Trajectory Analysis for British Columbia

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Abstract

Analyses of numerically calculated back trajectories for four British Columbia locations are presented. These are found to be consistent with synoptic experience and climatological data. Mean tracks of air parcels arriving at locations in southern B.C. are over Puget Sound and southwestern B.C., source areas of pre-cursor sulphate and nitrate pollutants. This indicates a potential exists for wet deposition of pollutants in B.C. from these sources.

A technique for forecasting POP (Probability of Precipitation) using forecast trajectories is suggested.

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1. INTRODUCTION

In the past decade, the study of Long-Range Transport of Atmospheric Pollutants (LRTAP) has come to the fore, because "acid rain" is generally a LRTAP phenomenon. Researchers investigating acid rain require a knowledge of the history of air parcels in order to establish relationships between sources and receptors. Parcel histories, usually used as input to deposition models, are necessary not only to infer sources of pollutants but to assess transformations of primary pollutants (SO_2, NO_x) to secondary pollutants ($SO_4^=$, NO_3^-). The application of a trajectory model and a deposition model to a western Canada sulphur deposition study (Kociuba et al, 1984) provided the impetus for the study described below.

A prime purpose of this investigation was to assess the reliability of numerically calculated trajectories used in the western Canada deposition study. An attempt to compare a small number of hand-calculated trajectories (by estimating winds from analyzed charts) with machine-produced trajectories proved inconclusive because of the difficulty of estimating wind speeds from isobaric charts for the eastern Pacific. It was decided as an alternative to assess their reliability on the basis of the consistency of a trajectory analysis with synoptic experience. The results are described below.

The trajectory data, if reliable, may be used as input to a deposition model from which one can infer source-receptor relationships. Short of taking that second step, however, it is possible to infer the potential for medium and long range transport of acidic pollutants from a trajectory analysis.

An analysis of trajectories may benefit other than acid rain investigators. A study of trajectories adds another dimension to the study of mean flows, most of which are based on mean pressure patterns. Use of the latter gives an approximation to mean trajectories but requires the assumption of unchanging flow fields. A trajectory analysis may provide insight into the properties of air parcels arriving at a particular location; a climatological study of trajectories may serve as an aid to forecasters, or may lead to objective (statistical) forecasting techniques.

2. TRAJECTORY DATA

One may compute trajectories backward or forward in time from analyzed wind fields (including vertical motions). Marvin Olson of Air Quality Research Branch, Atmospheric Environment Service Headquarters, Downsview, Ont. provided trajectory data to be used in this study from analyzed wind fields on a 381 km grid for the northern hemisphere available at the Canadian Meteorological Centre (CMC) in Montreal. These data are endpoints of trajectories at intervals of six hours up to 96 hours backward in time. Data are for four "receptor" stations, Vancouver, Terrace, Revelstoke and Fort Nelson (see Figure 1 for locations). Since the gridded wind field data are on a 381 km grid, the computed trajectories are only appropriate for long or medium range analysis.

Trajectories at the 85 kPa level (1500 m above sea level) were selected for all four stations for the year 1978. In the case of Vancouver, trajectories at the 92.5 kPa level (750 m) were also computed, however, only the higher elevation trajectories were analyzed.

Trajectory endpoints for each time step are calculated with an iterative technique described by Olson et al (1978). The technique assumes a constant acceleration (equal to zero for the first guess). Successive estimates are made assuming the acceleration is equal to the difference in velocities at the beginning and end points of the trajectory segment. Iteration continues until two successive trajectories differ by less than a pre-set value. Horizontal and vertical displacements are calculated starting at given levels (92.5, 85, 70, etc. kPa) above the receptor site for the required number of time steps.

3. DATA ANALYSIS

Several methods may be used to analyze trajectories. Desautels (1981), for example, analyzed trajectories for Quebec by length and by wind direction. He presented these as tables, as depictions of "corridors" representing most frequent tracks, and by a superposition of all tracks on one diagram. For the B.C. analysis, an attempt has been made to present the analyses in a simple manner by depicting the frequencies with which air parcels originate in grid squares of approximately equal area. As well, mean tracks were calculated for "wet" and "dry" cases.

A computer program was written to count the frequencies of trajectory endpoints in grids 2.5 degrees latitude by 5.0 degrees longitude. These counts were converted to "endpoint densities" by calculating the area of the grid squares in which they fell. The densities were plotted on charts and isopleths of equal densities drawn.

Appendix A contains endpoint density analyses for 12, 24 and 48 hours at the 85 kPa level for the B.C. stations. Annual and seasonal analyses (winter = January, February and December, summer = June to August) are included. Units used are endpoint densities per 100,000 km^2. Solid isopleths are for multiples of 100; dashed isopleths, when included, are intermediate values and so labelled.

The endpoints were divided into two classes, "wet" and "dry" for further analysis. A case was classed as "wet" if measurable precipitation (greater than a trace) fell at the receptor station in the 6-hour period preceding the time the air parcel arrived at the station; all others were classed as "dry".

For the wet and dry cases, mean latitudes and longitudes of endpoints were calculated for each time step. These represent mean locations of air parcels at successive time steps and, when plotted on a chart, may be considered to represent mean vector motions of the air parcels. Charts of these for wet and dry cases appear as Figures 2-7.

The relative frequencies with which precipitation occurs when air parcels originate in the grid squares 24 hr. previously were calculated and plotted. These appear as Figures 8-11. An example may clarify the meaning of these diagrams. Referring to Figure 8, we note .12 is plotted on the grid point just off Vancouver Island. This indicates that (in 1978), precipitation fell at Vancouver 24 hrs later in 12 percent of the cases when a parcel of air originated in the square 2.5° latitude by 5.0° longitude centred on that grid point. It should be noted, data are plotted only on those grid squares from which one parcel of air originated.

4. REPRESENTATIVENESS OF THE DATA

The data used in this study are for a one-year period (1978) only. Obviously, it would be preferable to have data for a, say, 10-year period but these were not available. Hence, before attempting to interpret the data in a long-term climatological sense, it is well to look at the "representativeness" of the year 1978.

On the basis of annual climatological parameters (mean temperature, total precipitation) of the four stations, it would seem that 1978 was close to a "normal" year. Table I shows that annual mean temperatures at the four stations deviated from the 1951-80 normals by no more than 1.1 C, total precipitation was within 5 percent of normal at each site. On a seasonal basis, as would be expected, the deviations were greater; temperature deviations were as high as 3.6 C (Terrace in the winter months), total precipitation was as low as 42 percent of normal (Fort Nelson in winter months).

Deviations from "normal" 70 kPa circulation patterns are also found (Wagner, 1979). Positive height anomalies prevailed most of the year in western North America as a block persisted in the area. The Arctic low was deeper than normal throughout the spring, summer and fall months but weaker than normal in January and February and again in late 1978.

The anomalous flow patterns noted above and the large seasonal temperature and precipitation anomalies suggest that 1978 was atypical. This should be considered in assessing the climatological representativeness of the trajectory analyses of Appendix A.

5. DISCUSSION

The dispersive nature of the atmosphere is clearly evident from the analyses of Appendix A. Trajectories of 48 hours for all stations show a very "flat" distribution over the eastern Pacific and western North America. In the 12 and 24-hour periods, well-defined maxima of densities are evident but these almost disappear by 48 hours. Beyond 48 hours (analyses not given here) very few well-defined maxima are observed.

The general west to east flow of air is also evident as the maxima generally move westward as the trajectory period increases.

Seasonal variations of the calculated trajectories may be related to the mean large scale pressure systems, namely the Aleutian Low and the

Pacific Anticyclone. In the winter months, the analyses indicate air parcels arriving at coastal sites (in particular, at Vancouver) tend to travel from the south and southwest. In summer, the paths are more from the west or northwest although a significant number arrive from the southwest. (These latter are important to note since, as will be seen later, they tend to be rain-bearing parcels). These flow patterns are consistent with the seasonal strengthening and weakening of the semi-permanent Pacific pressure systems. One might add that the analyses show that air parcels travel more rapidly in winter than in summer, as one would anticipate.

Seasonal variations for the two interior stations, Revelstoke and Fort Nelson are much less pronounced. At Revelstoke, the prevailing flows are generally westerly, although winter flows, of course, are much stronger. At Fort Nelson, the westerly circulation is less evident; the analyses suggest weak flows from the Yukon and northern B.C. but a significant number of parcels also come from the Mackenzie Valley.

We find marked differences in mean trajectories for "wet" and "dry" cases, particularly at the coastal sites. Rain-bearing flows are indicated to be more from the southwest and considerably stronger (see Figures 2-7). Interestingly, at Terrace in winter, the main difference appears to be the strength of the flow.

The summer mean "wet" and "dry" trajectories for Fort Nelson differ only slightly and it is believed this is due to the nature of precipitation in that region. Fort Nelson is in the lee of the Rocky Mountains and hence in a subsidence zone for westerly flows whereas Revelstoke, to the west of the Rockies, receives considerable orographic precipitation in the prevailing westerly flows. At Fort Nelson, precipitation is often associated with an easterly upslope circulation such as occurs when an upper cold low traverses central B.C. Also, Fort Nelson has a decidedly continental climate with a pronounced summer season maximum of precipitation. Much of this summer precipitation is convective and thus less dependent on circulation than the orographic-frontal precipitation which prevails at the other sites.

