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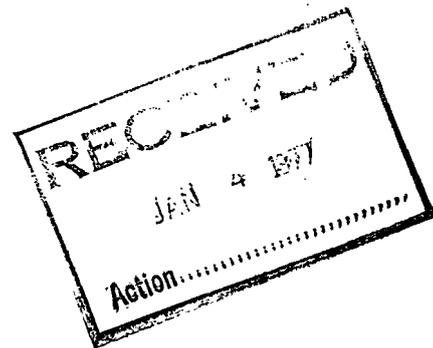
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AN EXAMPLE OF THE EFFECT OF OROGRAPHY ON A SQUALL LINE

by

M.J. NEWARK



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ABSTRACT

A mesoscale analysis of a squall line crossing the lower Great Lakes on August 25, 1975 shows that its behaviour was similar to the model proposed by Pedgley (1958). In one respect however it showed a marked difference. This was a "jump" over an area to the lee of the Niagara Escarpment and an area along the north shore of Lake Erie. The former is called the Toronto rain shadow area and received no precipitation whatsoever while in nearby locations as much as 40 mm of rain fell. In this respect the line showed a resemblance to other cases in Pennsylvania where there is a terrain feature similar to the Niagara Escarpment. Attempts are made to show that orographic effects played a large part in its behaviour, particularly with regard to the "jump". It is believed that the results of the analysis are consistent with the idea that two mechanisms transmitted the effects of terrain to the atmosphere. These are orographic lift in the case of thunderstorm formation and lee waves in the case of thunderstorm dissipation.

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EXEMPLE DE L'EFFET DE L'OROGRAPHIE SUR UNE LIGNE DE
GRAINS

par

M. J. Newark

RÉSUMÉ

Une analyse à moyenne échelle d'une ligne de grains qui a traversé la région inférieure des Grands lacs le 25 août 1975 indique que son comportement a été comparable au modèle proposé par Pedgley (1958). Sous un rapport, toutefois, une différence marquée s'est manifestée. Il s'agit d'un "saut" au-dessus d'une zone sous le vent de l'escarpement du Niagara et d'une zone située le long de la rive nord du lac Erié. Dans la première de ces zones, désignée sous le nom de zone protégée de la pluie, il n'y a eu aucune précipitation quelle qu'elle soit tandis que, dans les endroits environnants, les hauteurs de pluie ont atteint jusqu'à 40 mm. A cet égard, la ligne a présenté une certaine similitude avec d'autres cas survenus en Pennsylvanie où le relief du terrain est semblable à celui de l'escarpement du Niagara. On tente actuellement de prouver que les effets orographiques ont joué un grand rôle dans le comportement de la ligne de grains, en particulier pour ce qui est du "saut". On croit que les résultats de l'analyse sont compatibles avec l'idée que deux mécanismes ont transmis les effets du terrain à l'atmosphère. Ces deux mécanismes sont l'ascendance orographique, dans le cas de la formation de l'orage, et les ondes sous le vent, dans le cas de la dissipation de l'orage.

AN EXAMPLE OF THE EFFECT OF OROGRAPHY ON A SQUALL LINE

by

M. J. Newark

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1. Introduction

Climatological studies of precipitation in southern Ontario clearly show a minimum in the annual amount received in the area west and southwest of Toronto (Brown, McKay, Chapman 1968). In particular a summer minimum of rainfall exists in a band stretching from Long Point on Lake Erie, throughout the Niagara Peninsula and along a narrow zone bordering the north shore of Lake Ontario to approximately the Bay of Quinte.

Since summer rainfall is largely convective in nature, down-slope terrain has an inhibiting effect on its production. In this regard the south slopes of the Dundalk Highlands, the Niagara Escarpment and the Oak Ridges Moraine are the most important climatic controls. Toronto and surrounding communities nestle in the protective triangle formed by the Niagara Escarpment to the west, the Oak Ridges Moraine to the north and Lake Ontario to the south (Figure 1). Compared to such well known rain shadow areas as those produced by the coastal mountains of British Columbia for example, the effect in Southern Ontario is slight. The example of thunderstorm dissipation documented in this paper and a companion film shows however that the effect cannot be overlooked.

Studies of this type have not been really feasible in the past due to the lack of detailed data in the study area. The advent of SCEPTRE (System for Constant Elevation Precipitation Transmission and Recording, Try 1972) has produced among other things a permanent record of radar echo within 220 km of the radar site at Woodbridge.

The purpose of this paper is to augment climatological and statistical studies with an actual example of how topography acts as a climatic control in the Toronto area. The case chosen occurred on August 25, 1975 when a squall line with a continuous history of more than 24 hours was crossing southern Ontario. Although well developed,

it "jumped" over Toronto and other localities along the north shores of Lake Ontario and Lake Erie. Thereafter it continued as an intense line into Ohio and New York states. Why did the line "jump"? In seeking an answer to this question, it is hypothesized that lee waves played an important role in transmitting the effects of terrain to the atmosphere. The period of time of interest is August 25th, 2107 GMT to August 26th, 0231.

2. The Surface Synoptic Situation

On August 25, 1975, a large warm sector of maritime Tropical air straddled much of Ontario. Early in the morning the advancing edge of maritime Polar air lay over the upper reaches of the Mississippi Valley preceded by a squall line that was producing some fairly heavy thunderstorm activity. Figure 2 illustrates the development of this scenario through the period 0600 GMT August 25th, to 1200 GMT August 26th. Eastward motion of this system was at first quite rapid. At 1800 GMT a flat frontal wave formed south of Chicago and subsequently moved northeastwards along the front thereby slowing its eastward progression. The squall line ultimately took a northeast to southwest orientation and travelled across southern Ontario at 19.3 km hr^{-1} .

The squall line retained its identity through the 30-hour period (although difficult to find at 1800 GMT) and produced significant rainfalls over a large geographical area (Figure 3). Due to the sparse data of the synoptic network, few meaningful conclusions can be made concerning the time variation of rainfall amount. The only thing that can be said is that the reported maximums of 48 mm at Eau Claire, Wisconsin, 51 mm at Erie, Pennsylvania and 40 mm at Claude, Ontario, occurred during the usually observed time interval of peak squall line activity (Figure 3).

3. The Upper Air Synoptic Situation

At 700 millibars and higher levels of the atmosphere a slow moving warm ridge lay across the Lower Great Lakes. A jet stream separated this warm air mass from much colder air west of Lake Superior. At 0000 GMT August 26th, the jet core of 138 km hr^{-1} stretched from central Lake Superior to James Bay. Although it had been moving eastwards to that position during the preceding 24 hours the gradient of isotachs over southern Ontario showed no change. At the time of the squall line there was no appreciable divergence due to the jet stream at 300 millibars.

At low levels, a tongue of moisture was channeled along the Mississippi Valley from the Gulf of Mexico to the Lower Great Lakes and in Quebec. This was overlaid by much drier air at 700 millibars.

The low level southwesterly winds feeding the moisture northwards were a little stronger than the winds on either side. Some low level wind convergence was apparent over southern Ontario.

The 0000 GMT upper air sounding (Figure 4) made at Buffalo is believed to be representative of the undisturbed air preceding the line since the first thunderstorms did not reach the eastern end of Lake Erie until about 0200 GMT. Figure 4 shows that the air was potentially unstable through a deep layer from 1 to 5 km. Lift of only 250 m would completely saturate the air below 1.5 km and release the instability. Allowing for entrainment of drier environmental air, cumulonimbus cloud to 10.5 to 12 km was possible.

The slopes rising from Lake Huron to the Dundalk Highlands provide somewhat more than 300 m of lift (more than enough to trigger the thunderstorms). According to the charts of Jarvis and Leonard (1969), terrain induced vertical velocities in this particular situation were of the order of 6 mm sec^{-1} .

The wind profile observed at Buffalo indicates that wind direction remained very steady with height. The average throughout the troposphere was 250° with maximum deviation $\pm 20^\circ$. The speed showed two maxima, the first of 18 m sec^{-1} at 2.1 km and the second of 17 m sec^{-1} at 6.7 km.

4. Procedure

(a) The SCEPTRE Output

Data from the Woodbridge radar is received by facsimile transmission at intervals of approximately 7 minutes. Radar returns from precipitation are indicated in 4 shades of grey which represent various threshold values of precipitation intensity namely 25 mm hr^{-1} , 2 mm hr^{-1} , 8 mm hr^{-1} and 32 mm hr^{-1} . The minimum spatial resolution is a 2 km square. The data in this case is at a constant altitude of 1.5 km.

Facsimile charts depicting the progress of the squall line are available from the time that it moved inland from Lake Huron to the time that it moved into the states south of the lower Great Lakes.

(b) Mapping of the SCEPTRE data

Two approaches were tried to combine the data into one map of rainfall distribution for the period 2107 GMT to 0231 GMT. The first was a simple manual integration of the echoes shown on each individual

chart. Each and every echo on each and every chart was shaded in on an overlay. Within an 18.4 km radius of the origin of the chart, echoes are automatically blanked out to eliminate ground clutter. In the manual integration, returns within this ring were interpolated from those outside but adjacent to it. Heavier shading was used for the more intense echoes. Figure 5 shows the outline of the composite rain area along with envelopes of heavier rain caused by the more obviously intense individual cells. A general area of heavier rain (labelled A) is also indicated.

The second approach was a computer calculated integration of the data which is also stored on magnetic tape. In this form of storage more threshold values of intensity are available than on the facsimile chart. The computer program calculates a map of dBZ for each 7 or 8 minute period of radar data. This is converted into a rainfall rate map R based on the empirical relationship between Z (mm^6m^{-3}) and R (mm hr^{-1}) developed by Marshal and Palmer (1948).

$$Z = 200R^{1.6}$$

The next step is to calculate the amount of rain (in mm) that fell in that 8 minute period in each 2 km square. Finally this rainfall is accumulated over the time period 1912 GMT August 25th, to 0155 GMT August 26th. The composite map is shown as Figure 6.

In both approaches there is a common source of error. In spite of the fact that 1.5 km CAPPI (Constant Altitude Plan Position Indicator) data was used, it is suspected that fairly strong ground returns intrude immediately to the west of the blanked out circle around Woodbridge. Their contribution is evident when calculated rainfalls in that area are compared to raingauge information. Calculations of over 300 mm are obtained whereas the largest reported amount was 40 mm at Claude.

(c) Animation of the SCEPTRE Data

A third method of ordering the SCEPTRE data was to record each chart on 16 mm motion film. A longer time period was used than in the mapping, namely 1943 GMT to 0307 GMT. This 7 hour 24 minute period was reduced to about 30 seconds. A projection rate of 18 frames per second clearly shows the temporal changes in the squall line and the relationship of these changes to topography. The motion of individual line components was from west to east while the line motion was towards the southeast. The Niagara Escarpment lies squarely across the cell trajectories and appears to be linked with the most interesting feature of the film. This is the fact that strong development of thunderstorm cells as well as a more general rain area took place on its

windward side, followed by a dramatic dissipation on its lee side. One segment of the line whose elements formed over Georgian Bay showed some development east of Lake Simcoe but failed to cross the Oak Ridges Moraine before dissipating almost entirely. The film shows quite clearly that no cells developed in the area immediately adjacent to the north shore of Lake Erie, and that no rain at all was received in Toronto and areas eastward along the north shore of Lake Ontario. This is also shown by Figures 5, 6 and 7. In an effort to discover why this happened, a closer look is now taken of the mesoscale situation and the topography and its known effects on summer weather.

5. The Mesoscale Situation

Considering the relatively short time period under consideration (5.5 hours) in which little synoptic scale change of temperature, wind and moisture were observed it seems reasonable to assume:

- i) that the dynamic and thermodynamic properties of the atmosphere remained unchanged relative to each other.
- ii) that the changes due to diurnal intensity variation were minimal. This leaves topography as the main control over the behaviour of the squall line.

(a) Rain Gauge Information

The Atmospheric Environment Service and the Ontario Ministry of Natural Resources, Conservation Authorities Branch maintain a fairly dense network of rain gauge stations in southwestern Ontario. The records of 60 automatic gauges were examined. Rainfall for the appropriate period of time has been extracted and plotted. The resulting isohyet analysis is shown in Figure 7. While this figure was modelled to agree with Figure 5 it nonetheless shows quite clearly the area of no precipitation in the jump zone. This stretches from about Long Point, Lake Erie through the Niagara Peninsula and around the north shore of Lake Ontario.

The numbered areas of heavier precipitation in Figure 5 can clearly be seen in Figure 7. For the most part, the gauges in these areas recorded amounts in excess of 5 mm with maximums of 40 mm at Claude, Ontario and 51 mm at Erie, Pennsylvania.

(b) Topography and Related Climatology

Figure 8 shows the main topographical features of southern Ontario. These constitute a sloping rise of land from Lake Huron to a north-south oriented ridge known as the Niagara Escarpment. The total rise is about 345 m. The highest point (603 m ASL) is 427 m above Lake Huron. The escarpment stretches from the west end of Lake Ontario to Georgian Bay and is part of a larger system running from Niagara Falls to Manitoulin Island. The east facing slope falls sharply as shown by the cross sections of Figure 18. Perpendicular to this ridge and about halfway along it is the Oak Ridges Moraine, the height of land which separates the Lake Simcoe basin from the Lake Ontario basin. This narrow ridge is about 260 m above the level of Lake Ontario. Together these two ridges form the west and north sides of the protected triangle mentioned in the introduction. For the purposes of this paper, this area will be called the Toronto rain shadow area.

While not pertinent to the Toronto rain shadow area, the third main topographical feature shown in Figure 8 is the basin of Lake Simcoe and the Kawartha Lakes complex with the slopes of the Haliburton Highlands to the northeast. Between Georgian Bay and Lake Simcoe, the Ore Sand Hills make a knob of land which is 241 m above the former and 198 m higher than the latter.

Booker (1962) has found that terrain in Pennsylvania similar in nature to the Niagara Escarpment produces mesoscale variations in lee summer rainfall amounts. Similarly Clodman (1966, 1967) has presented climatological evidence that the escarpment exerts a strong control over convective rainfalls in its lee. He found a maximum of mean monthly precipitation directly east of the escarpment followed by a distinct minimum between 6.4 km and 2.8 km to the east. A second minimum lay between 32 km and 45 km to the east. He points out that his results can be interpreted from the point of view that lee waves have contributed to these variations. The fact that once formed, lee waves are dependent on the atmospheric winds and stability rather than the physical characteristics of the initiating ridge, is examined more closely later in this paper. However, waves interfering constructively with the preferred wavelength due to terrain forcing would tend to give distinct precipitation maxima and minima. A climatology of waves to the lee of the escarpment might reveal that certain wavelengths are more common than others.

(c) The Thunderstorm Line

Figures 9, 10, 11 and 12 show selected stages of the progress of the line echo across southern Ontario. Its motion was from 315°

at 19.3 km hr^{-1} . Its behaviour can be categorized by four different phases as follows:

- Phase 1 The line presented a compact, well formed appearance with few gaps. Little change occurred with time.
- Phase 2 Elements of the line in the Toronto rain shadow area dissipated while at the same time elements over the upslopes of the Dundalk Highlands began intensifying.
- Phase 3 The elements over the upslopes blossomed and took over as the main segment of the line. Concurrently a new line began to form over Lake Erie.
- Phase 4 The Lake Erie line became the only one as the Dundalk Highland elements dissipated completely in the Toronto rain shadow area.

(d) Thunderstorm Cells

A detailed study of each facsimile radar chart revealed that a number of individual thunderstorm cells in the line could be identified. Figure 13 shows the tracks of 23. Their average motion was from 252° at a speed of $54(\pm 6) \text{ km hr}^{-1}$. Out of 12 cells with observed origins anywhere over land, 11 (90%) formed over an upslope area. Out of 22 cells observed to dissipate, 18 (81%) did so over downslopes or at least over flat areas. For what constitute upslope and downslope areas see Figures 20 to 28. Out of 15 cells with observed origins west of the escarpment, 10 (66%) dissipated either on the lee slopes or over flat sections of the escarpment.

