° of longitude) and zero large-scale gradient for levels of divergence—see Table 1.

The results for 0800 LST are shown in Fig. 9. At this hour the maximum easterly winds reach 9 m s^{-1} and the vertical velocities 6 cm s^{-1}. By that time the research airplane had already landed but Milwaukee was reporting "TCU NE–SE OVR LK"[2] and the visible satellite photograph three hours later showed a N–S line of clouds well defined on the lake's western side but more diffuse on the eastern side. See Fig. 10 which is identical with Fig. 4 in PB. It is suggested that the sharp boundary between the cells of upward and downward velocities east of Milwaukee, in contrast to the diffuse boundary above the lake center, explains rather clearly the picture in Fig. 10.

In comparing the observed and simulated temperature distributions, some discrepancies between the two should be noted. (Figs. 6 to 8 and Fig. 9 corresponding to 0400 and 0800 LST respectively represent the simulated fields which will be compared to the observations performed by the flight between 0500 and 0700 LST, Fig. 4.) First, although the slope of the potential temperature from east to west is simulated (see 280°K curve in Fig. 9), the simulated slope is gentle compared to observations (see 280°K curve in Fig. 4). This is especially noticed near the coast and inland and it is caused by the more stable land-air above the Michigan shore in the simulation. Also, the relatively stable layer near the lake surface on the Wisconsin side is weakly simulated. These show clearly the limitations of initializing with a single sounding.

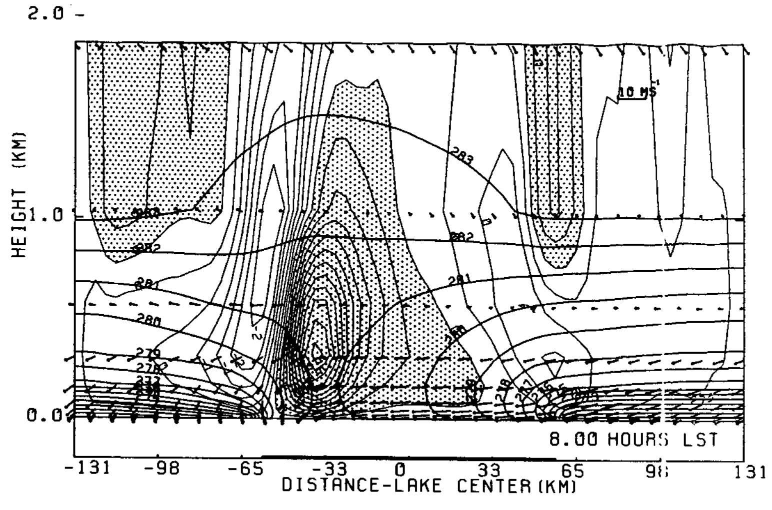

FIG. 9. Same as Fig. 8 at 0800 LST.

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[2] i.e., "Towering CUmulus North East–South East OVeR LaKe".

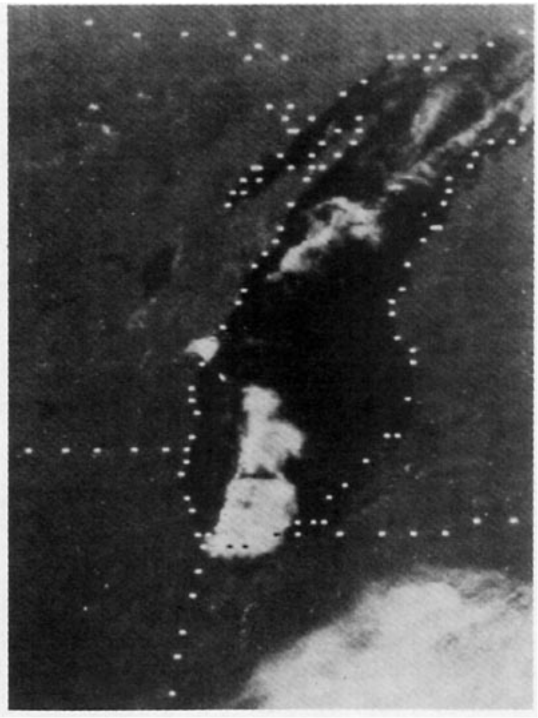

FIG. 10. 7 Nov. 1978 1601 GMT GOES-East visible photograph of Lake Michigan region. From PB—Fig. 4.