The last four diagrams (Figures 8-11) show the relative annual frequency with which precipitation occurs when air originates in the grid squares 24 hour prior to arrival at a receptor station. They should be interpreted cautiously because of the small data base used. In particular, the fractions for the fringe grid squares are not reliable since in many cases they are determined from only one or two observations. Nevertheless, the diagrams are useful since they support earlier comment on rain-bearing flows and they suggest a possible technique for forecasting probability of precipitation (POP).

Although the data base employed was too small to make absolute values of POP reliable, it is evident that consistent patterns emerge. For Revelstoke, Vancouver and Terrace, where precipitation is largely frontal and orographic, the higher POP is associated with strong southwesterly flows (long trajectories). It is this consistency which suggests a successful forecast technique might be devised using such analyses (prepared from a larger data base) and using predicted trajectories from NWP prognostic 85 kPa charts.

The analysis for Fort Nelson exhibits a pattern unlike those for the other three stations. Easterly flows there are more likely to bring precipitation than westerly ones. However, because of the nature of precipitation at Fort Nelson, the suggested forecast technique is less likely to be successful than at the other sites.

6. SUMMARY AND CONCLUSIONS

Patterns of backward trajectory endpoint densities have been analyzed and presented for four B.C. stations. The patterns of trajectory densities and of "mean" air parcel tracks are consistent with synoptic experience and climatological data. One, therefore, has a degree of confidence that the trajectory data are reliable and are suitable for input to a deposition model.

The analyses give an estimate of the long-term trajectory climatology. However, because the year 1978, for which the analysis was performed, is atypical, analysis of a larger data base is necessary to establish a more reliable climatology representative of long-term conditions. An analysis of a minimum of five years data is suggested in order to establish a trajectory climatology.

The mean "wet" tracks (based on the analyses for 1978) indicate a high potential for wet deposition of sulphates and nitrates in southern B.C. The main source areas of pre-cursor pollutants are the Lower Mainland of B.C. and the Puget Sound area of Washington. (Two large SO_2 emitters, a smelter and a coal-fired electrical generating station, are located just south of Seattle, at Tacoma and Centralia respectively). The mean track of rain-bearing parcels for Vancouver, particularly in winter, lies just to the northwest of Puget Sound and obviously many trajectories traverse that area. (The 92.5 kPa annual mean "wet" track is directly over Puget Sound which reflects the veering of low-level winds.) Similarly, the mean "wet" track for Revelstoke is just south of the B.C. Lower Mainland and directly across Puget Sound. By contrast, the mean track at Terrace is well north of both source regions, ie. most trajectories are across the open waters of the Pacific. This suggests the possibility of searching for differences in $SO4^{=}$ and $NO3^{-}$ concentrations in precipitation samples at the three sites which might be attributed to the differing trajectories. Such differences, if found, would assist in inferring sources of pollutants deposited in southern British Columbia.

A technique using predicted trajectories for forecasting POP has been suggested.

REFERENCES:

Desautels, G., 1981: Trajectories of Air Parcels Reaching Quebec in 1978. Scientific Services Division, Atmospheric Environment Service, Quebec Region, Montreal.

Kociuba, P.J., D. Faulkner and R. Hopkinson, 1984: Sulphur Deposition Modelling in Western Canada. Report in preparation.

Olson, M.P., K.K. Oikawa and A.W. MacAfee, 1978: A Trajectory Model Applied to Long Range Transport of Air Pollutants. Atmospheric Environment Service, Downsview, Ontario, Report No. LRTAP 78-4. 24 pp.

Wagner, A. James, 1979: The Circulation and Weather of 1978. Weatherwise, Vol. 32(1), Helen Dwight Reid, Education Foundation, Washington, D.C.

TABLE I

Deviations of 1978 Mean Temperatures and Total Precipitation Amounts from 1951-80 Normals

	VANCOUVER	TERRACE	REVELSTOKE	FORT NELSON
Temperature Deviation (°C) From Normal (actual - normal)				
ANNUAL	0.0	+0.5	-0.3	+1.1
WINTER	0.0	-3.6	-0.7	+2.9
SUMMER	+0.7	+1.4	-0.1	-0.5
Percent Normal Precipitation				
ANNUAL	90	99	95	95
WINTER	70	80	50	42
SUMMER	112	117	134	90