(e) Thunderstorm Groups

A number of cells were observed to develop and/or cluster together in groups. These groups followed the life cycle of growth that has already been well documented in the literature by Pedgley (1958) and others. Figures 14, 15 and 16 show the behaviour of the groups. In addition the vectors of cell motion are compared to the vectors of group motion.

(f) Discussion

Pedgley (1958) as well as Fujita and Brown (1958) proposed a model meso-system of such thunderstorms as are studied in this case. Their proposed growth stage, mature stage and decay stage for the

thunderstorm groups was evident in the behaviour of the groups comprising the squall line. The groups labelled (iii) and (vii) in Figures 15 and 16 are particularly good examples, changing from a cluster of developing cells to groups of intense echoes and finally into large amorphous rain area that dissipated within minutes.

The velocity of the groups (vectors labelled G) was typically to the right of the cell velocity (vectors labelled C). This displacement has been described by Pedgley as well as by Newton and Katz (1958), Fujita and Brown and several others. Vector P, the difference of C and G, represents the propagation of new cells within the group. P determines the orientation of the group as a whole as well as the length of the group (speed of P x lifetime of group). Newton and Katz have suggested that the speed of P is determined by the magnitude of vertical wind shear. They also suggest that the movement of the groups is most highly correlated with either the 700 millibar wind or the mean wind direction between 850 and 500 millibars. In this case the average group motion was from 258° while the mean wind in the 850 to 500 mb layer was 253° and the 700 mb wind was 260° . They found very little correlation between wind speeds at any particular level and the speed of the storm groups.

In one respect, the squall line exhibited a very significant departure from the orderly cases documented by Pedgley et al. This was the "jump" of phase 4. Their cases did not deal with the effects of topography. In this case no other reason appears likely for the discontinuity in an otherwise orderly line. Similar cases however have been observed by Hosler, Davis and Booker (1962) in Pennsylvania where there is a terrain feature called the Allegheny Front which in many respects is similar to the Niagara Escarpment.

The results described under the heading 'Thunderstorm Cells' bear the earmarks of topographically induced behaviour. Since the line is nothing more than an instantaneous arrangement of groups then its behaviour can be accounted for by the effects of topography on the individual cells.

In 1967 Fujita dealt with the importance of mechanical orographic lift in the release of latent heat of condensation in conditionally unstable air. In this study several thunderstorm cells were observed to originate over the upslopes of the Dundalk Highlands after a lift of only 170 m from Lake Huron. (Recall that about 250 m of lift was indicated as necessary by the Buffalo tephigram.) Generally speaking, most cells or groups showed intensification while moving upslope.

Although orographic lift adequately explains the stimulation of convective cells on the windward slopes, downslope heating on the steep lee slopes is insufficient to explain thunderstorm dissipation. This is because only the lowest layers of a convective cell would be subject to heating by compression (if at all), while large upward velocities would continue unchanged elsewhere in the thunderstorm. The computed terrain induced vertical velocities according to Jarvis and Leonard (1969) are of the order of -15 mm sec^{-1} , while thunderstorm vertical velocities are typically $20-30 \text{ m sec}^{-1}$ or more (Chisholm and English 1973).

Obviously some other mechanism must be sought as the vehicle for transferring terrain effects through a very deep layer of the atmosphere. Hosler, Davis and Booker (1962), and Fujita (1967) suggest lee waves. These researchers point out that they have no direct evidence of lee waves at the time of thunderstorm dissipation but Hosler et al claim to have indirect evidence.

6. Lee Waves

(a) Literature Survey

In a theoretical treatment of airflow over ridges Scorer (1953) shows that the disturbance to a laminar flow extends upwards through the troposphere and even into the stratosphere under the right circumstances. He shows that lee waves are possible only if a parameter ℓ^2 decreases with height. ℓ is defined as follows:

$$\ell^2 = \frac{g\beta}{u^2} - \frac{u''}{u}$$

where $\beta = \frac{\gamma_a - \gamma}{T_0}$, and is thus a stability coefficient,

U is the undisturbed horizontal wind speed,

g = acceleration of gravity,

γ_a = adiabatic lapse rate,

γ = actual lapse rate,

T_0 = absolute temperature.

The second order term U'' makes the second ratio very small and it is usually considered negligible. Note that this decrease is a necessary but not sufficient condition for lee wave formation.

Given that ℓ^2 must decrease with height, this equation says that

lee waves are most likely in an atmosphere where, (i) the wind speed increases with height and (ii) T_0 increases with height (in other words, an inversion). Under thunderstorm conditions T_0 actually decreases with height. This means that β can only become smaller if the decrease of $(\gamma_a - \gamma)$ > decrease of T_0 . This limitation can be expressed as

$$\frac{d\gamma_a}{dz} - \frac{d\gamma}{dz} > \frac{dT_0}{dz}$$

but, since $\gamma_a = \text{constant}$, then

$$\frac{d\gamma}{dz} > -\gamma$$

Then for the normal case of decreasing T_0 with height, decreasing stability with height is required.

Booker (1962) has pointed out that conditions of instability and vertical windshear prevalent in thunderstorm situations also produce the necessary decrease of ℓ^2 with height and thus make lee waves possible. Furthermore the cold outflow from the base of a thunderstorm cell may produce the condition where T_0 increases with height in a certain layer thus creating a more favourable state for the formation of lee waves. As a consequence the thunderstorm aids in its own dissipation. As Booker sees it, the cold thunderstorm downdraft causes a layer of relatively stable air to spread out across the terrain ahead of the storm. This terrain conforming laminar flow is important in lee wave formation, particularly if it is normal to the ridge. In the downward section of the lee wave, the environment would experience dry adiabatic warming, while within the cloud moist adiabatic warming would result. These two factors lead to a net buoyancy loss of the cloud. Old cells would dissipate more rapidly under such circumstances and new cell formation would be inhibited. As will be shown later, downward vertical velocities in lee waves at least approach typical upward values in thunderstorm. This, combined with the net buoyancy loss should be sufficient to cause even vigorous thunderstorms to dissipate.

The research of the Department of Meteorology at Pennsylvania State University (Hosler, Davis and Booker 1962) shows the existence of lee waves over the Allegheny mountains and attempts to relate ℓ^2 profiles with cases of squall line dissipation. Winds and temperatures from the evening Buffalo radiosonde sounding of August 25th, gave the ℓ^2 profile shown in Figure 17. It is comparable to the average profiles found by Hosler et al for two cases where squall lines jumped ahead, and for eight days when showers dissipated upon moving across the Allegheny Front.

(b) Niagara Escarpment Lee Waves

On August 26th, the ESSA-8 weather satellite orbit number 30694 showed a train of lee wave clouds north of Lake Ontario at about 1525 GMT. At least 16 waves can be identified stretching from the lee of the Escarpment as far east as about Kingston. It is interesting to note that the wave train is split into two halves, one north of the Oak Ridges Moraine and the other south of it. Measurement shows their wavelength averages 10.5 km.

The Escarpment is an asymmetrical ridge with a steep east-facing slope and a more gently rising westfacing slope. Figure 18 shows cross sections of it both north and south of the Oak Ridges Moraine. Scorer's equation for the amplitude of lee waves is

$$\frac{u}{u_1} a^2 \int_0^{\infty} e^{-kb + ikx - \mu z} dk$$

$\frac{u}{u_1}$ is a windshear term and $a^2 \int_0^{\infty} e^{-kb}$ is the term relating to the physical characteristics of the ridge where

- a = summit height above its surroundings
- b = effective ridge half-width
- c = wave number ($\frac{2\pi}{\lambda}$, λ = wavelength).

It can be seen that the maximum effect of the ridge on wave amplitude occurs when $b = k^{-1}$. In the case of the Escarpment, b_n north of the Moraine is 16 km and b_s south of the Moraine is 20 km. Thus the maximum effect of the ridge is for wavelengths of $2\pi b$, or $\lambda_n = 100$ km, $\lambda_s = 125$ km.

Queney, Corby et al (1960) point out that the largest amplitude waves are not necessarily over the highest ridges since the term $\frac{u}{u_1}$ is involved. In fact, once waves are formed they are U dependent only. For waves downstream from a ridge Corby has found that

$$\lambda(\text{km}) = 0.585U (\text{m sec}^{-1}) - 2.8$$

For August 25th, this gives the result $\lambda = 8.0$ km. A better result for λ is obtained from Casswell's graph (1966). This gives $\lambda = 10.9$ km.

(c) Relationship Between Lee Waves and Thunderstorm Dissipation

According to Casswell, when marked waves occur, large vertical velocities extend over only short distances perpendicular to the

ridge. His method of calculating maximum vertical velocity gives a value of 18 m sec^{-1} , which at least is comparable to thunderstorm vertical velocities. Queney, Corby et al say that the first lee wave crest is displaced approximately $3/4 \lambda$ downstream from the ridge. Figure 19 combines these two factors. The relationship of the first three wave crests to the ridge is shown according to their distance downstream. (Note that the amplitude of the waves is not to scale.) This is then compared to the distance from the ridge that thunderstorm cells were observed to dissipate. It can be seen that dissipation took place at discrete distances from the ridge, and that the location of dissipation is in reasonable agreement with the areas of downward vertical velocities in the lee wave train. Firstly the number of cases is small and secondly the location of cell dissipation can only be found within $\pm 6 \text{ km}$ due to the 8 minute gap in information between each radar chart.

7. Conclusions

These are presented as a set of hypotheses as obviously more cases should be studied and supported by field evidence before meaningful conclusions are possible. It is not intended that these hypotheses should apply to cases where all the factors conducive to severe thunderstorms are present. If the various dynamic and thermodynamic parameters that contribute to lift in the atmosphere are present only to a limited degree, such that the forces due to terrain are comparable, then the following are proposed when squall lines or summer cold fronts cross southern Ontario.

- a) It is the influence of terrain on individual thunderstorm cells rather than on cell groups which is the predominant reason for the behaviour of the line.
- b) The mechanisms transmitting terrain influences to the cells in the case of formation are:
 - i) the upward flux of moisture from Lake Huron which increases the potential instability of the air passing over it and offsets the cooling effects of the lake surface,
 - ii) orographic warming in which locally warmer areas heat the adjacent air,
 - iii) orographic lift by the slopes of the Dundalk Highlands which provides the trigger to set warm and moist air parcels into motion. This includes the upstream forcing of lift over Lake Huron due

to the Highlands.

- c) In the case of cell dissipation the chief mechanism is that of lee wave downward velocities when the main component of the upper winds is within $\pm 30^\circ$ of normal to the Niagara Escarpment.
- d) If the 700 mb wind, or the mean wind in the layer from 850 to 500 mb is within the range 240° to 300° then significant dissipation of line echoes can be expected to the lee of the Niagara Escarpment, regardless of the orientation of the line.
- e) In cases where cell motion is within the 240° to 300° range, some groups of cells that survive the crossing of the Escarpment north of the Oak Ridge Moraine may intensify over the Ore Sand Hills, or Lake Simcoe and its eastern slopes.
- f) The south slopes of the Dundalk Highlands present very little slope to cells moving from the directions between 240° and 300° and less precipitation may be expected there than elsewhere west of the Escarpment.

8. Acknowledgements

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9. Appendix

The following diagrams (Figures 20 to 28) show the upslope and downslope areas of southern Ontario for wind directions every 20 degrees from true north. Each diagram is labelled with an appropriate direction from which the wind is blowing. Upslope and downslope areas for winds of opposite direction can be determined by reversing the shading scheme as indicated in the key to use.

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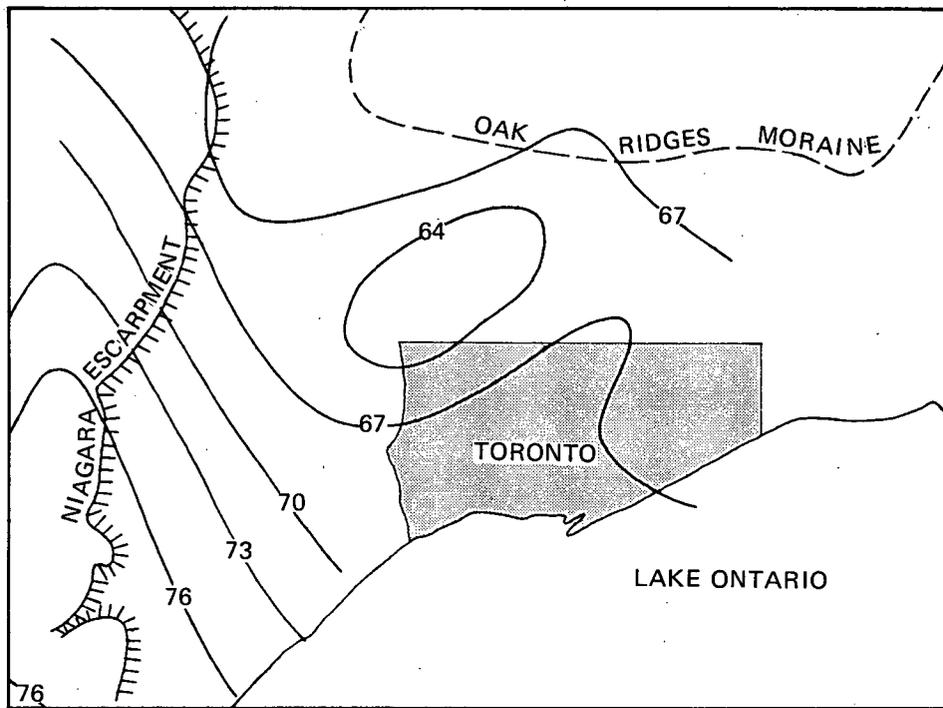


Figure 1

Average monthly precipitation in the lee of the Niagara Escarpment for May to October from 1955 to 1963