On the other hand, the location where the cold air is modified to the relatively warm lake temperature of 281°K is simulated quite well (see Fig. 9). Also, notice that the convectively unstable layer near the lake surface which grows gradually from the east coast to a maximum depth of 300 to 400 m at about 25 km west of the lake center, is quite well simulated, compare Fig. 4 to Fig. 9.

In a fourth experiment, where the large-scale pressure gradient was put to zero, the circulation picture becomes completely symmetrical with the center of convergence exactly above the lake center. Obviously, this could not have been the case if we had assumed different surface temperatures on the two shores. The results for 0400 LST are shown in Fig. 11. They indicate that the two primary factors which have to be considered when trying to forecast the snow bands above Lake Michigan are: a) the surface-temperature difference between lake and land for the two shores and b) the vertical profile of the large-scale pressure gradient. Both factors introduced into a 'simple'[3] two dimensional model might help the forecaster to prepare a first-order forecast for the location and intensity of possible snow bands, should any be anticipated, already in the evening before the snow-band event. We expect that a grid of 30 horizontal points with 4 to 6 levels might do the work on a small computer and run in a reasonable time.

4. Summary and conclusions

A two-dimensional model was applied to the simulation of air circulation over Lake Michigan. The results of the simulation for the 7th of November 1978 are very encouraging. Particular mention should be made of the fact that the predicted location of the maximum upward velocities close to the Wisconsin shore of Lake Michigan and the associated lake-breeze front at the convergence zone of the lake breezes of the opposite shores are well predicted by the model.

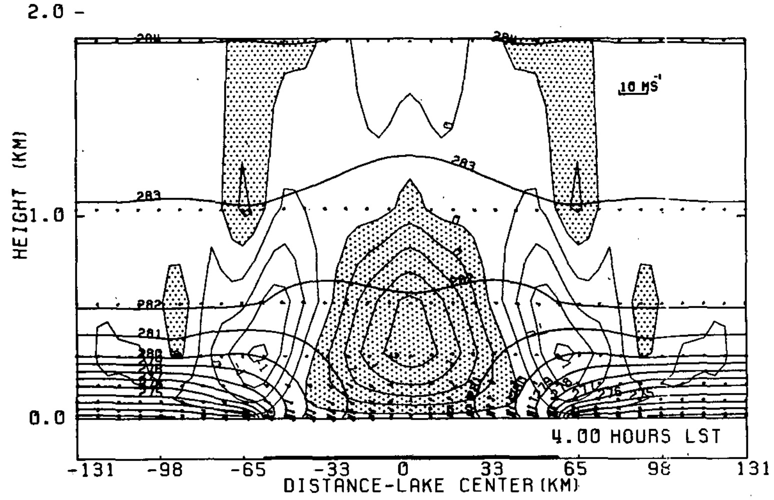

FIG. 11. Same as Fig. 8 except with zero large-scale pressure-gradient.

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[3] Simple in the sense that no moisture conditions need to be considered for forecasting the circulation *preceding* the formation of snow bands. Further, simple surface temperature estimates are the main forcing and no radiation calculations are included.

The same model was previously applied to Lake Kinneret whose physical and meteorological conditions differ greatly from that in the present study. Table 1 lists the parameters used as input in the two studies. These are the only changes needed in order to turn from the case of circulation over Lake Kinneret to that of Lake Michigan.

As was previously stated, the results of the simulations are encouraging and in view of this it is suggested that the model constructed has the capability of simulating the circulations over different lakes including the case of modification by the lake of a cold air mass influenced by a changing large-scale pressure gradient with height, and a small lake with steep topography about the lake, with sea and lake breezes etc. The measure of agreement found with observations favors the use of the two-dimensional model for local forecasting in appropriate situations, viz. where approximate uniformity exists in one direction. Of course we cannot escape from the discrepancies caused by the two-dimensional idealization. It is suspected that the Lake Kinneret case is less appropriate for two-dimensional simulations and probably the deviations from observations are partly due to this fact. Although, cases without any variation in one direction are probably unrealistic, yet this study suggests that when the major change in the main forcings is in one direction, good simulation with 2-D models are indeed possible. Thus, a useful insight into complex problems could sometimes be gained through an economical tool.

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