List of Figures

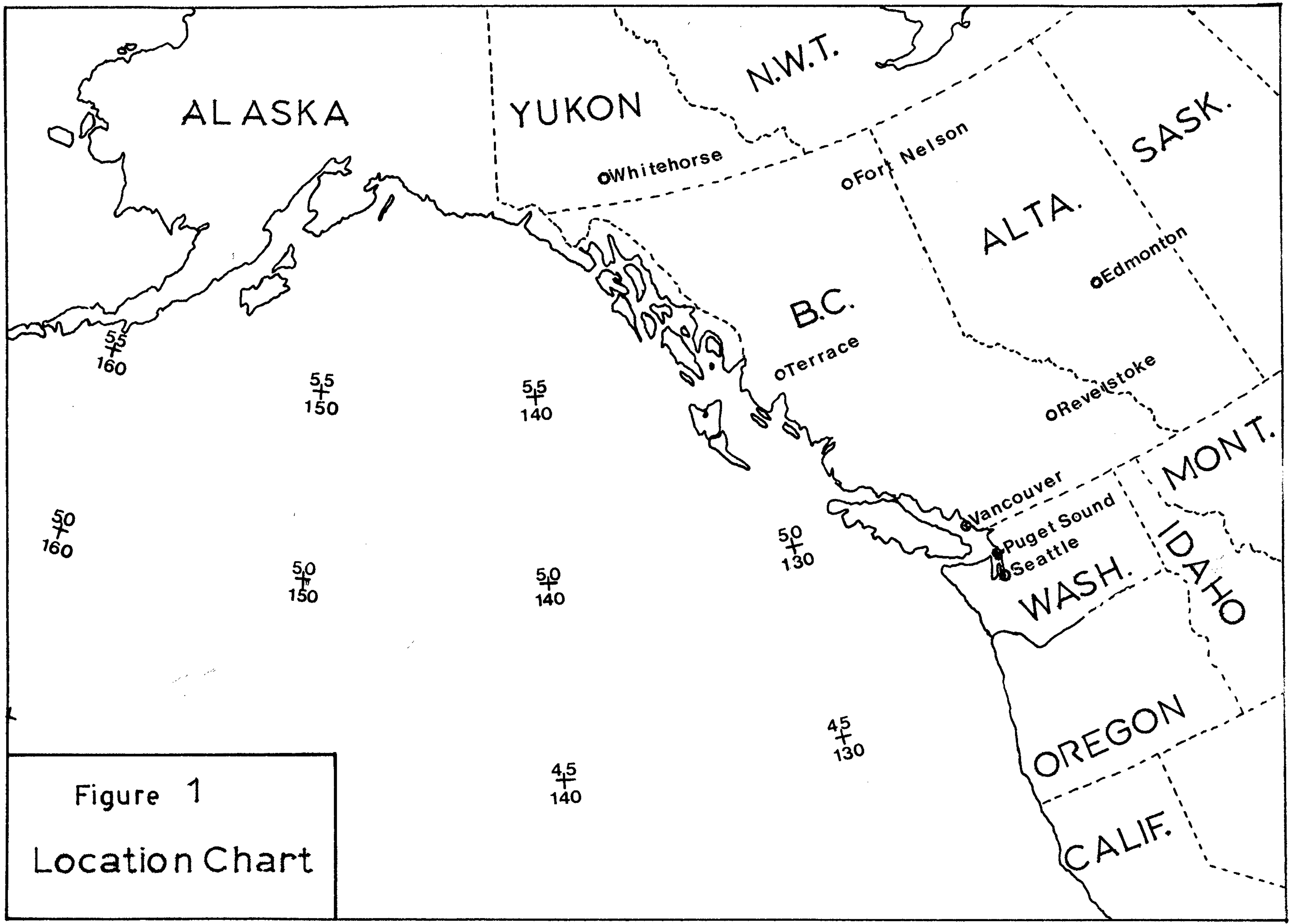


Figure 1

Location Chart

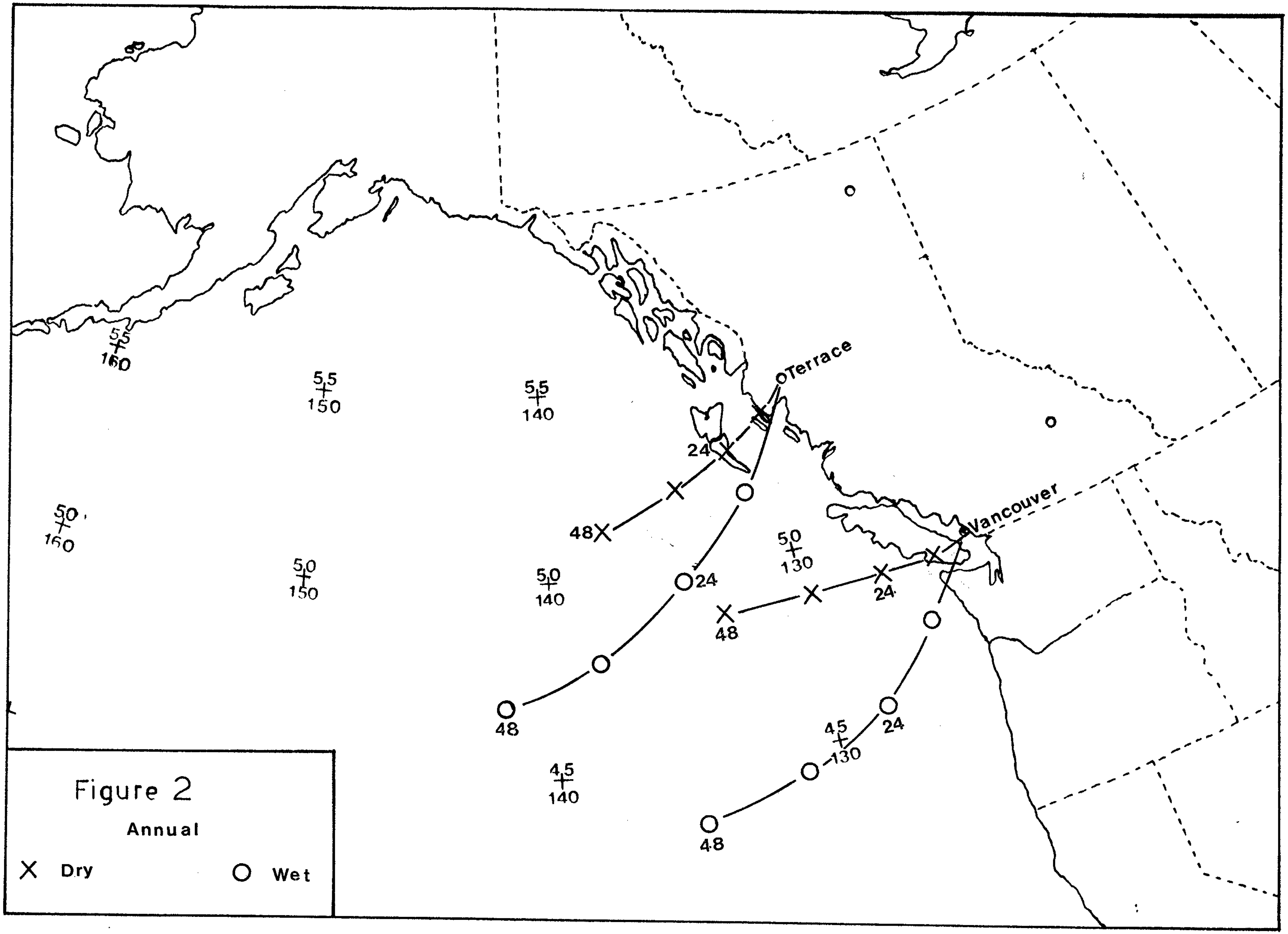


Figure 2

Annual

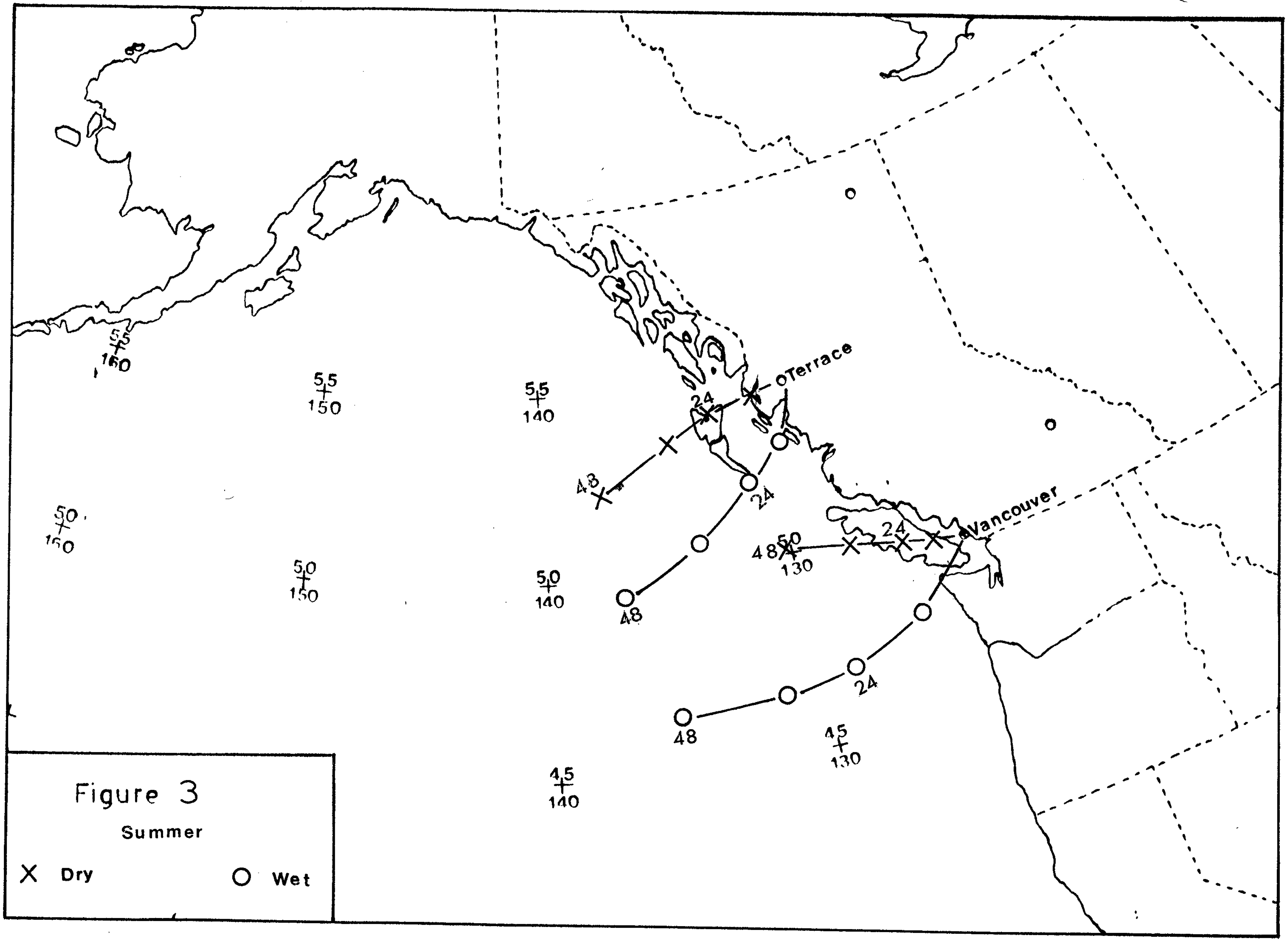


Figure 3

Summer