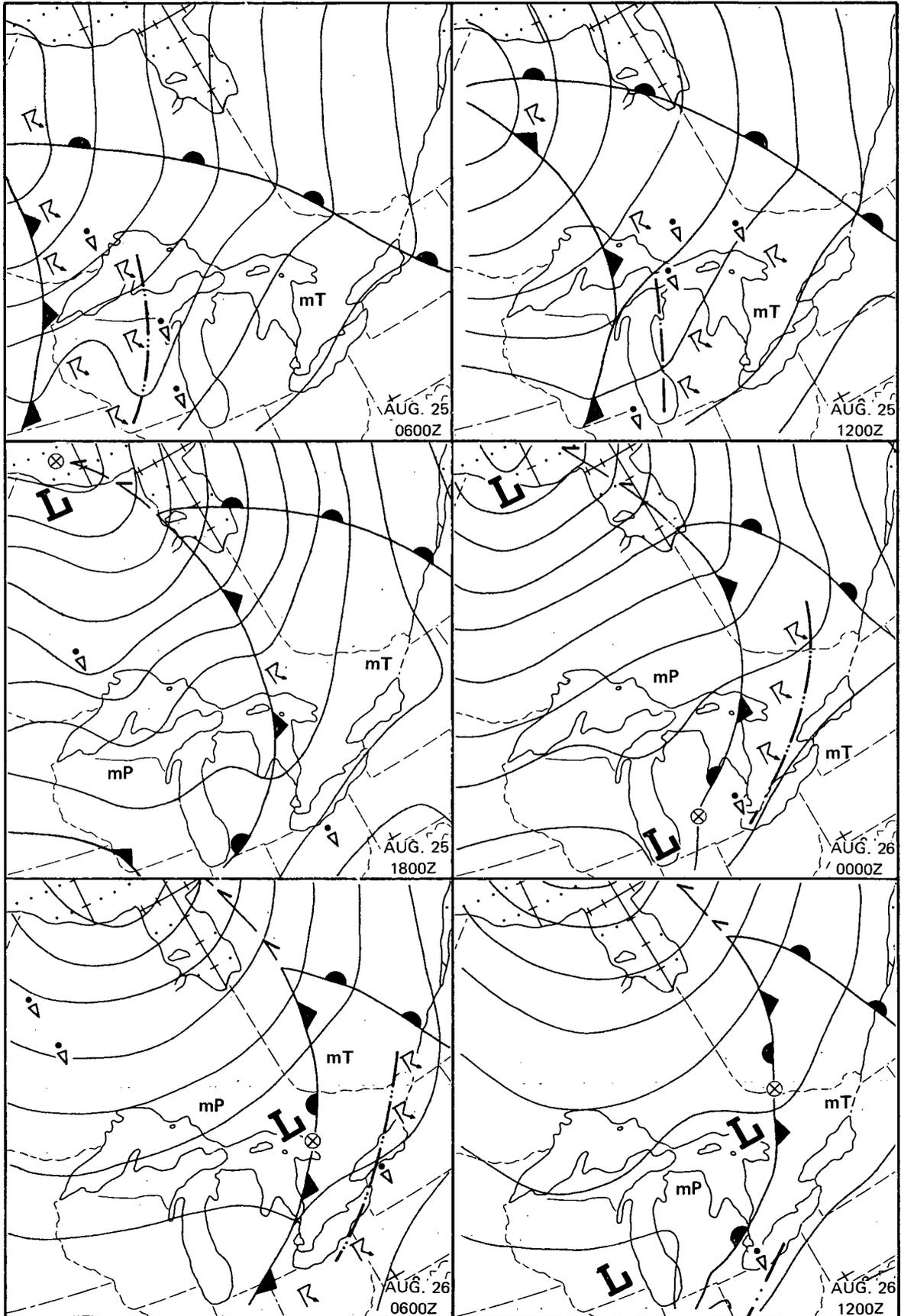


Figure 2

Sequence of Surface Weather Maps showing the advancing squall line

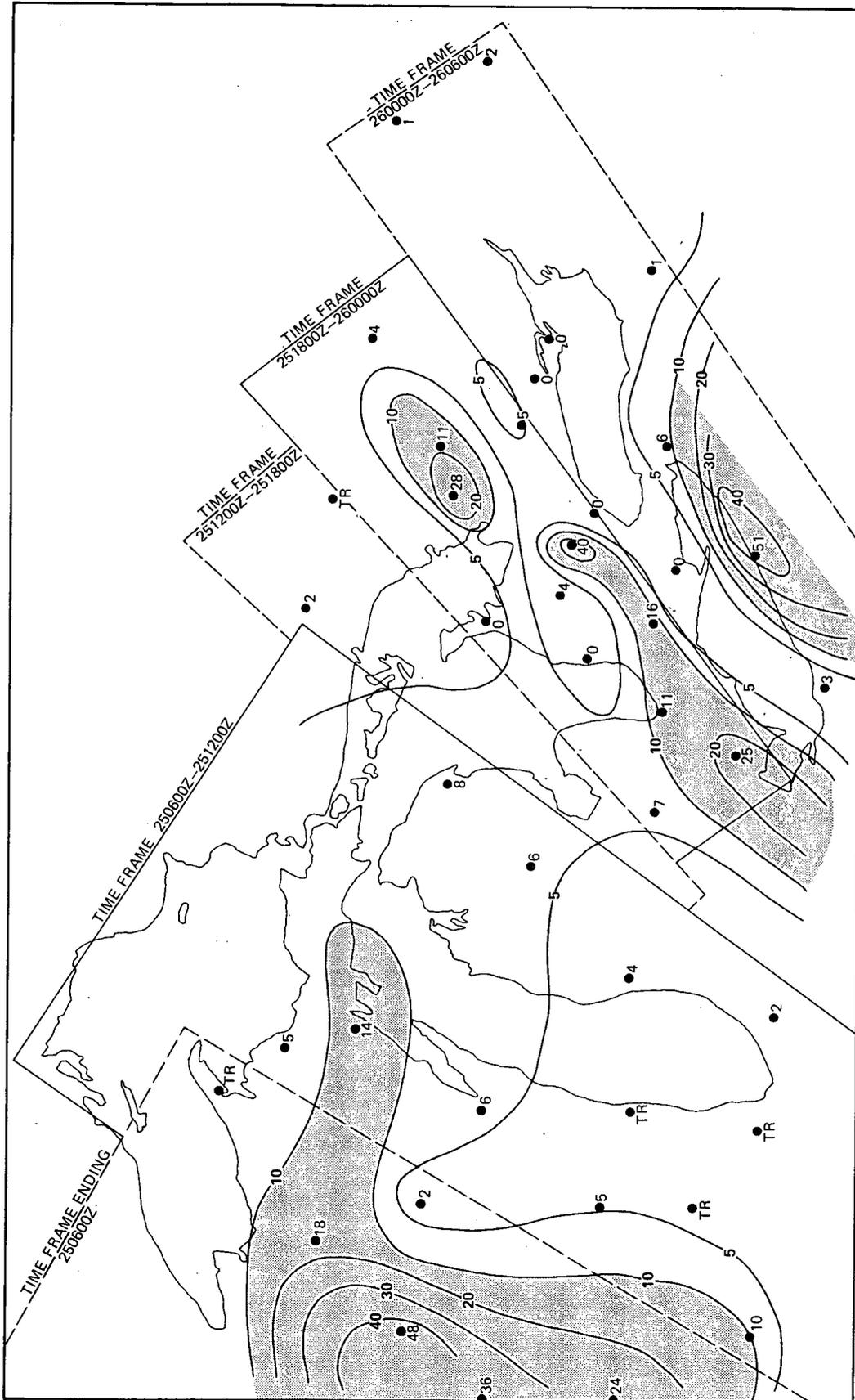


Figure 3

Isohyets and the time intervals in which rainfall occurred

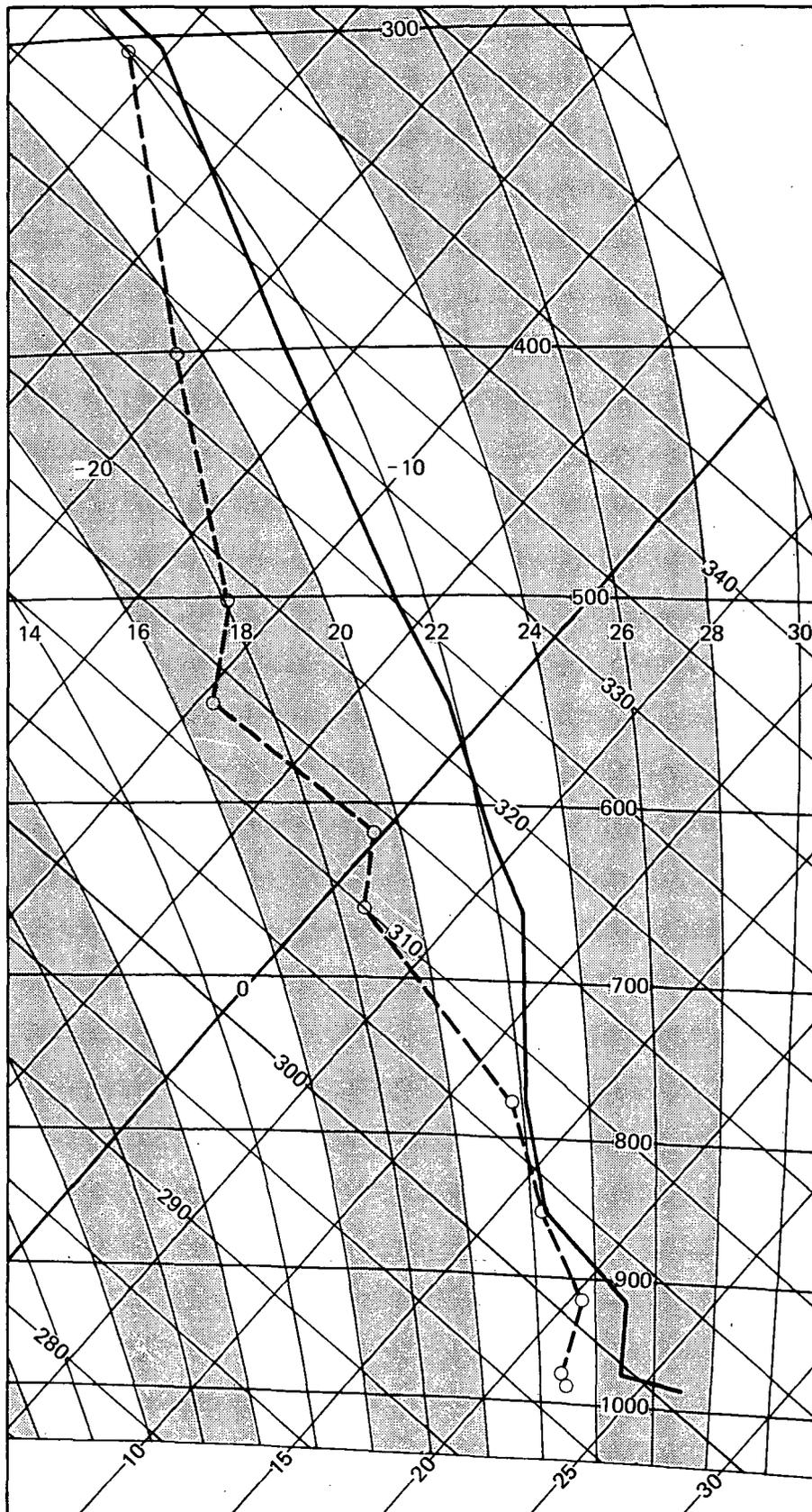


Figure 4

Buffalo tephigram at 0000 GMT August 26, 1975

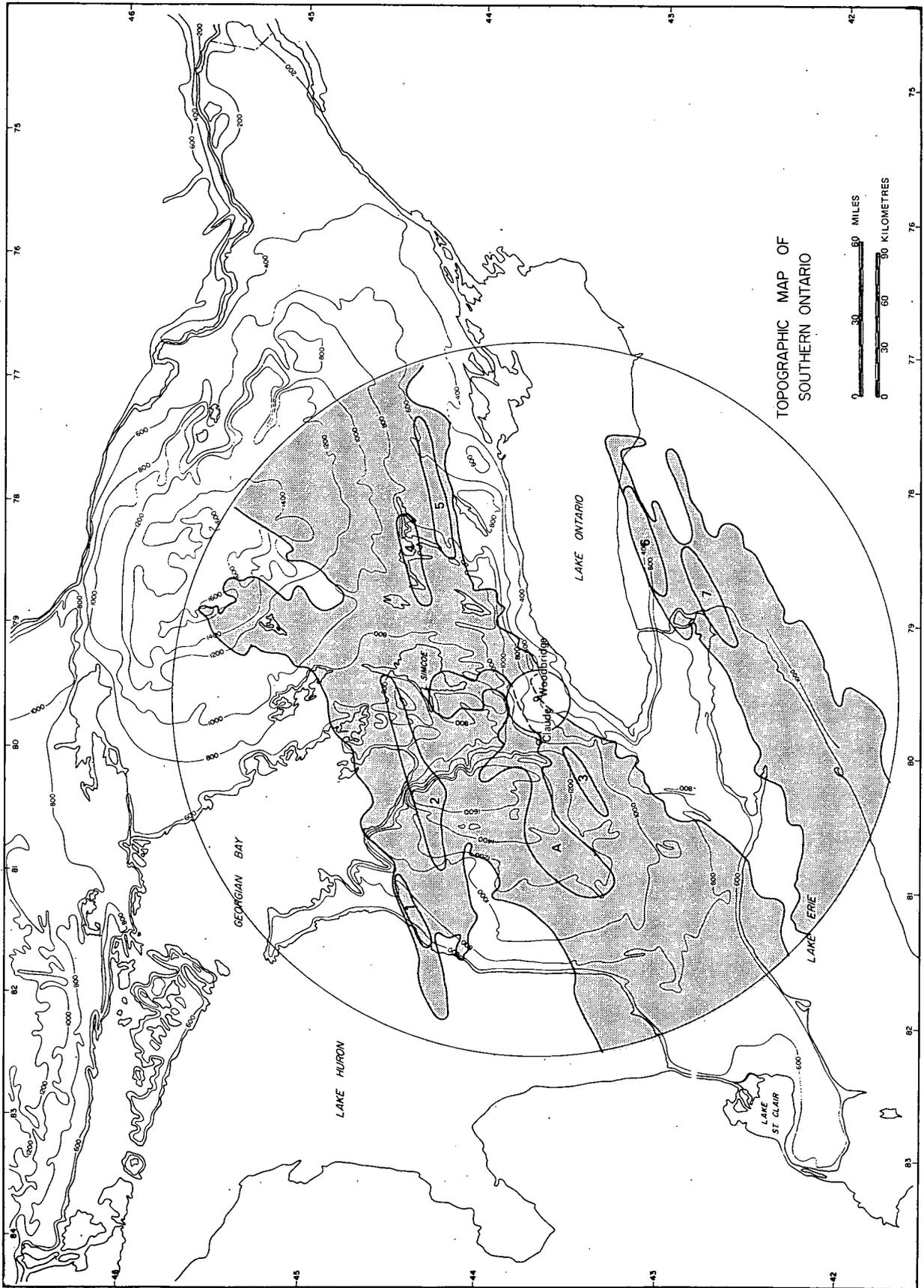


Figure 5

Rainfall map derived by manual integration of all SCEPTRE echoes in the time period 2107 GMT August 25 to 0231 GMT August 26

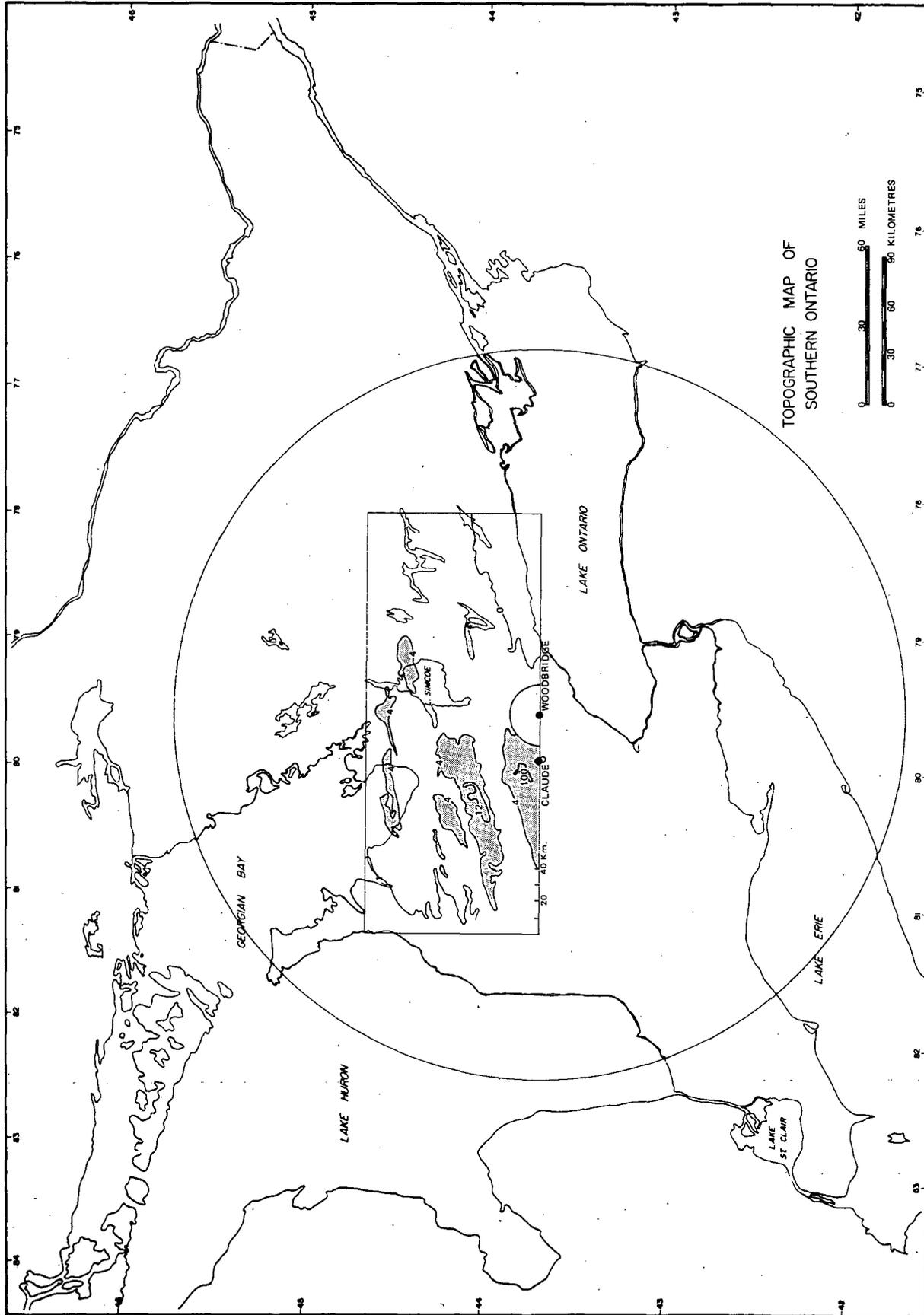


Figure 6

Computer derived rainfall map for the period 1912 GMT August 25 to 0155 GMT August 26