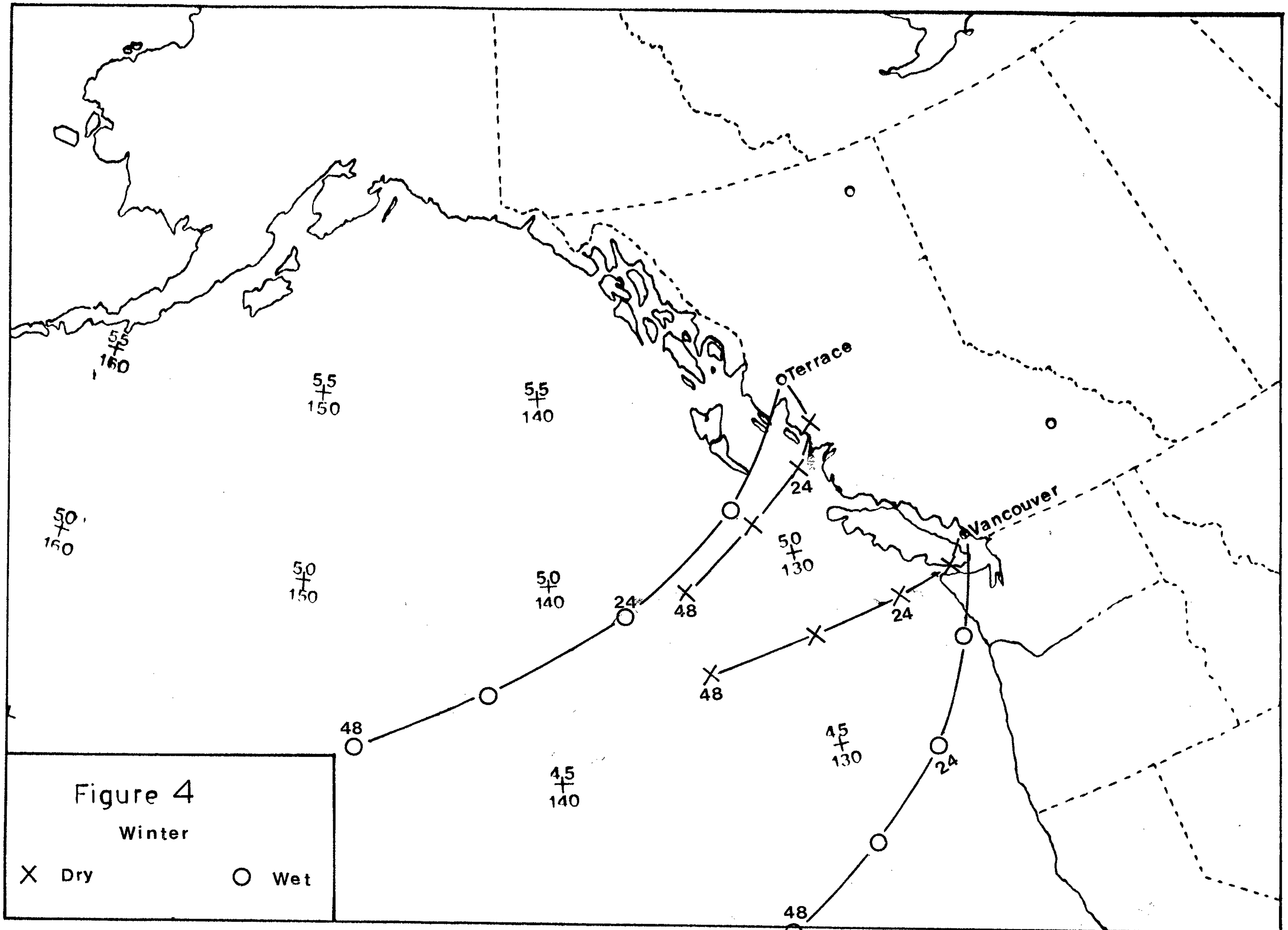

Terrace
Vancouver
5.5 160
5.5 150
5.5 140
5.0 160
5.0 150
5.0 140
5.0 130
4.5 140
4.5 130
24
48
Winter
Dry
Wet

Figure 4

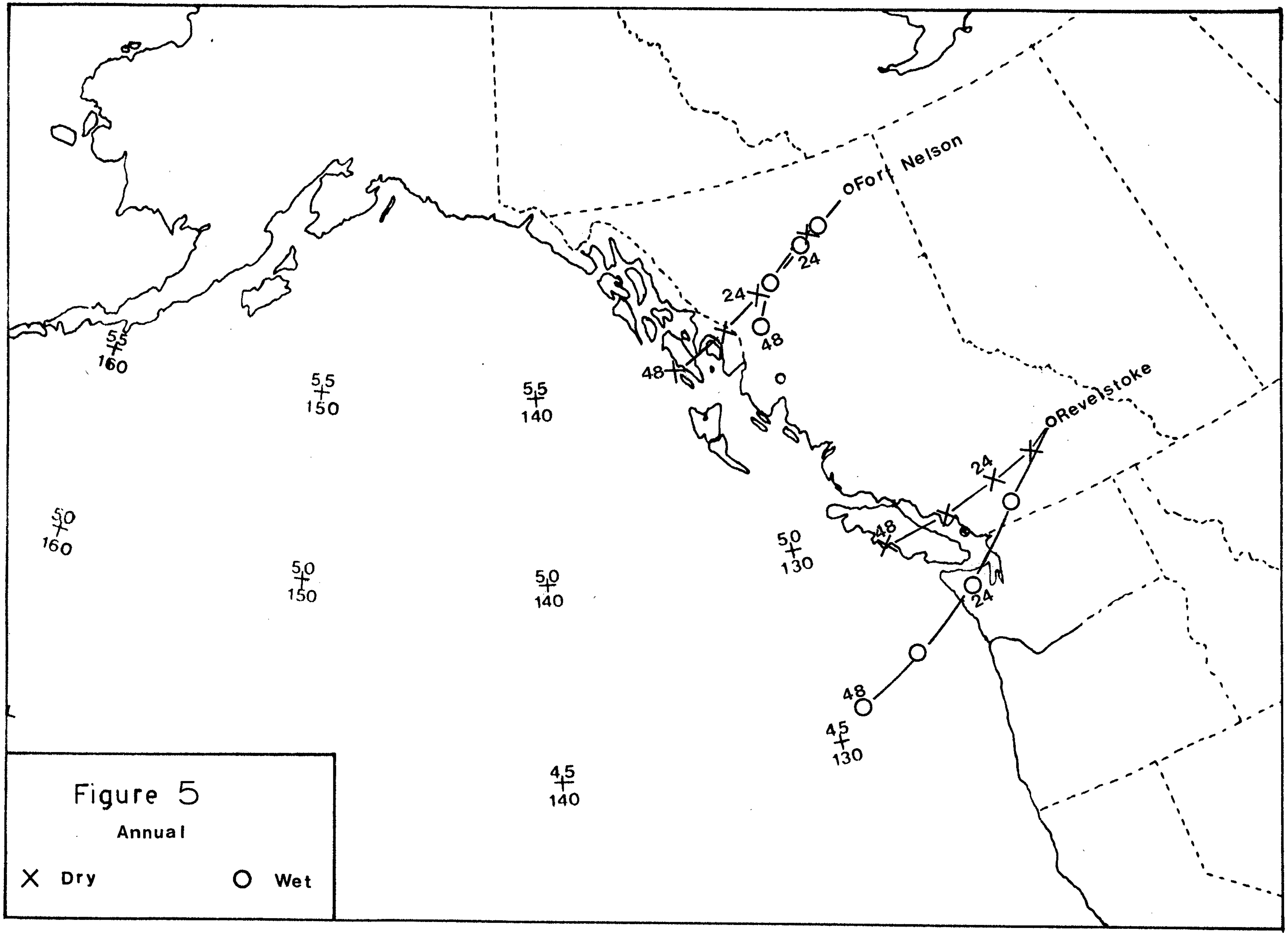
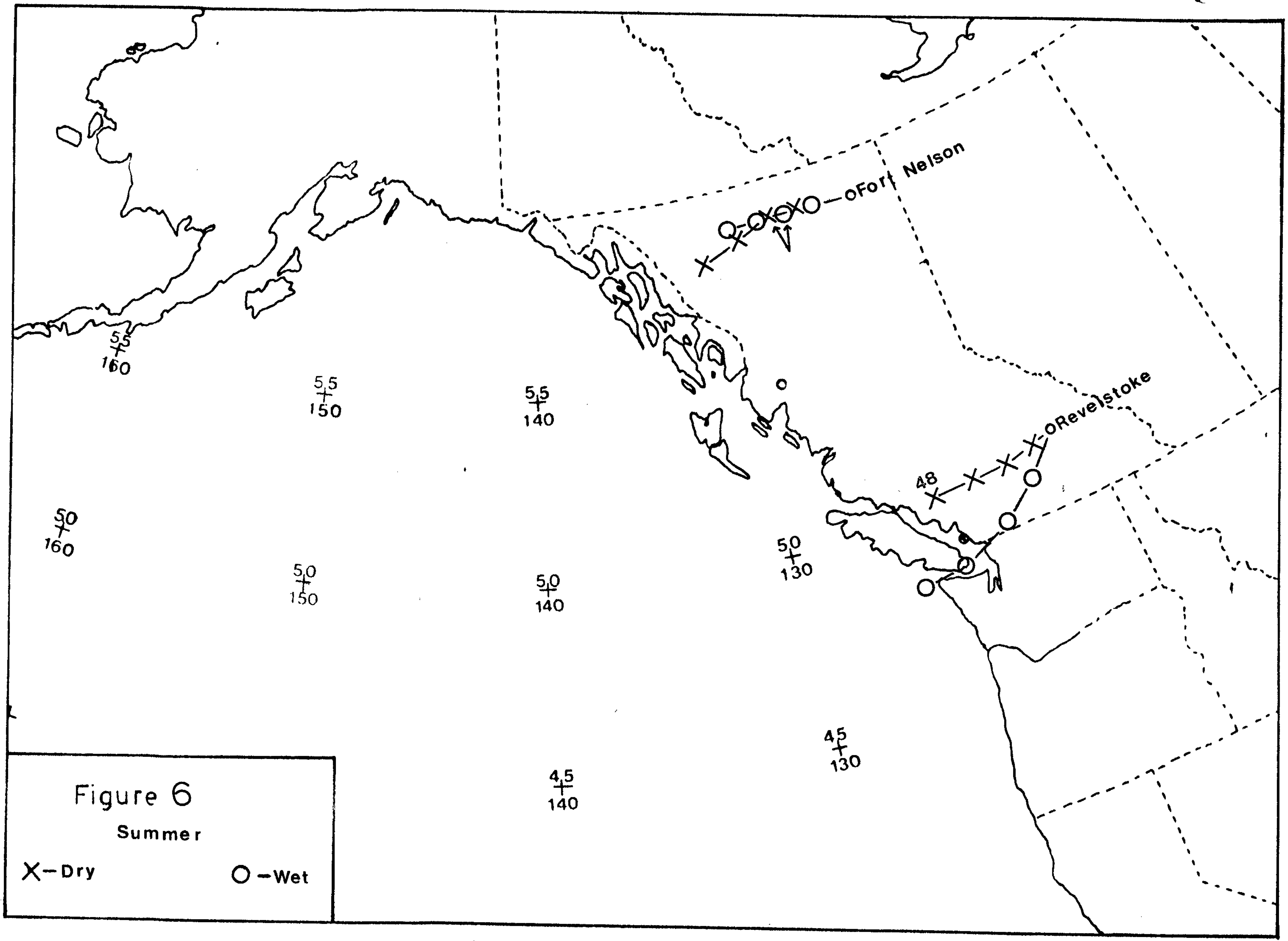

Fort Nelson
Revelstoke
24
48
24
48
24
48
24
48
5.5
160
5.5
150
5.5
140
5.0
160
5.0
150
5.0
140
5.0
130
4.5
140
4.5
130
Annual
Dry
Wet

Figure 5


Fort Nelson
Revelstoke
48
5.5
160
5.5
150
5.5
140
5.0
160
5.0
150
5.0
140
5.0
130
4.5
140
4.5
130
Figure 6
Summer
X–Dry
O–Wet

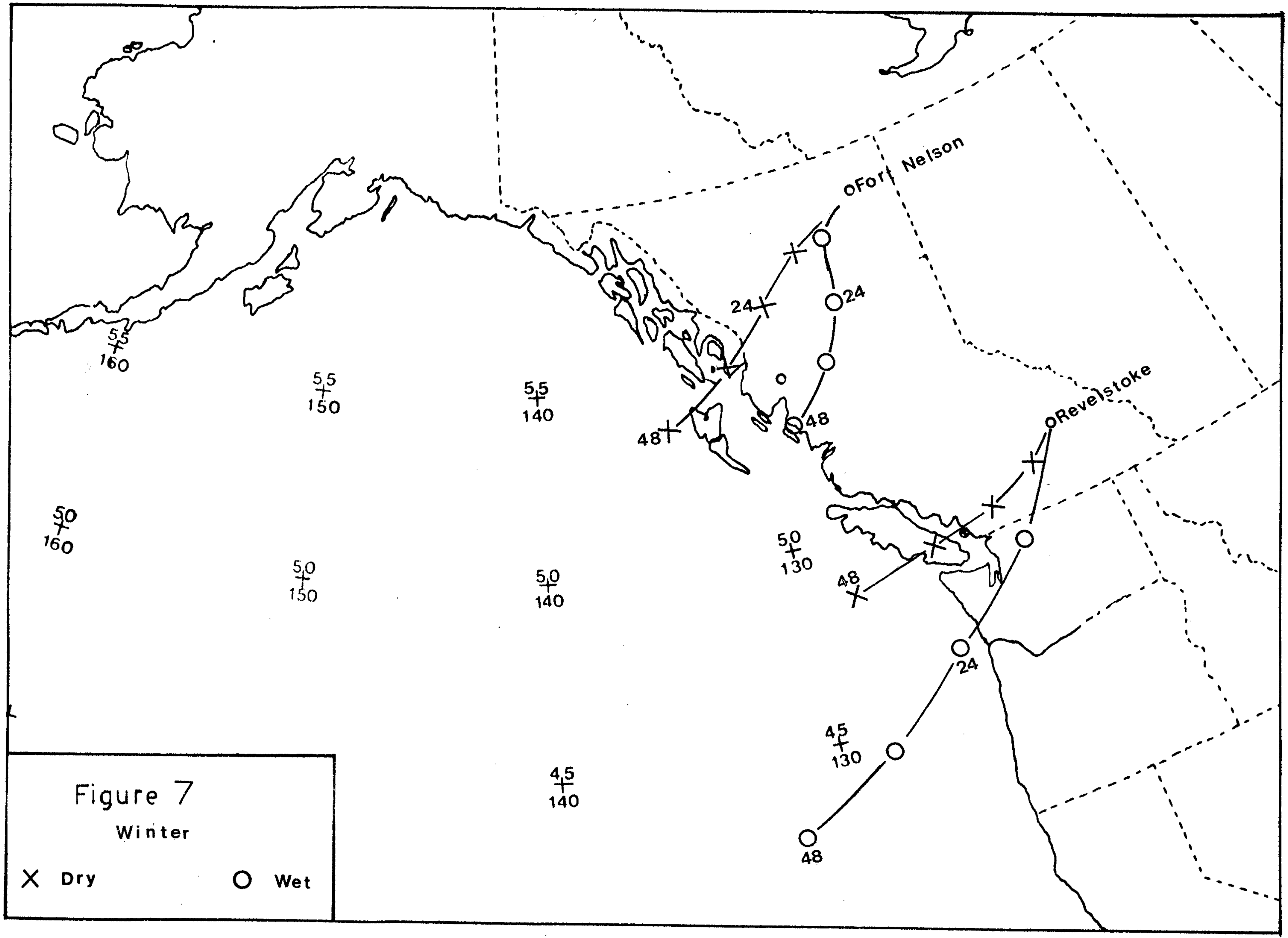


Figure 7
Winter

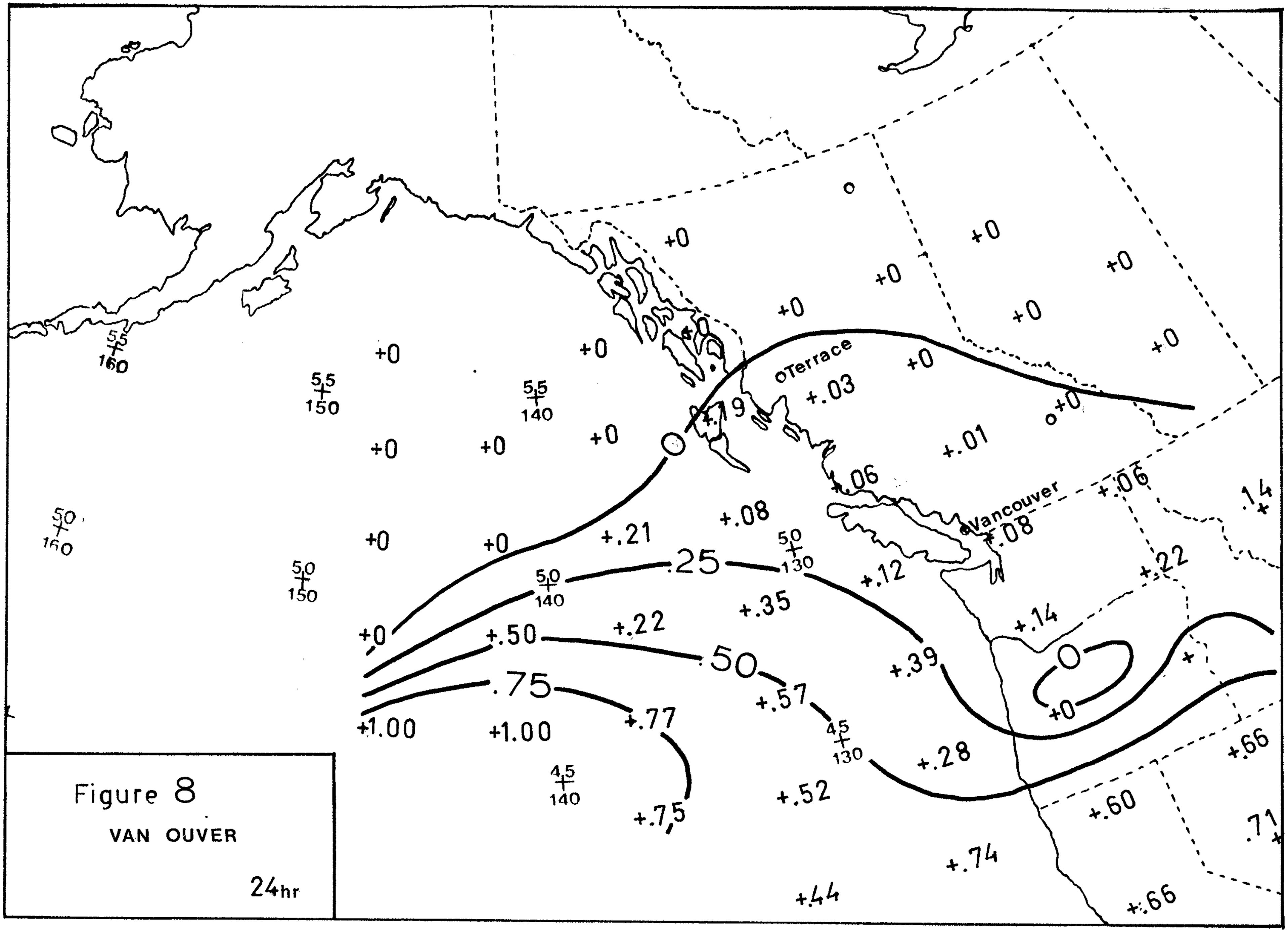


Figure 8

VAN OUVER

24hr

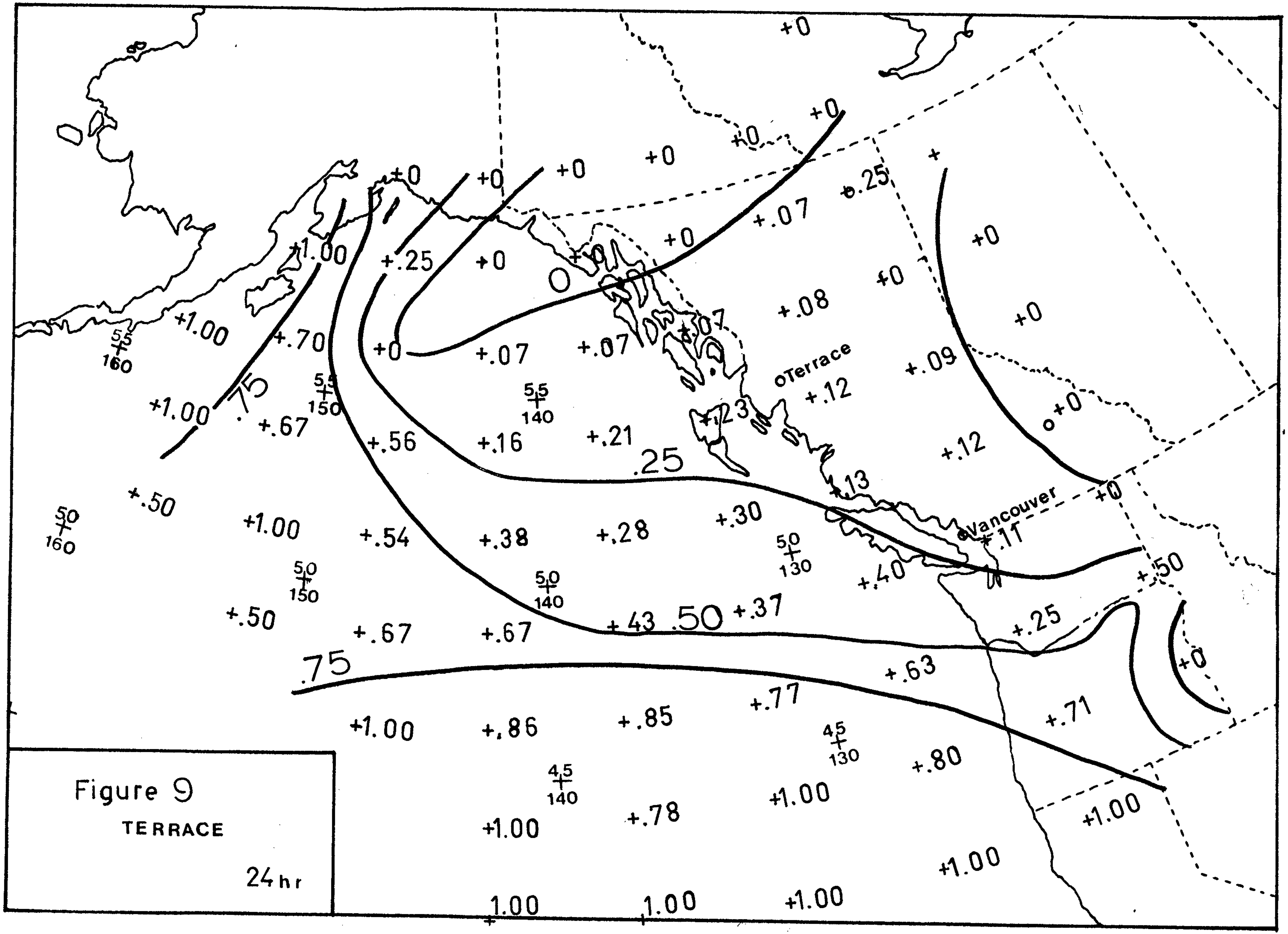