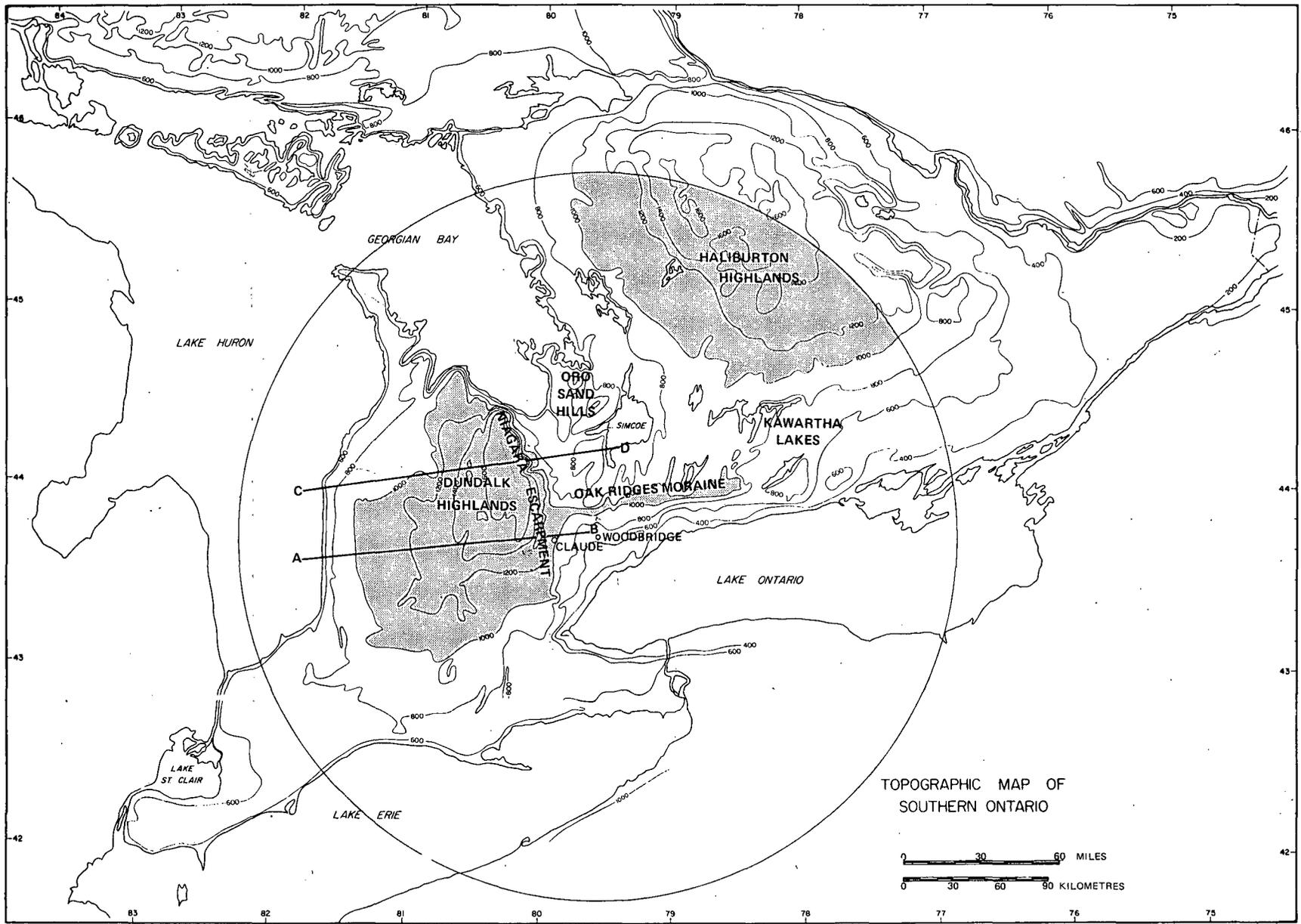


Figure 8

Main topographical features of southern Ontario

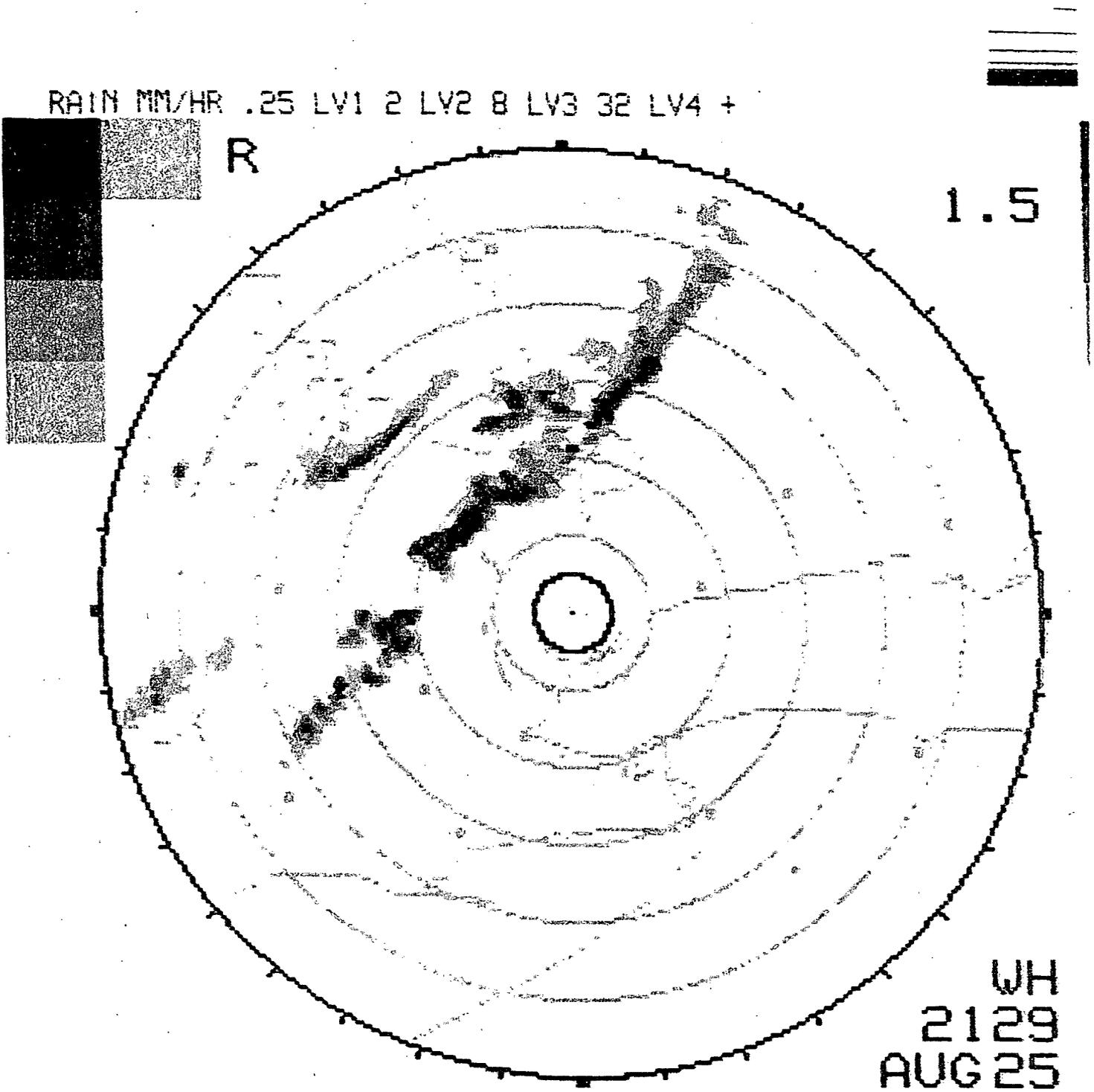
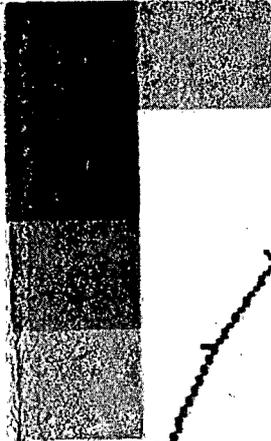