Figure 9
TERRACE
24hr

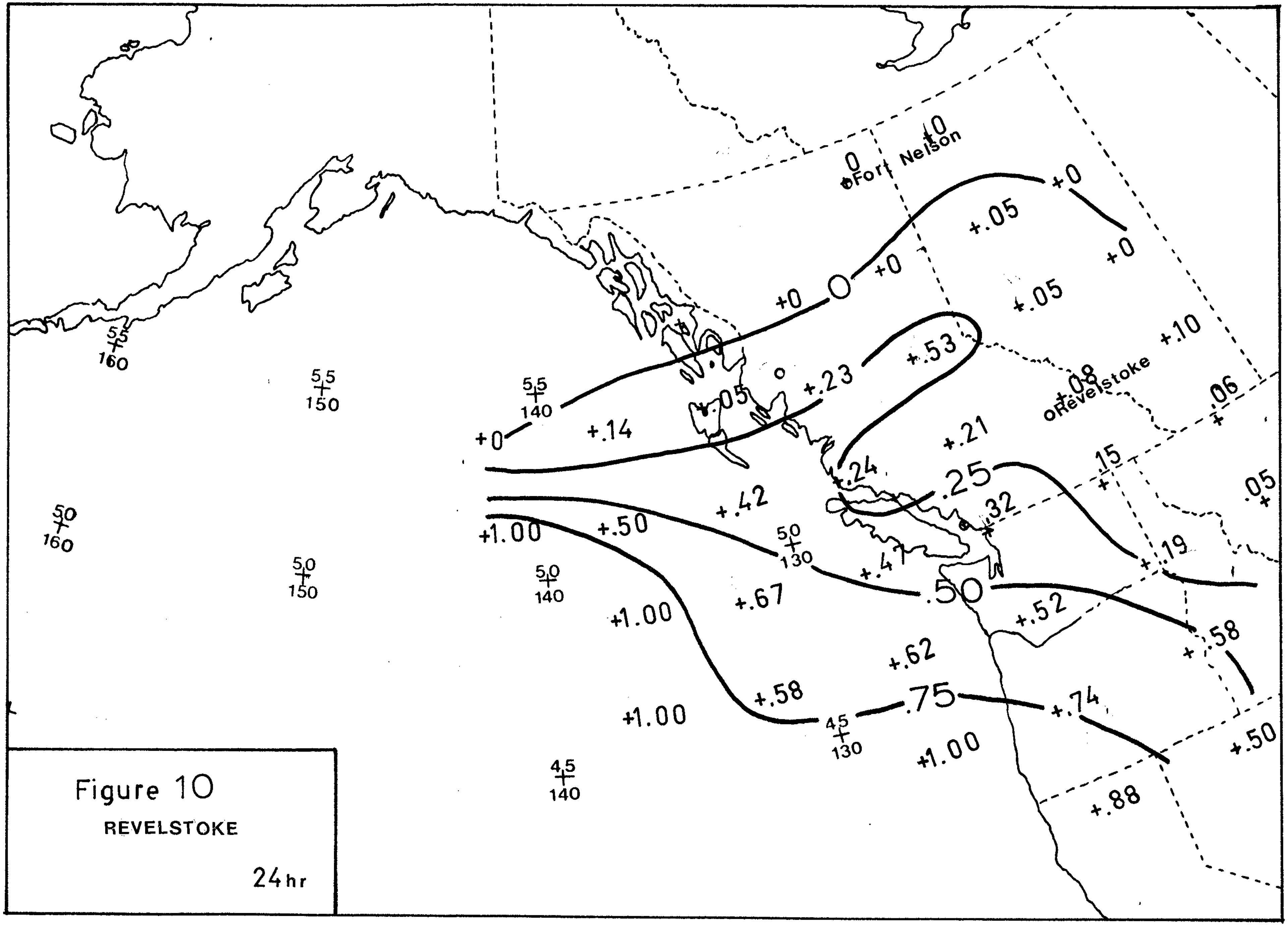


Figure 10

REVELSTOKE

24hr

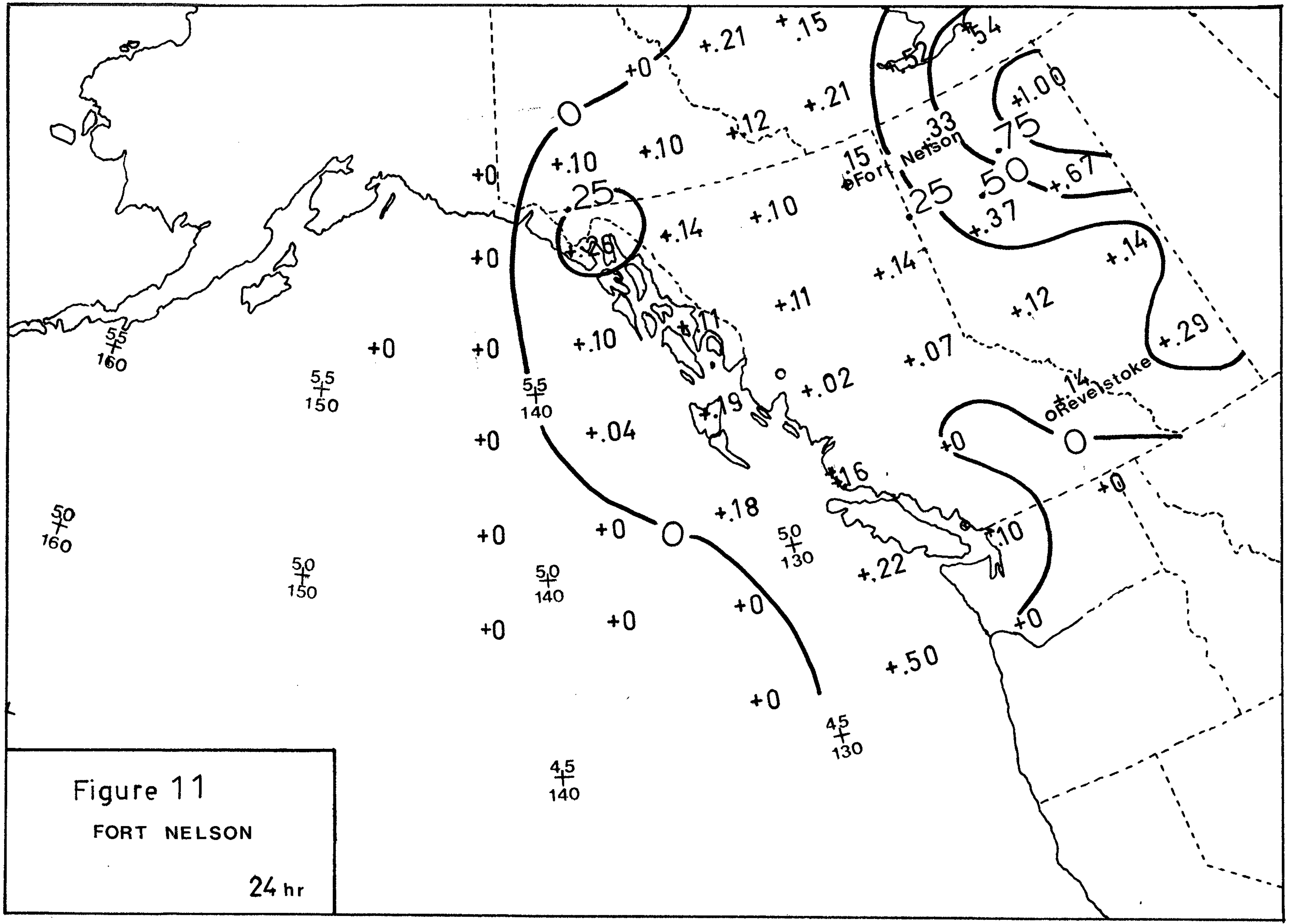


Figure 11
FORT NELSON
24 hr

Appendix A

Annual (1978), summer (June - August) and winter (January, February, December) end point densities for 12, 24 & 48 hr back trajectories from Vancouver, Terrace, Revelstoke and Fort Nelson. Units are endpoints per 100,000 km^2. Minor maxima are indicated by an "M".

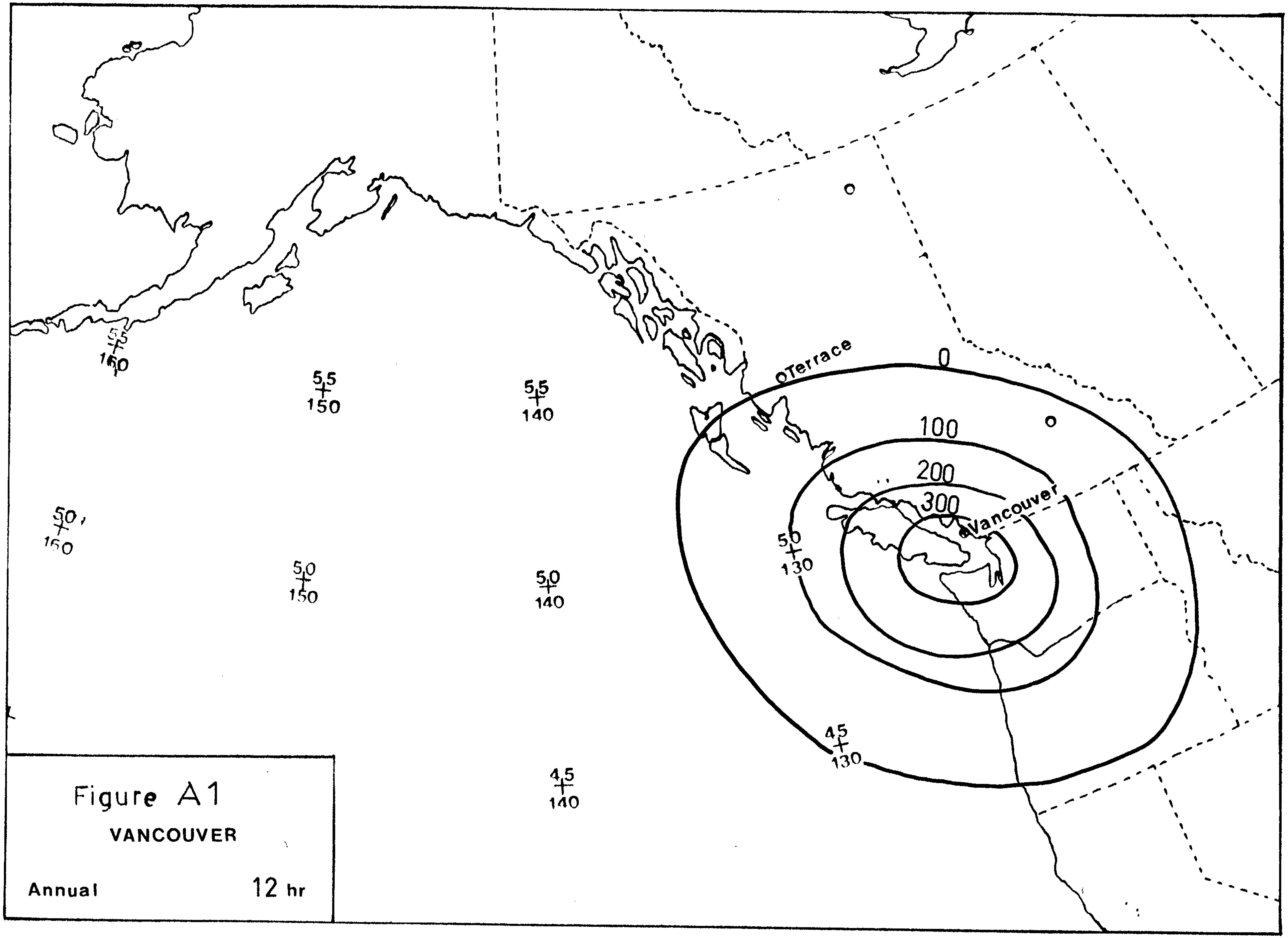


Figure A1

VANCOUVER

Annual 12 hr

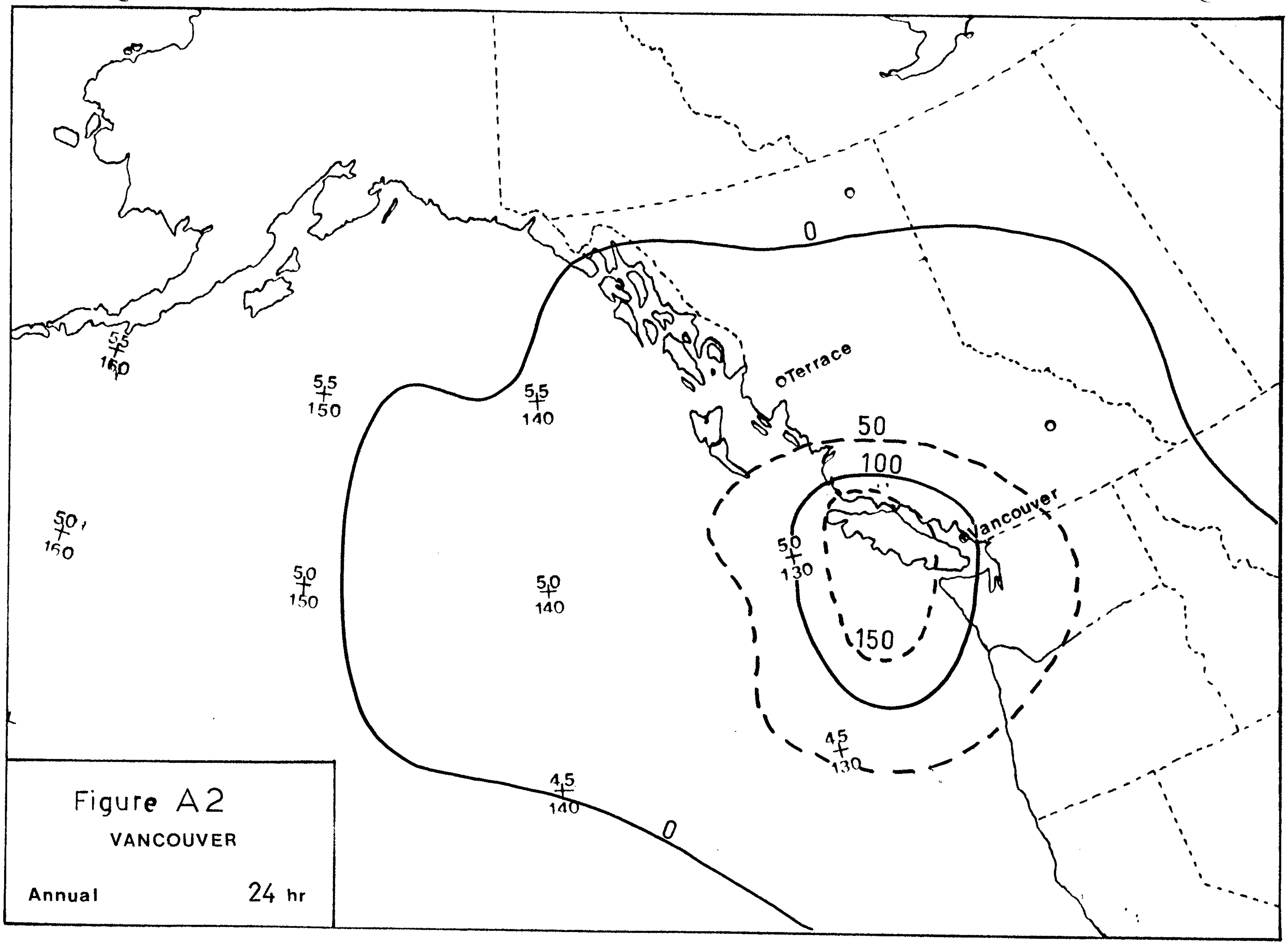


Figure A2
VANCOUVER
Annual 24 hr