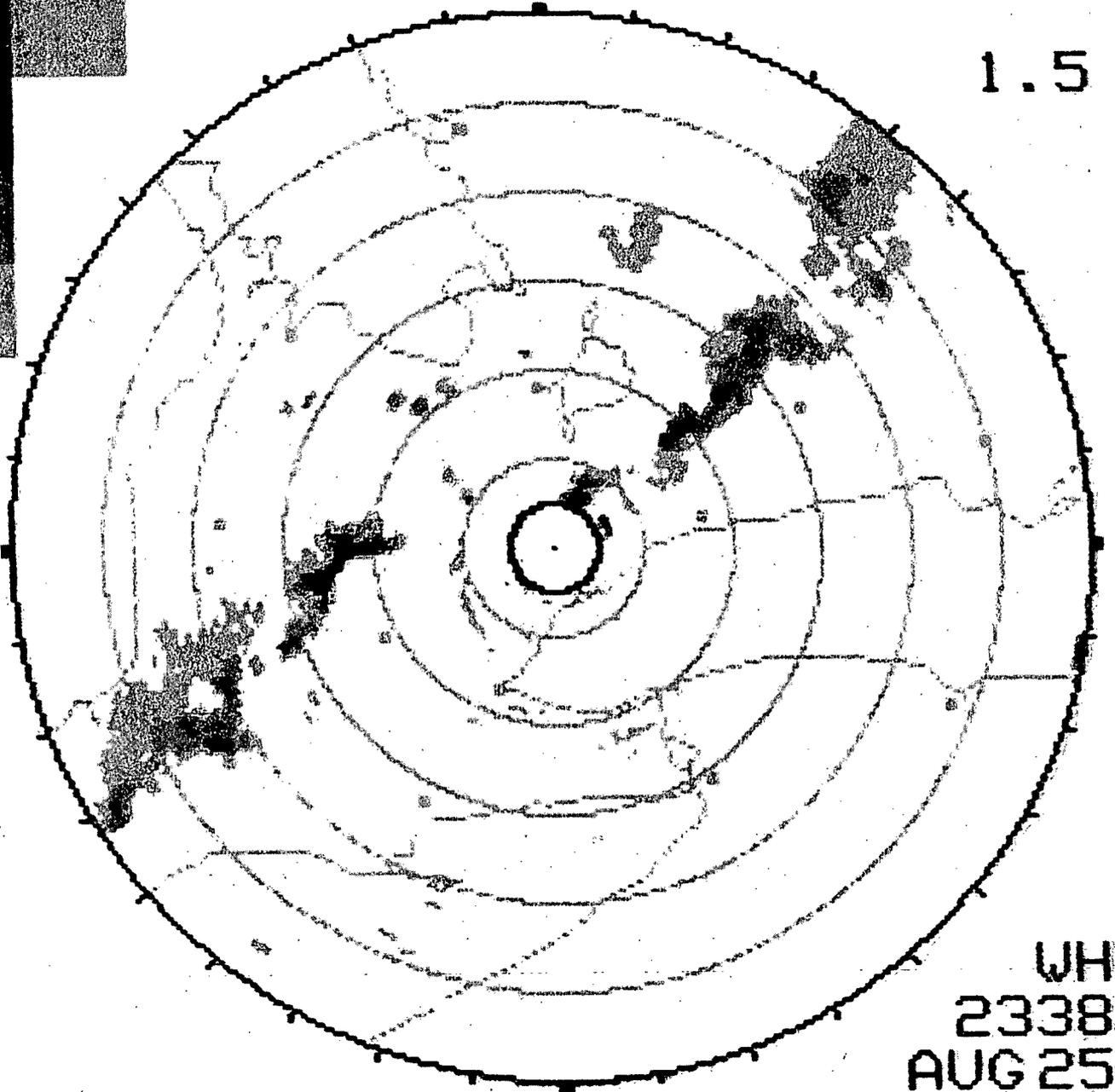
Figure 9

Facsimile SCEPTRE chart showing the squall line at 2129 GMT
August 25. Phase 1

RAIN MM/HR .25 LV1 2 LV2 8 LV3 32 LV4 +



1.5



WJH
2338
AUG 25

Figure 10

Facsimile SCEPTRE chart showing the squall line at 2338 GMT
August 25. Phase 2

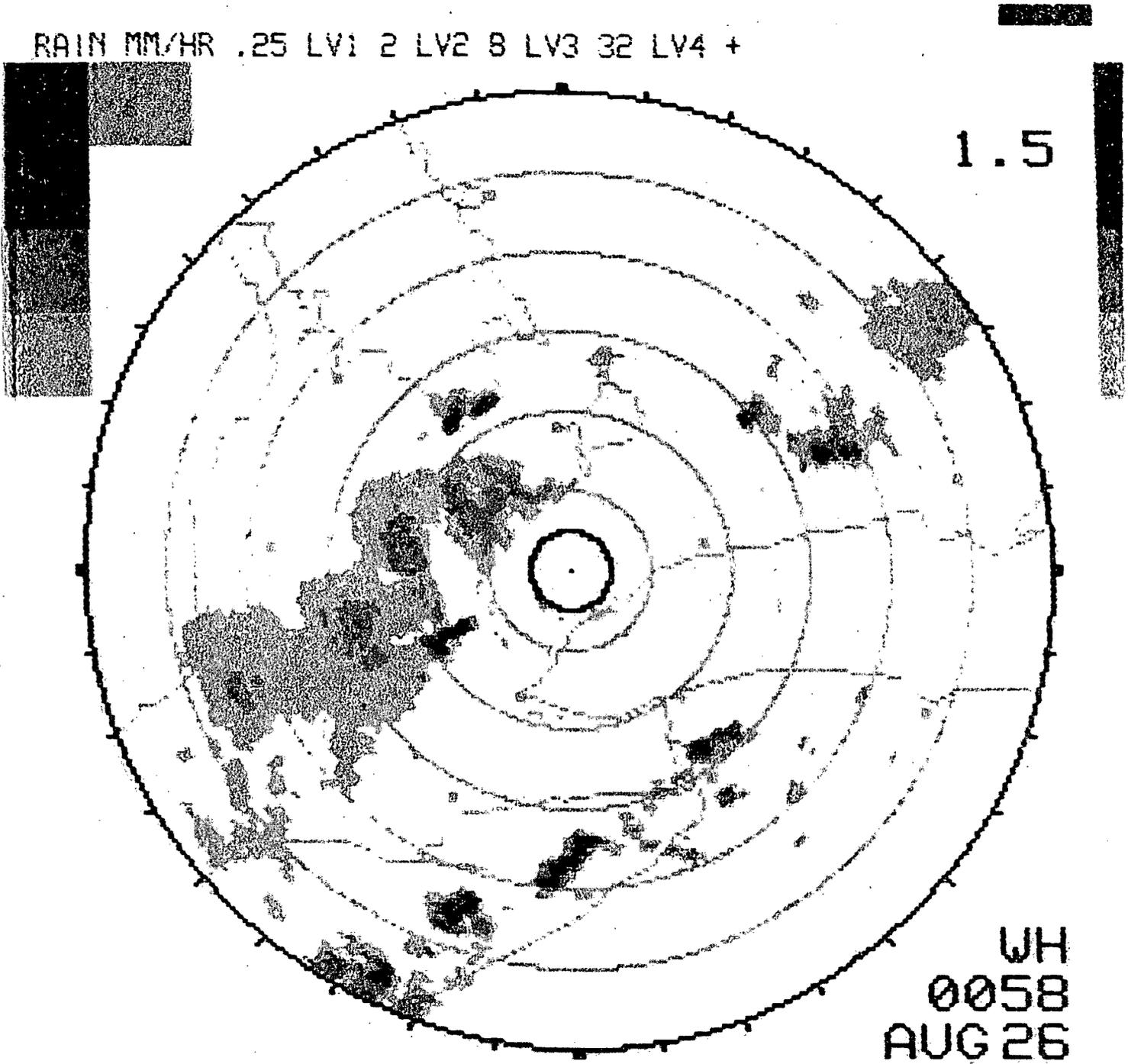


Figure 11

Facsimile SCEPTRE chart showing the squall line at 0058 GMT
August 26. Phase 3

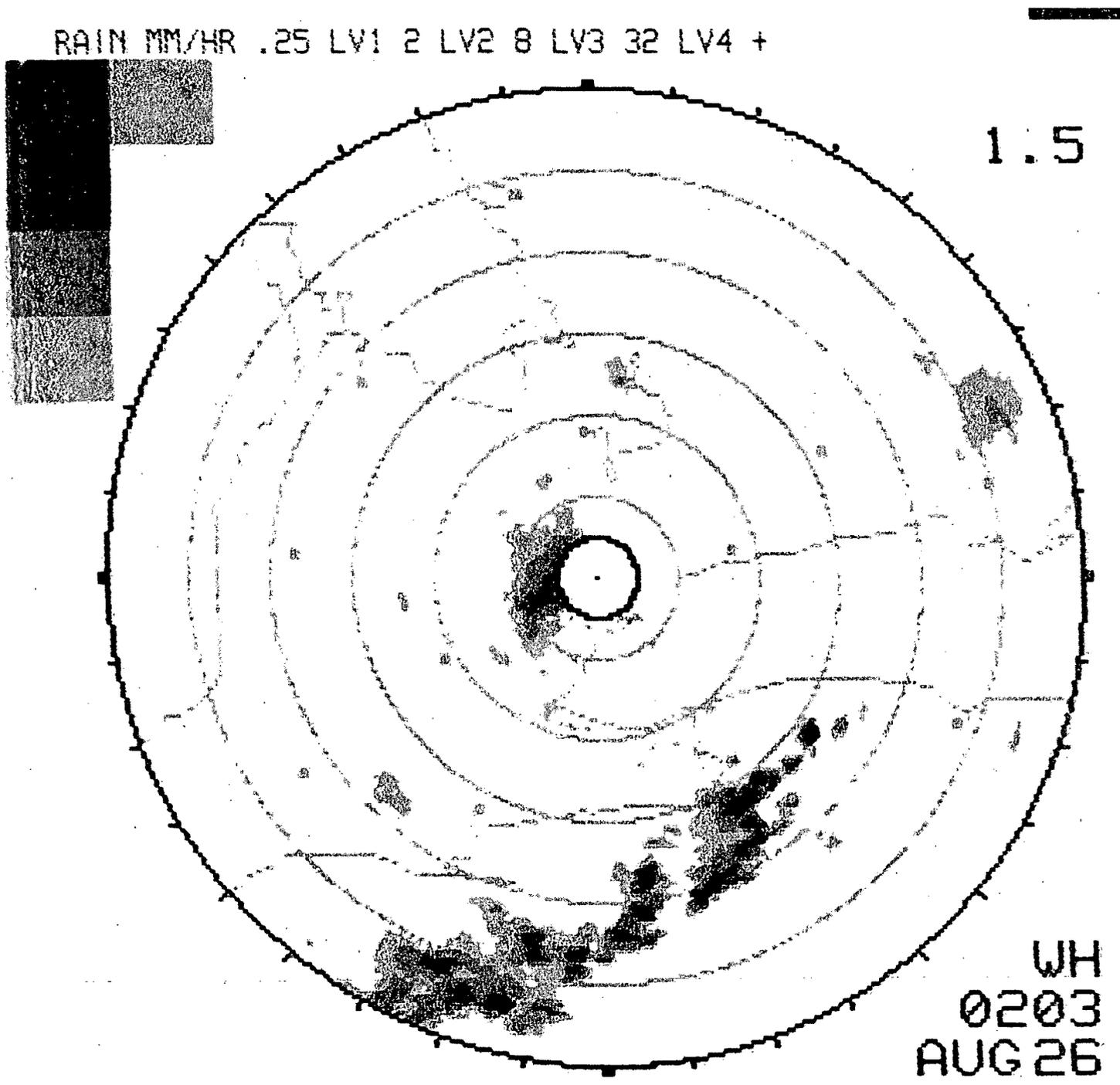


Figure 12

Facsimile SCEPTRE chart showing the squall line at 0203 GMT
August 26. Phase 4

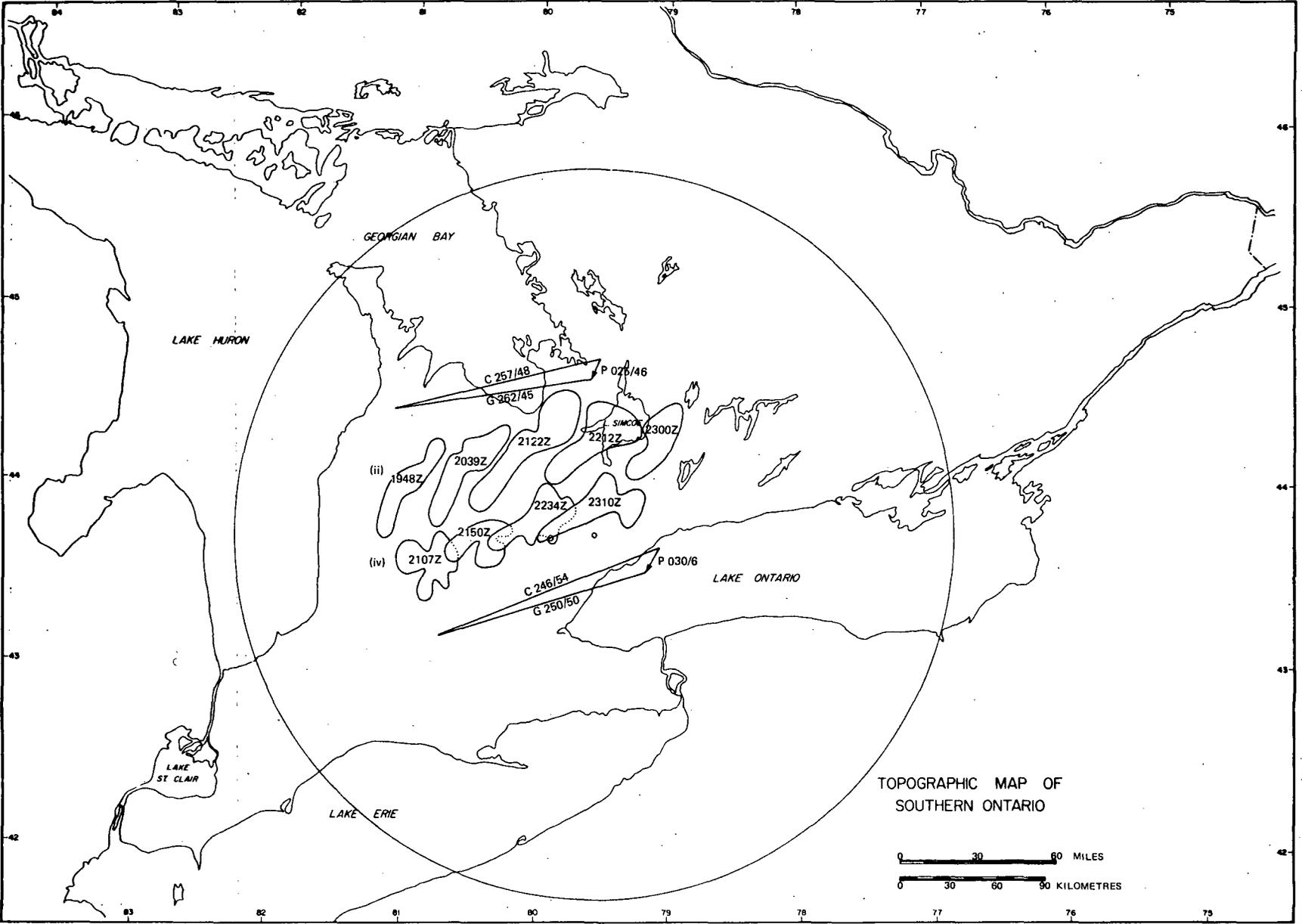


Figure 14

Tracks of thunderstorm groups and vector diagrams of cell and group motion

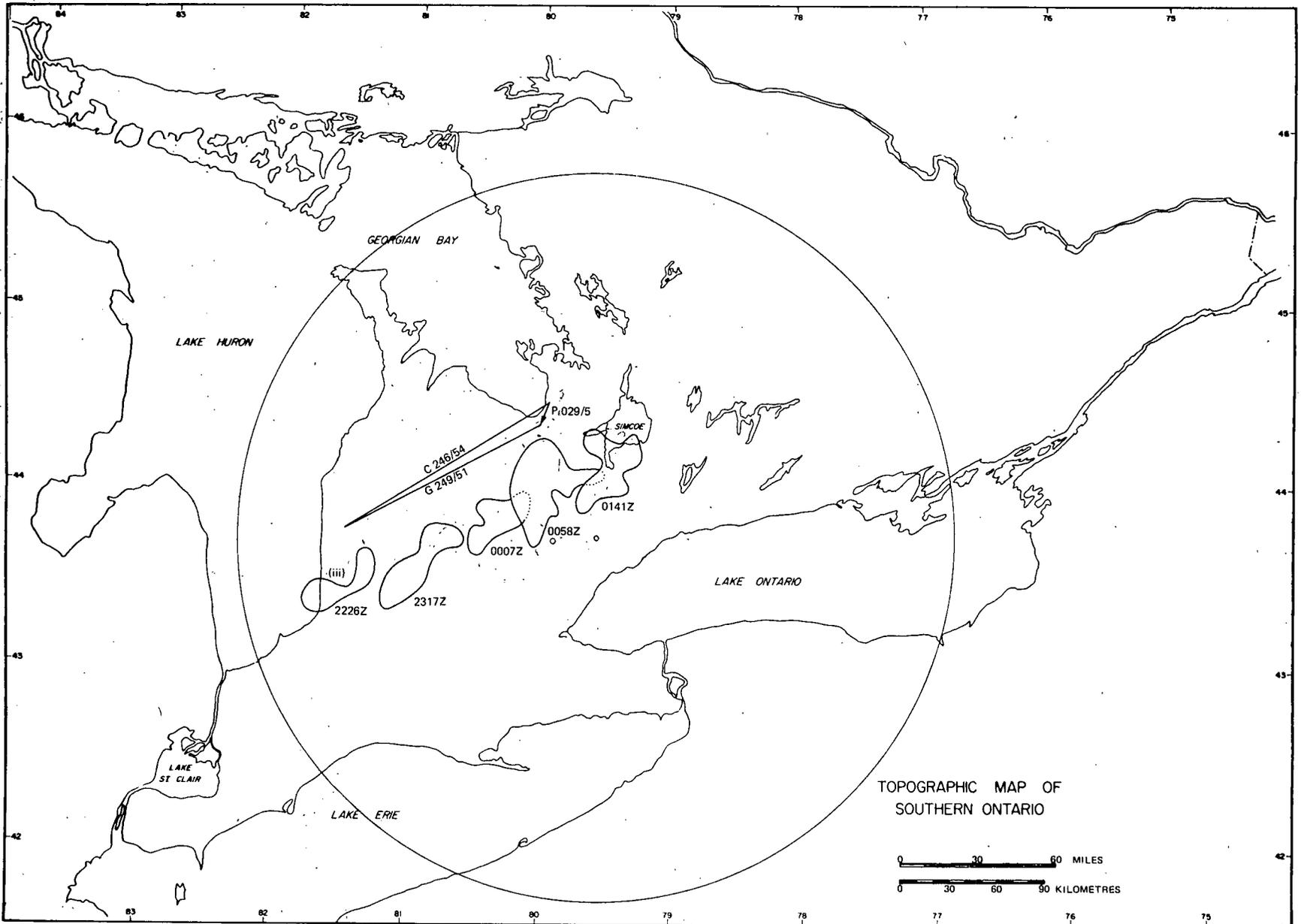


Figure 15

Tracks of thunderstorm groups and vector diagrams of cell and group motion

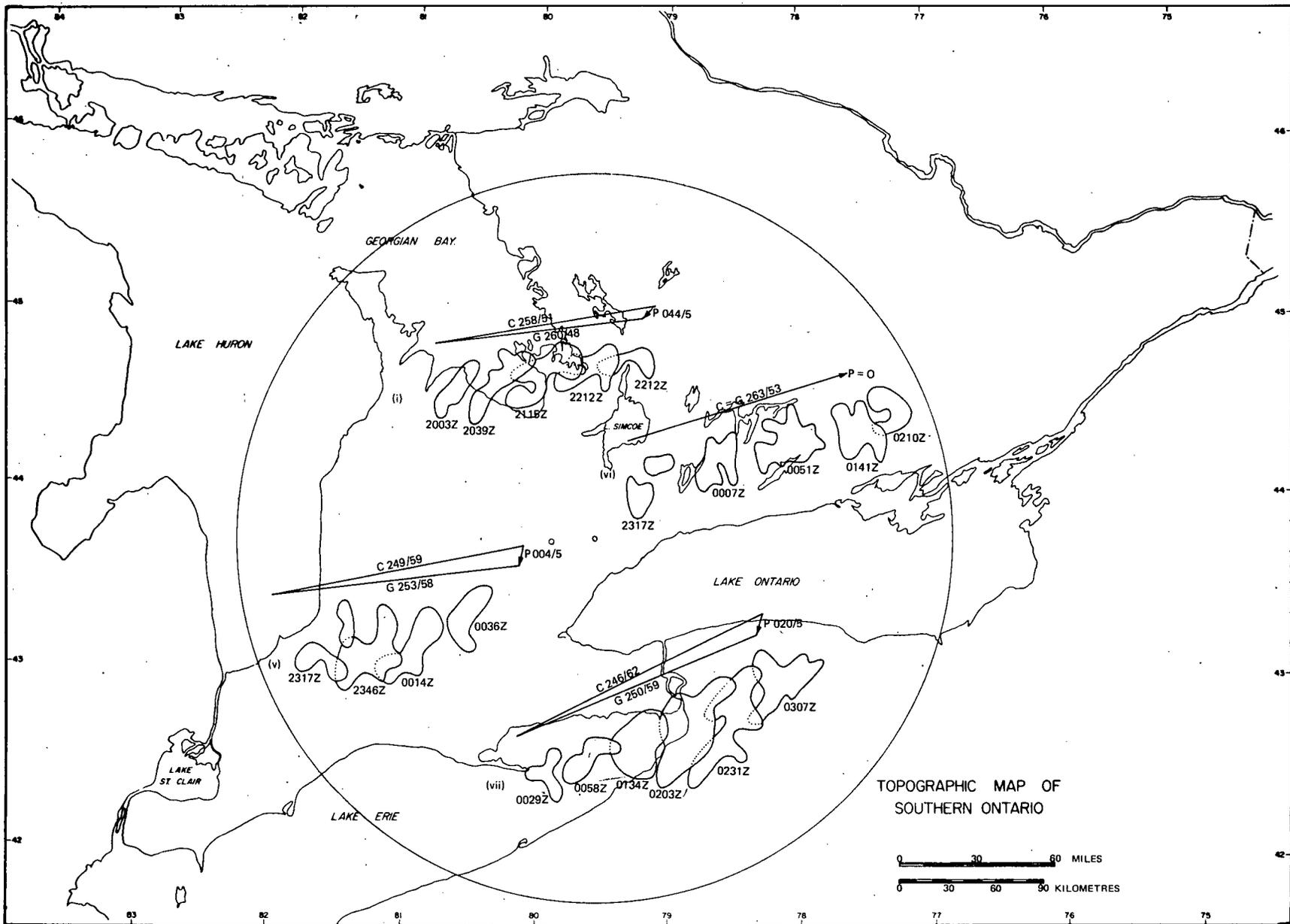


Figure 16

Tracks of thunderstorm groups and vector diagrams of cell and group motion

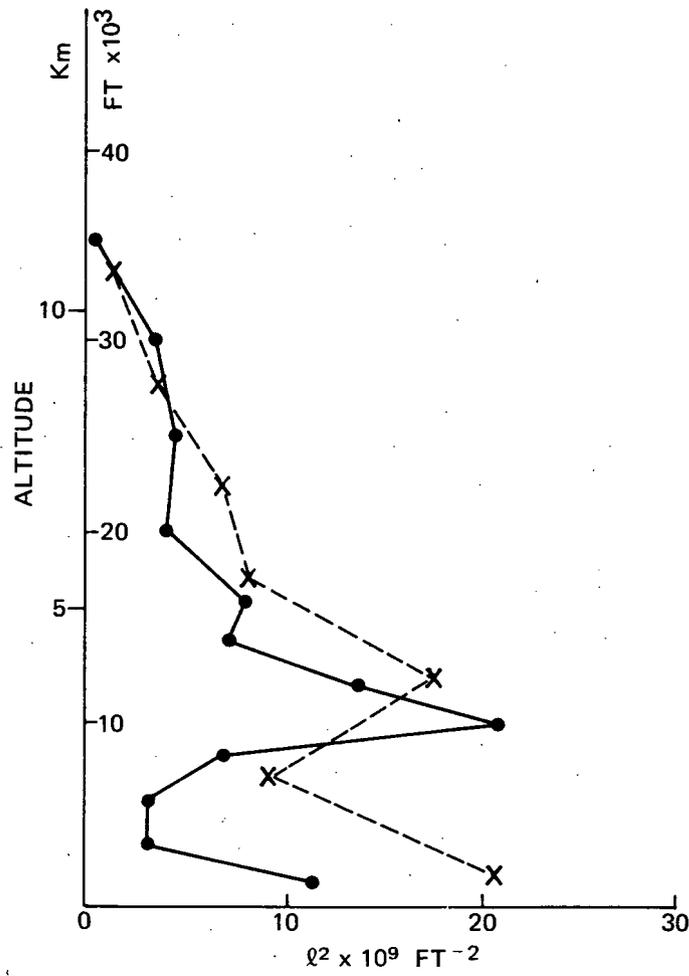


Figure 17

2 profiles when squall lines were observed to jump ahead

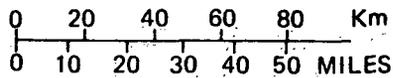
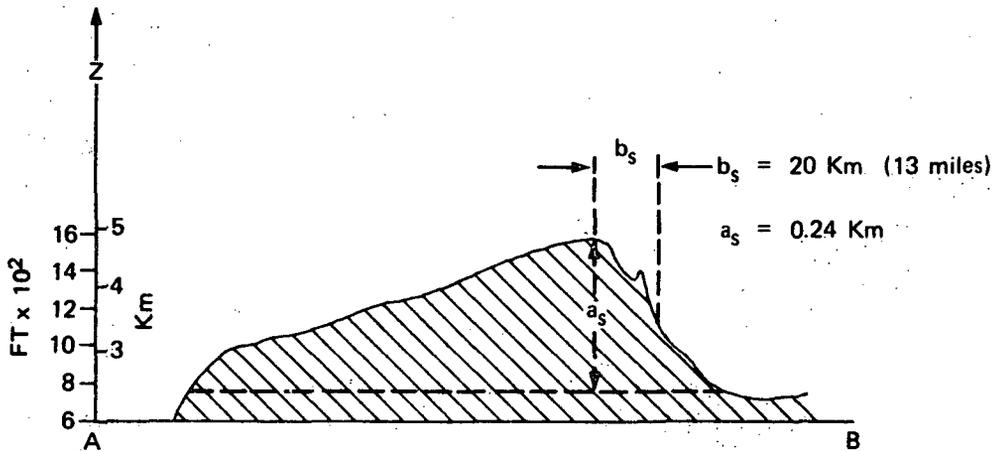
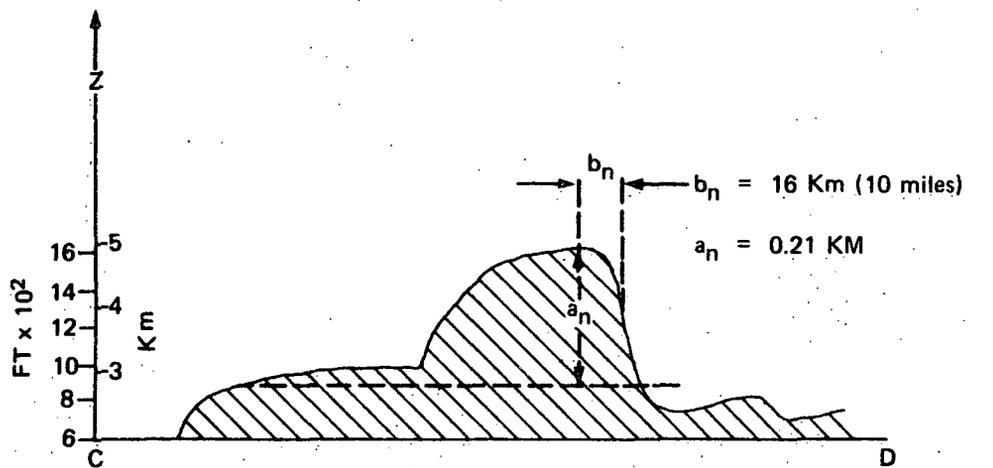


Figure 18

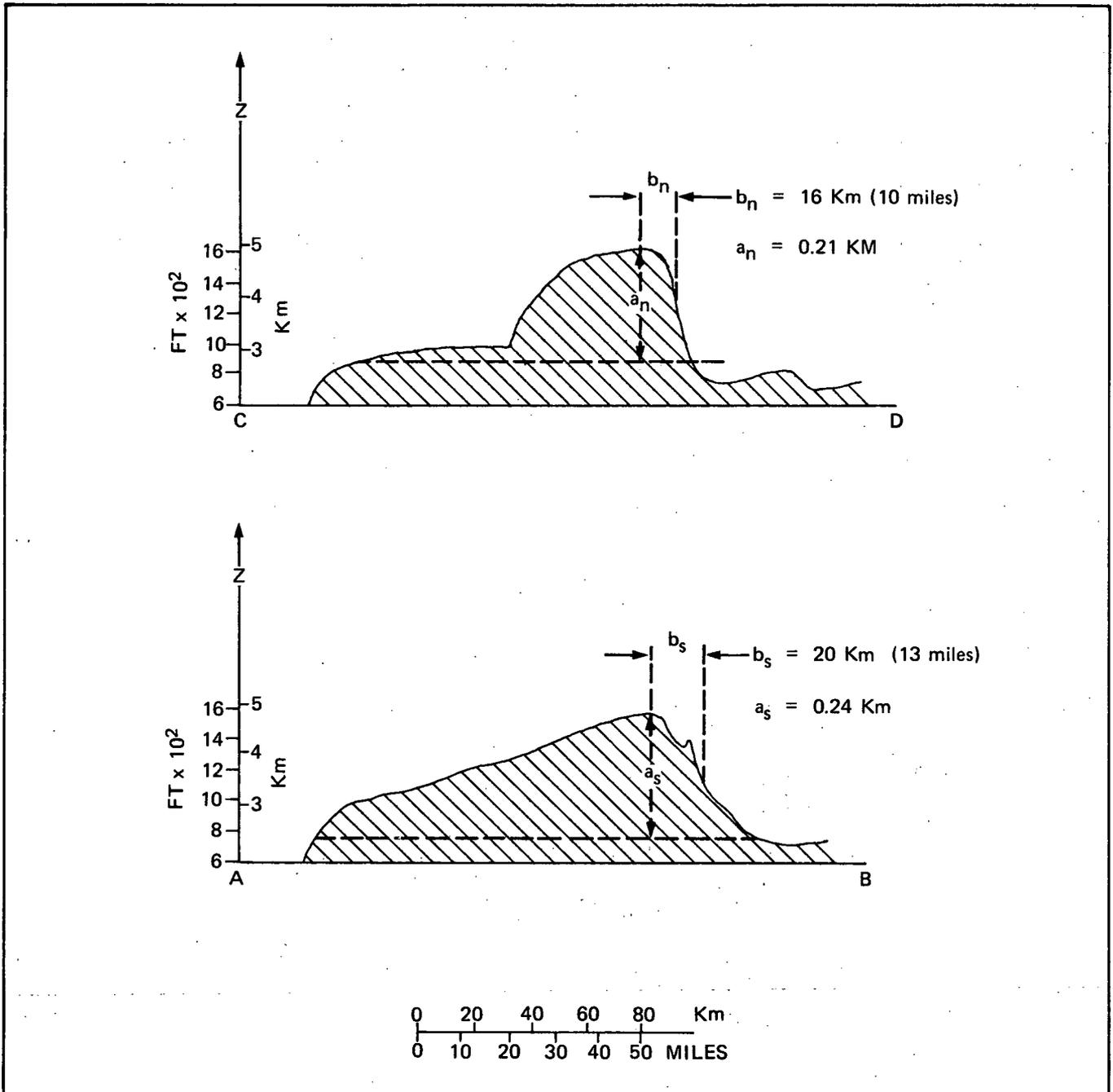


Figure 18

Cross-sections of the Niagara Escarpment

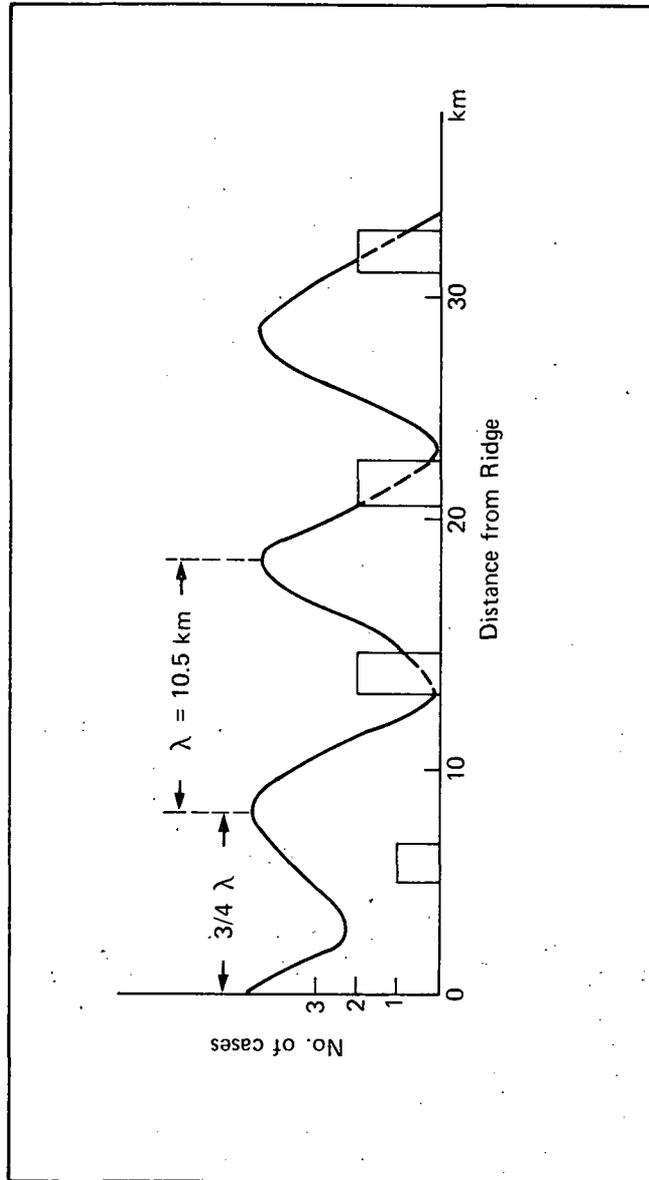


Figure 19

Relationship between thunderstorm cell dissipation and lee waves

Figure 20 2000°

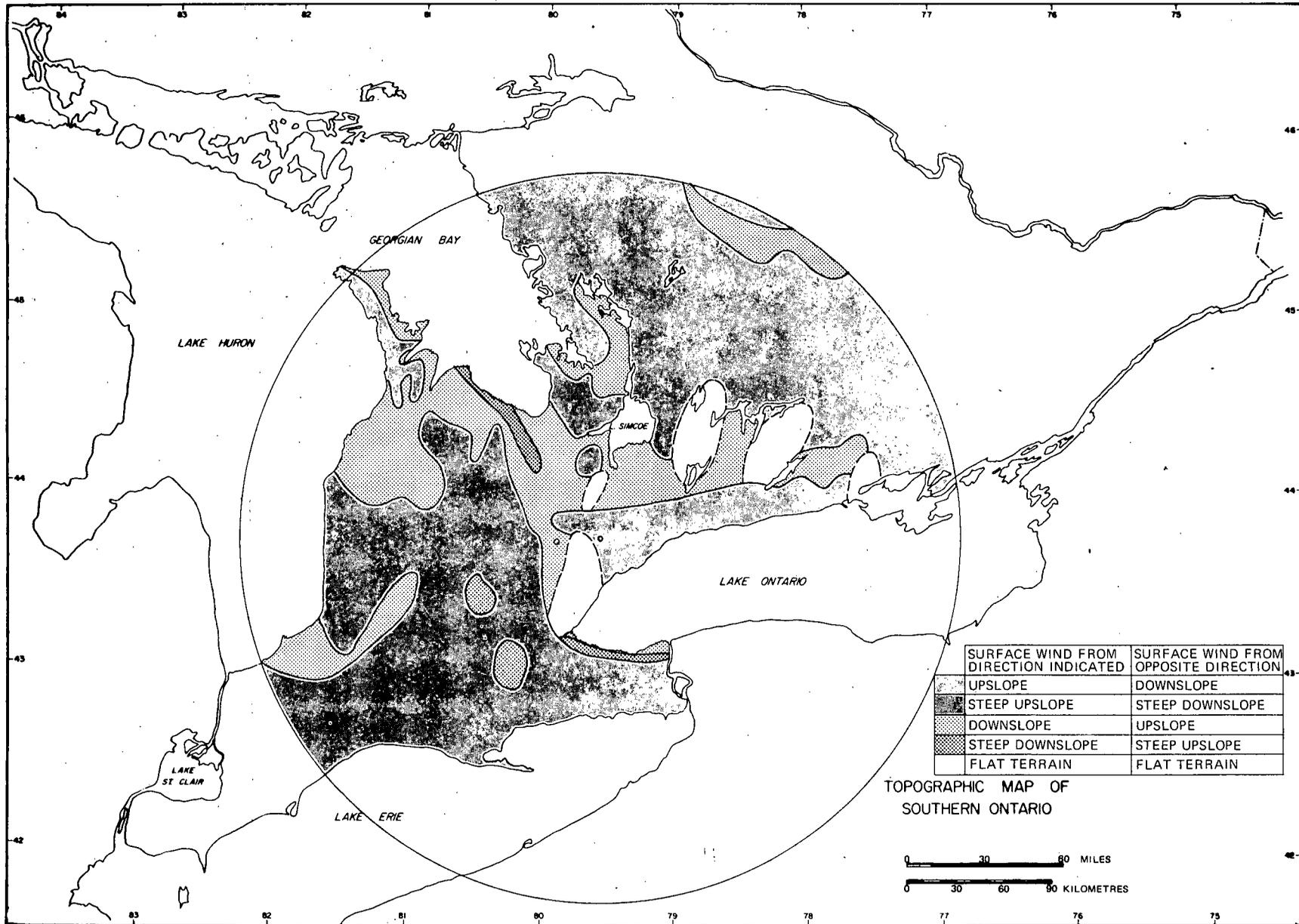


Figure 21 220°

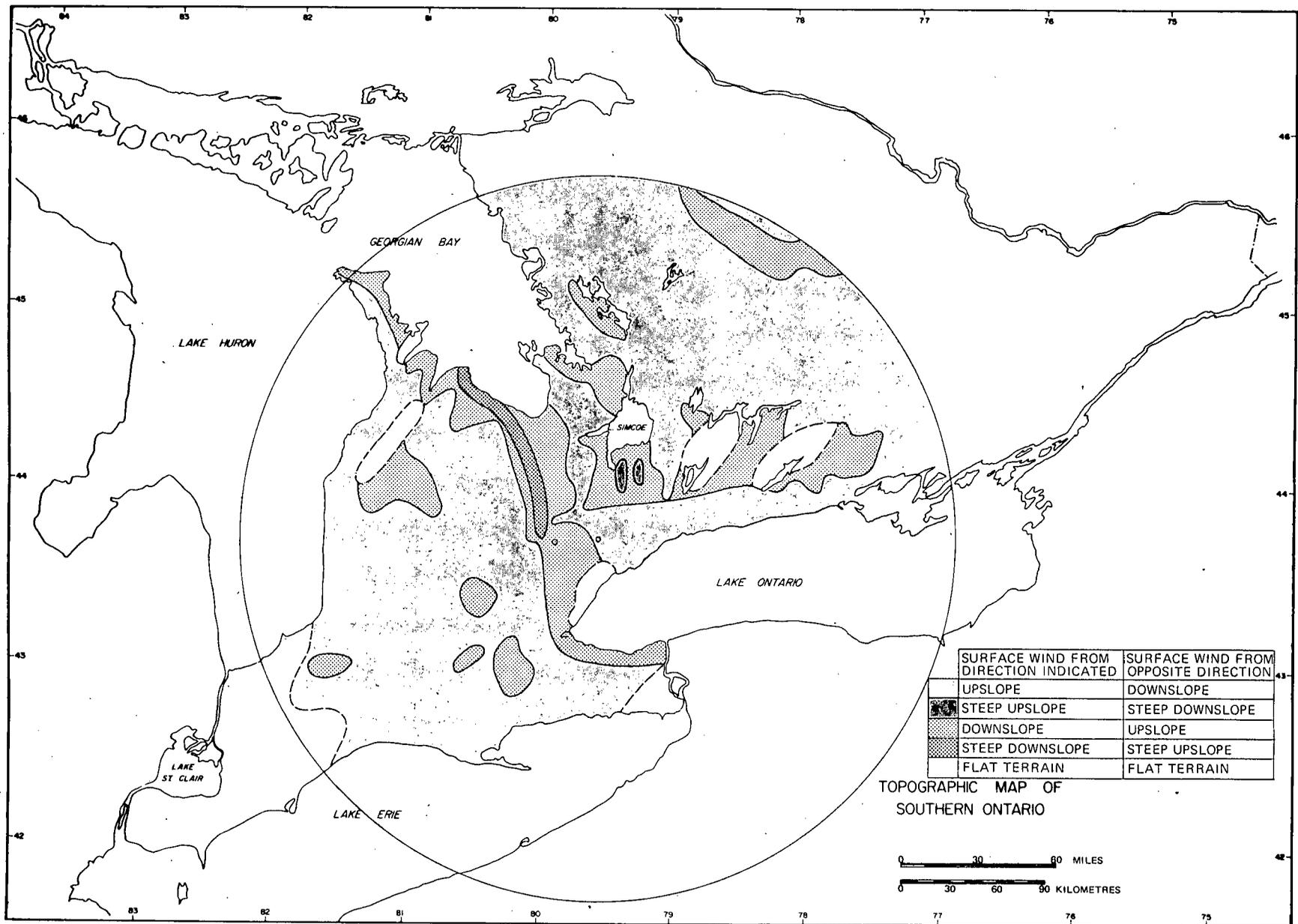


Figure 22 240°

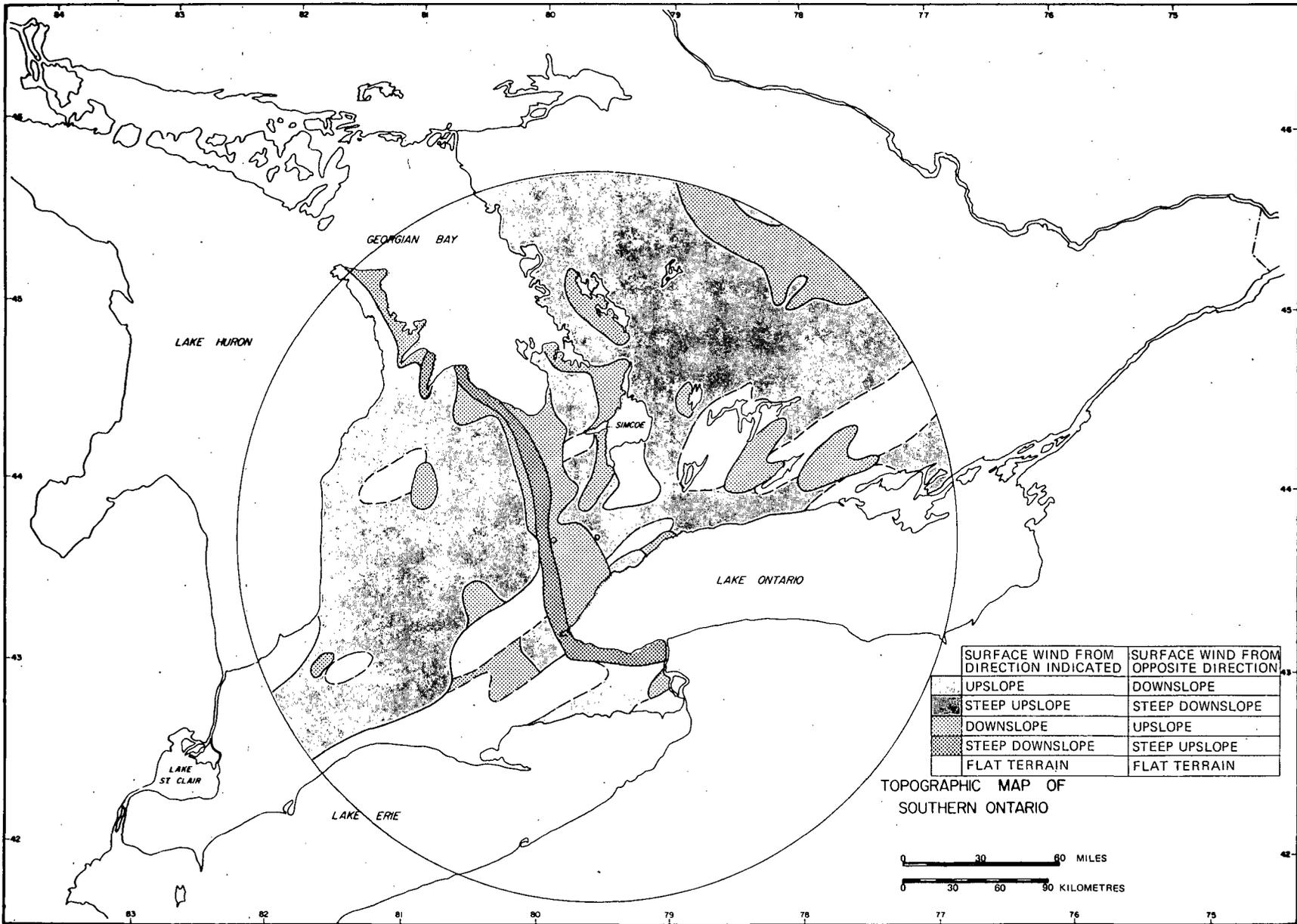


Figure 23 260°

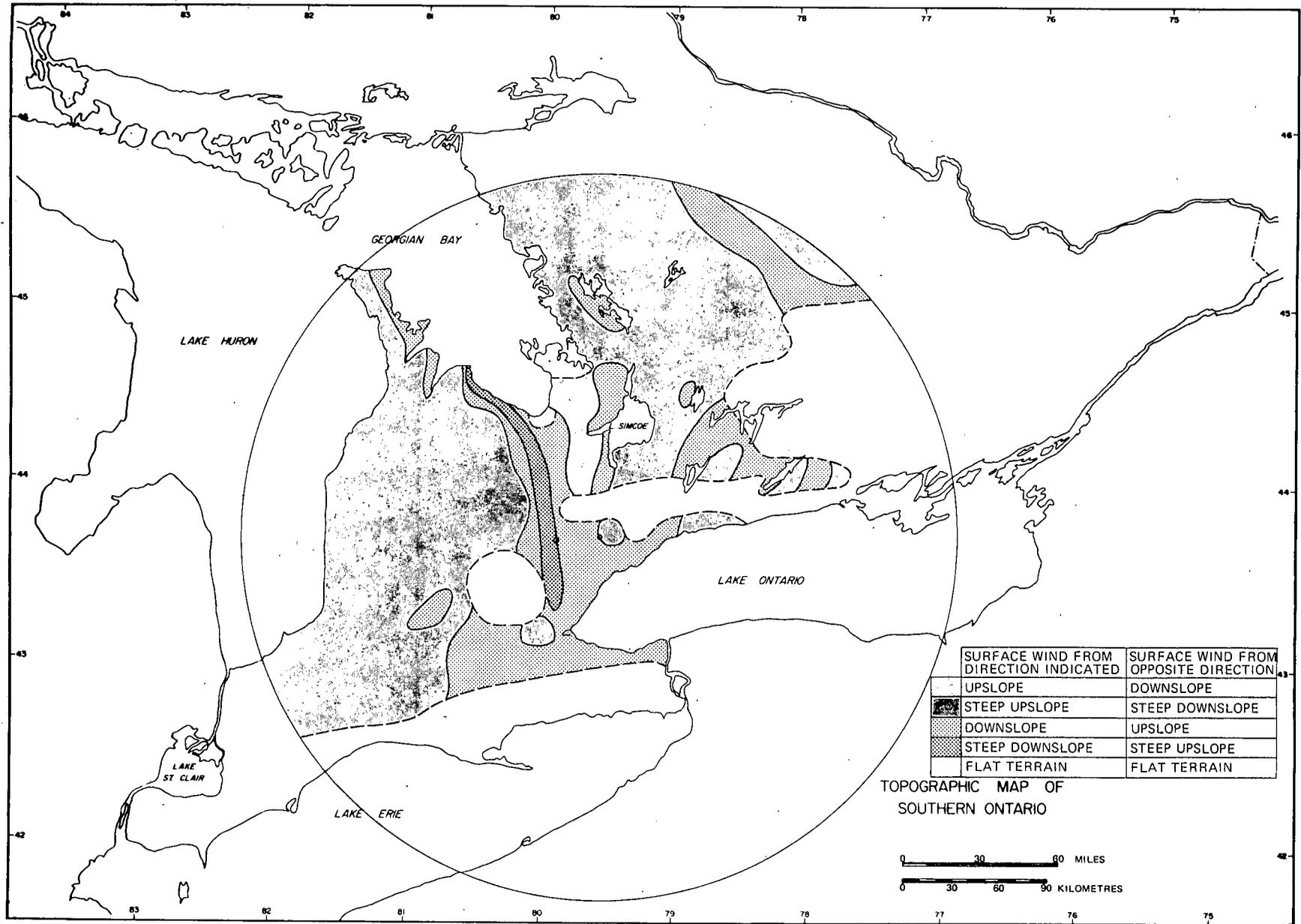


Figure 24 280°

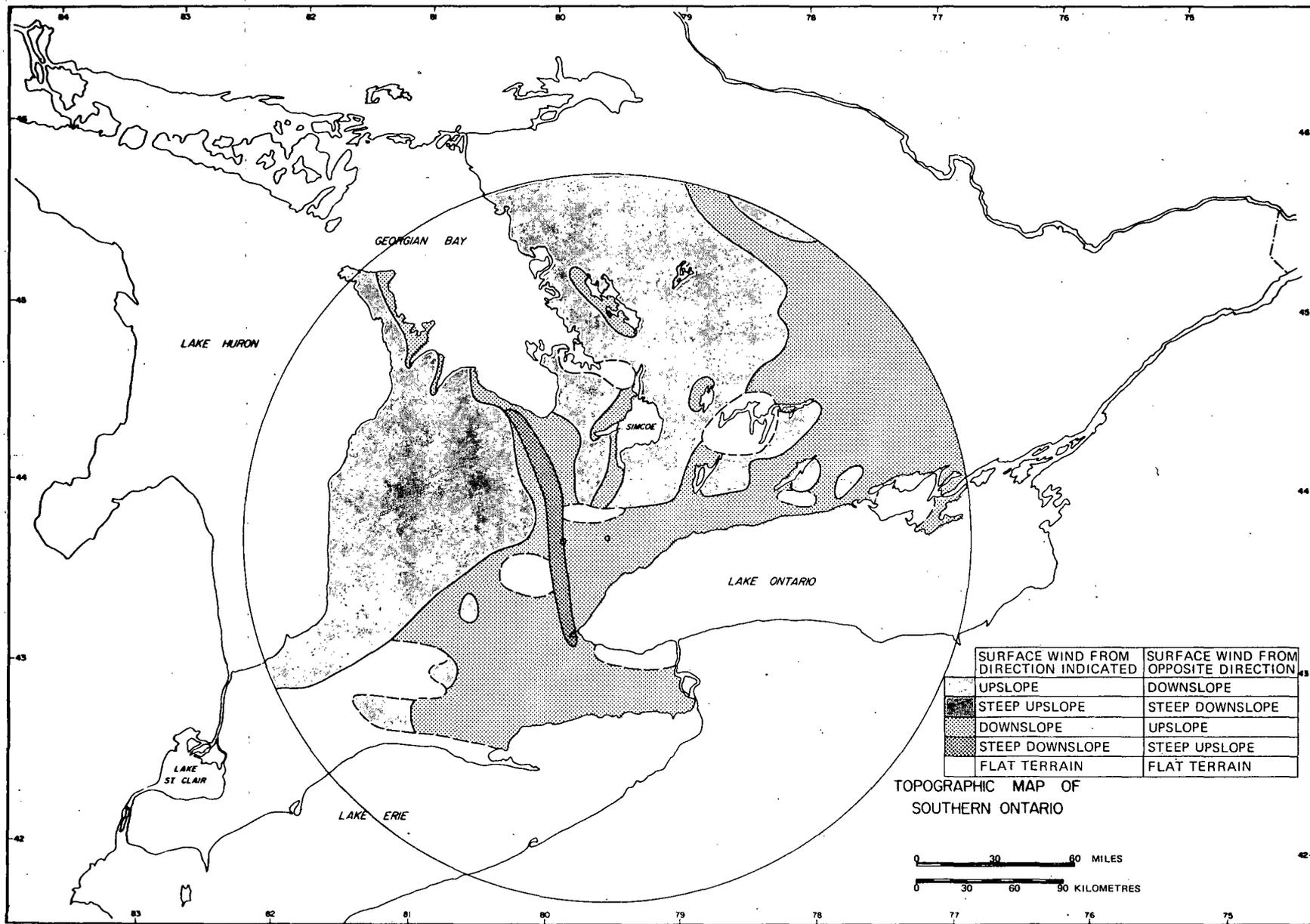


Figure 25 300°

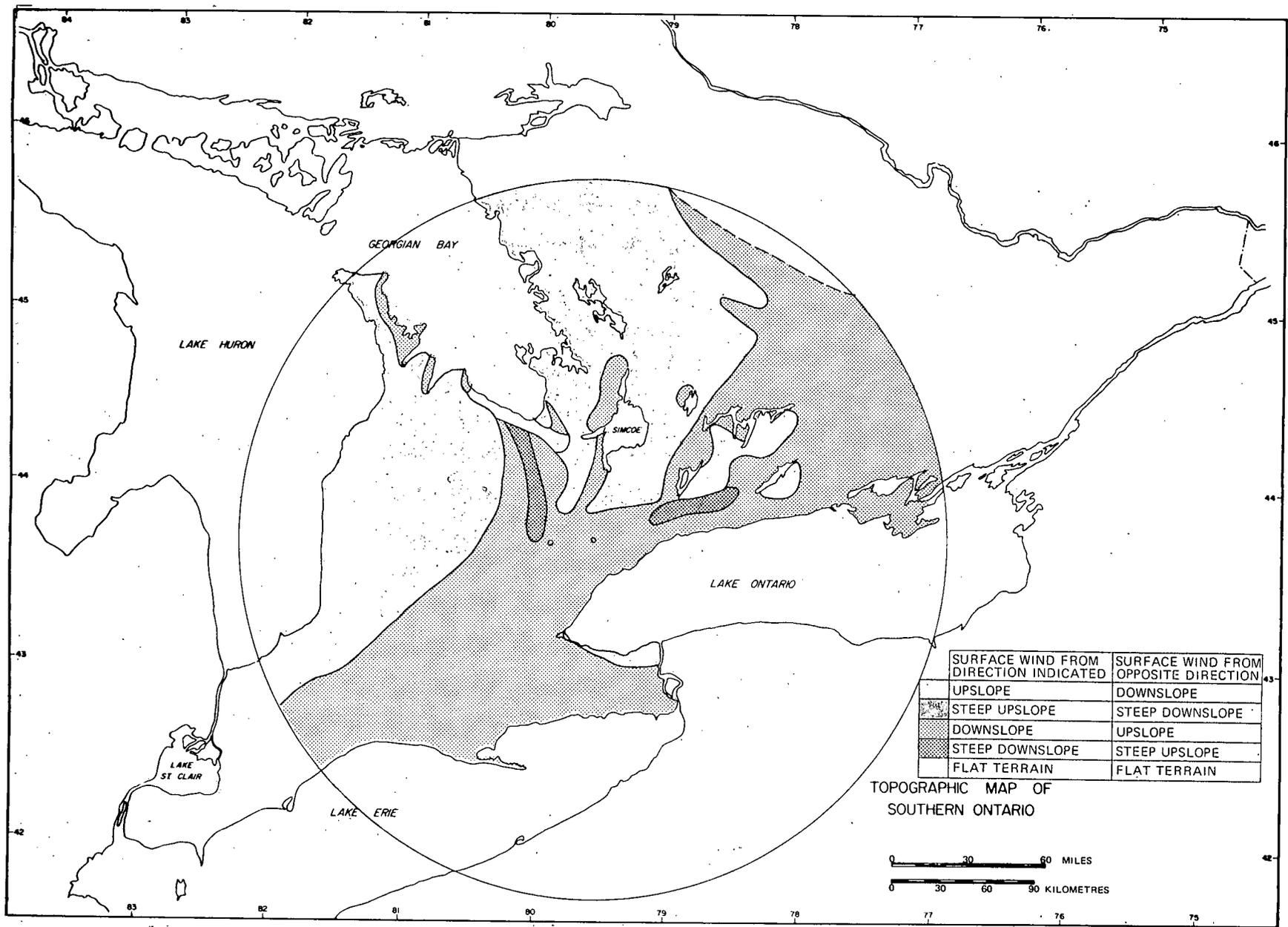


Figure 26 320°

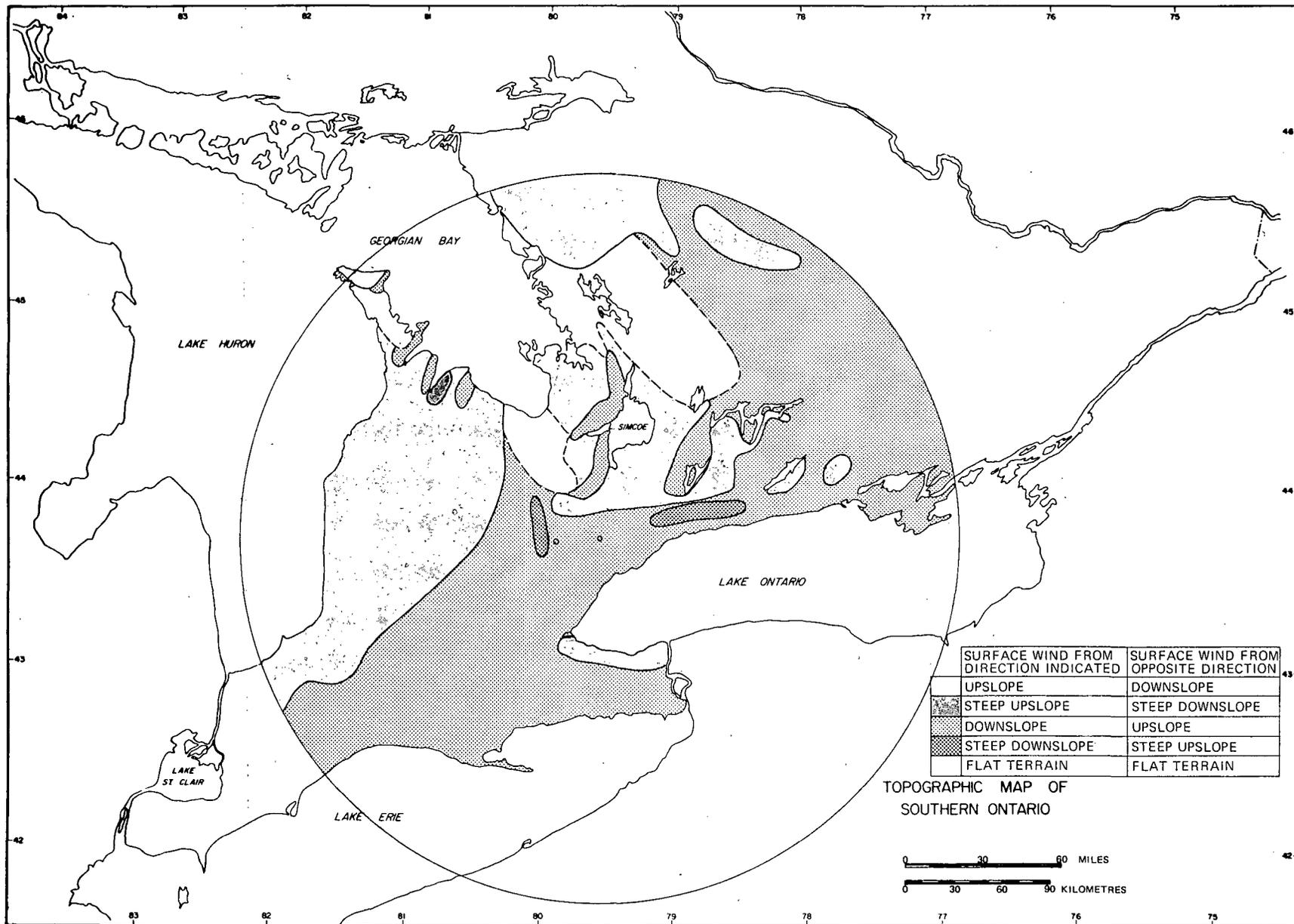


Figure 27 340°

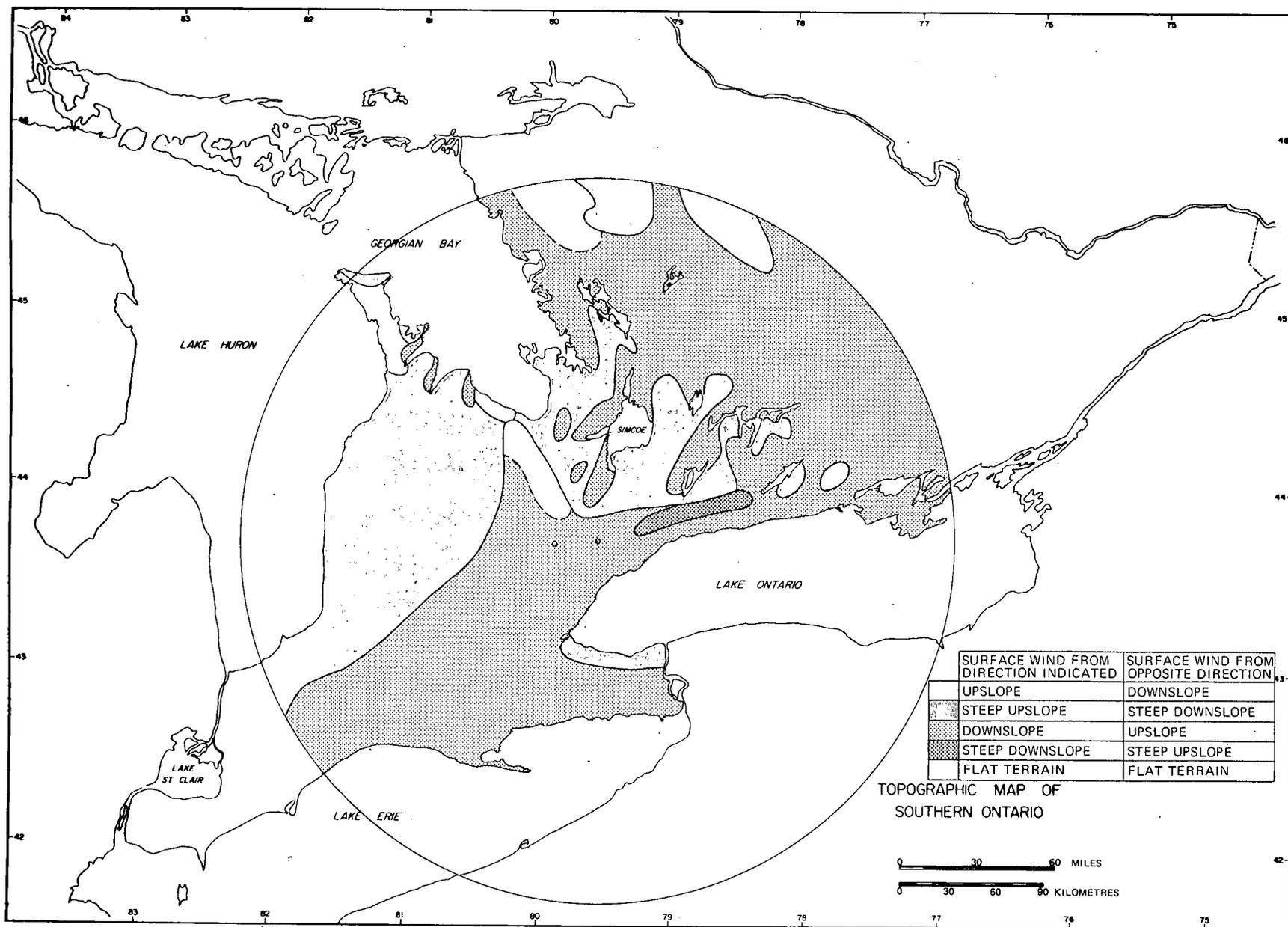
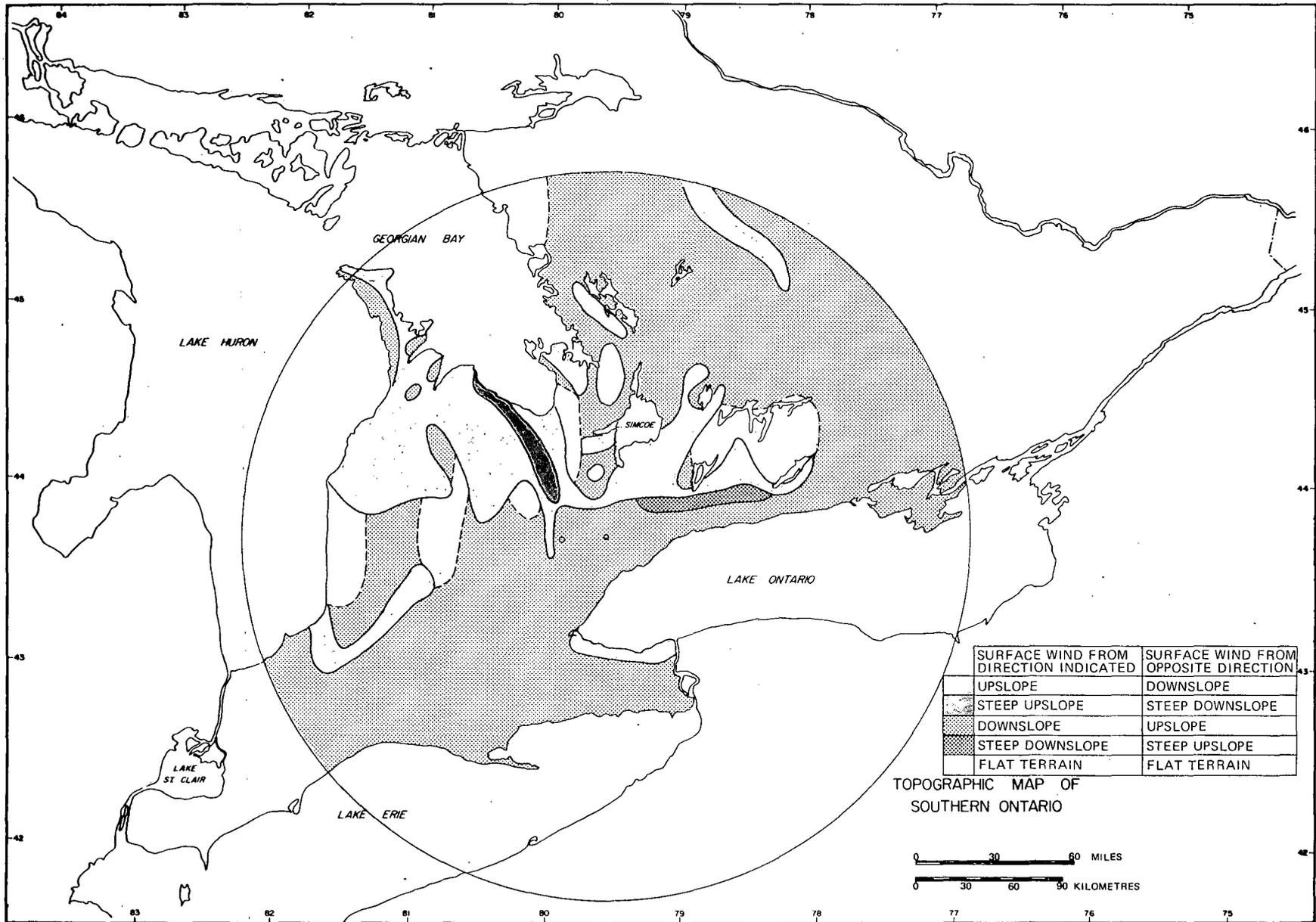


Figure 28 360°



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2 March 1976

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