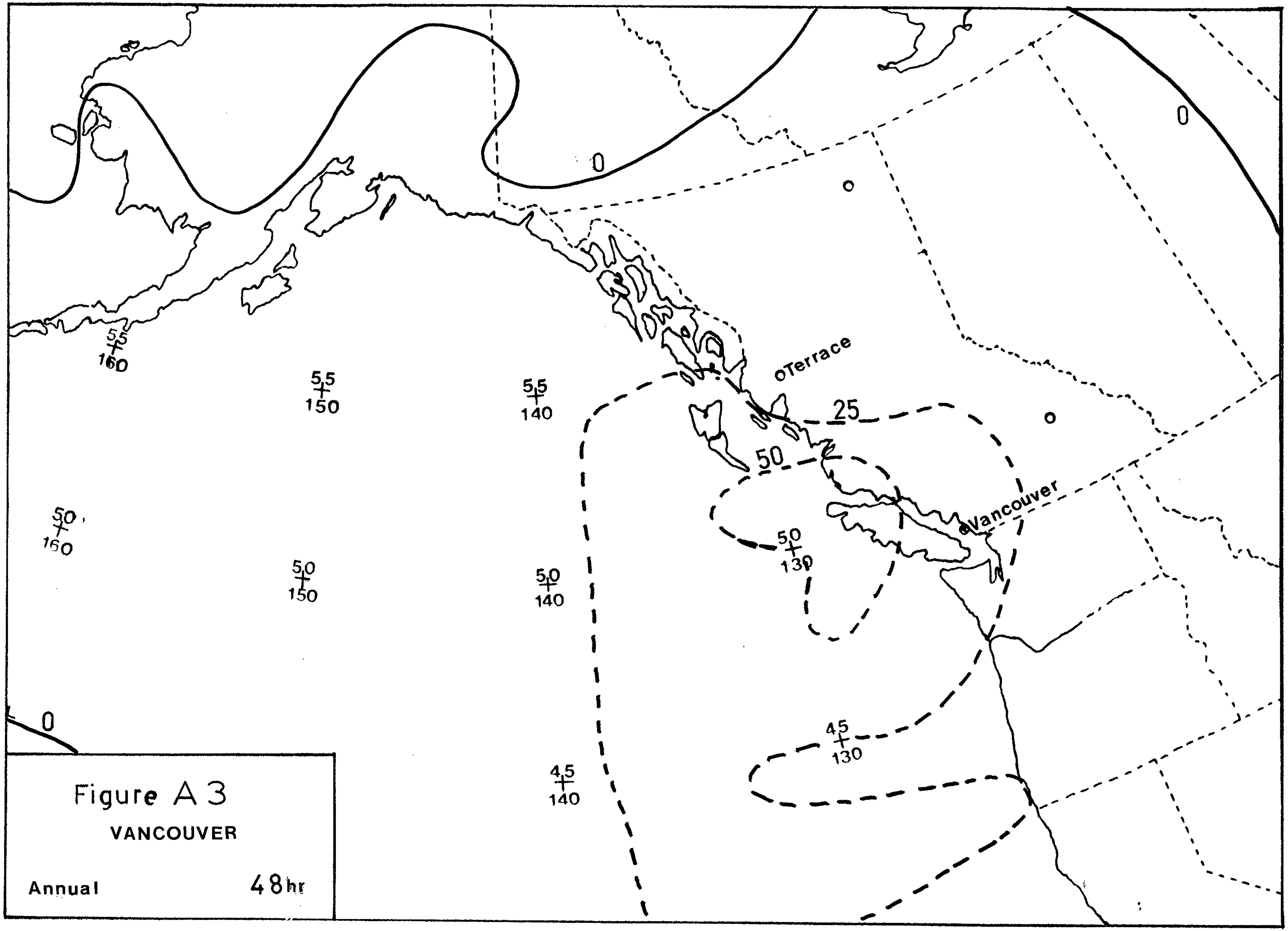


Figure A3
VANCOUVER
Annual 48hr

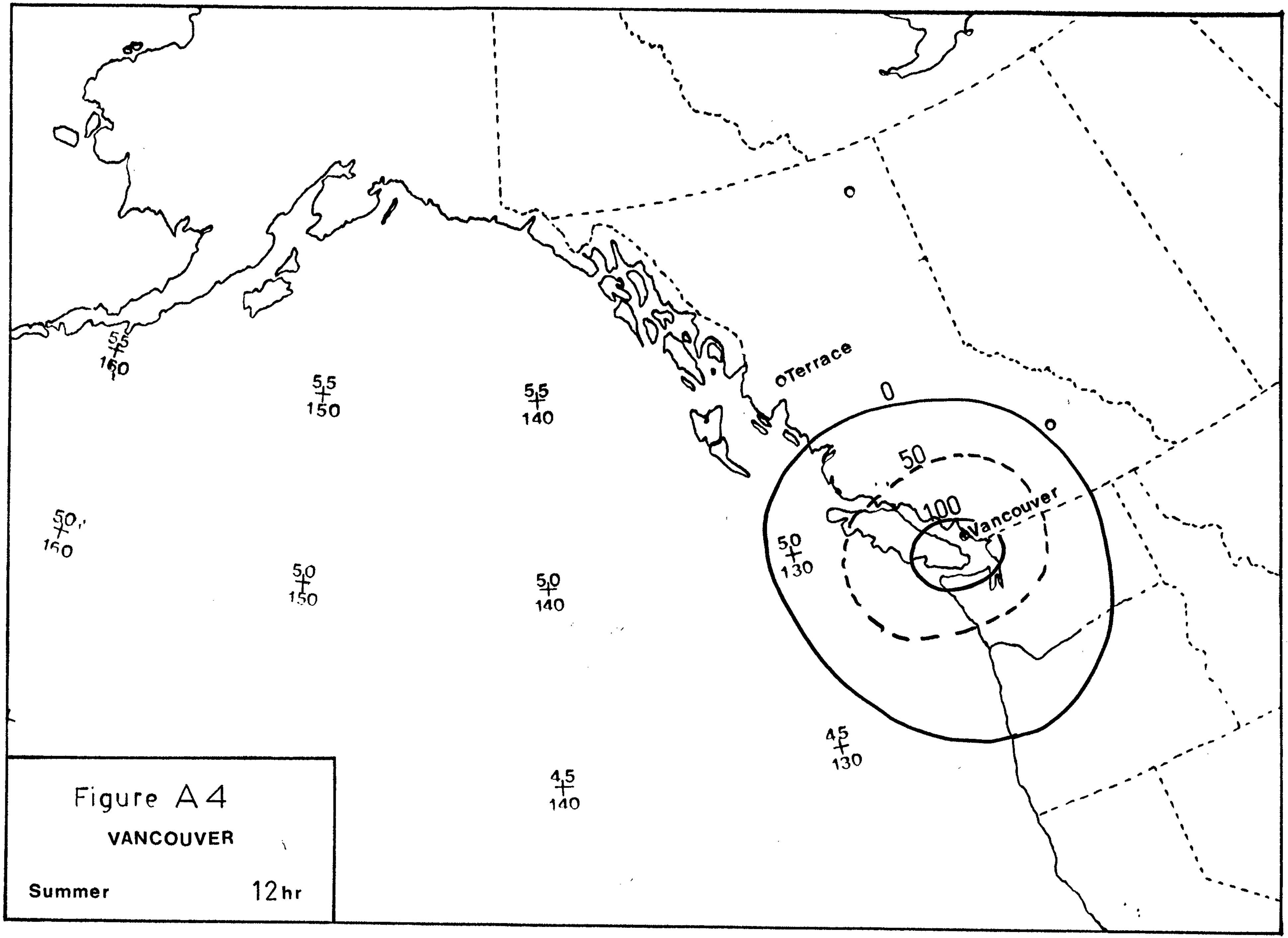


Figure A4

VANCOUVER

Summer 12 hr

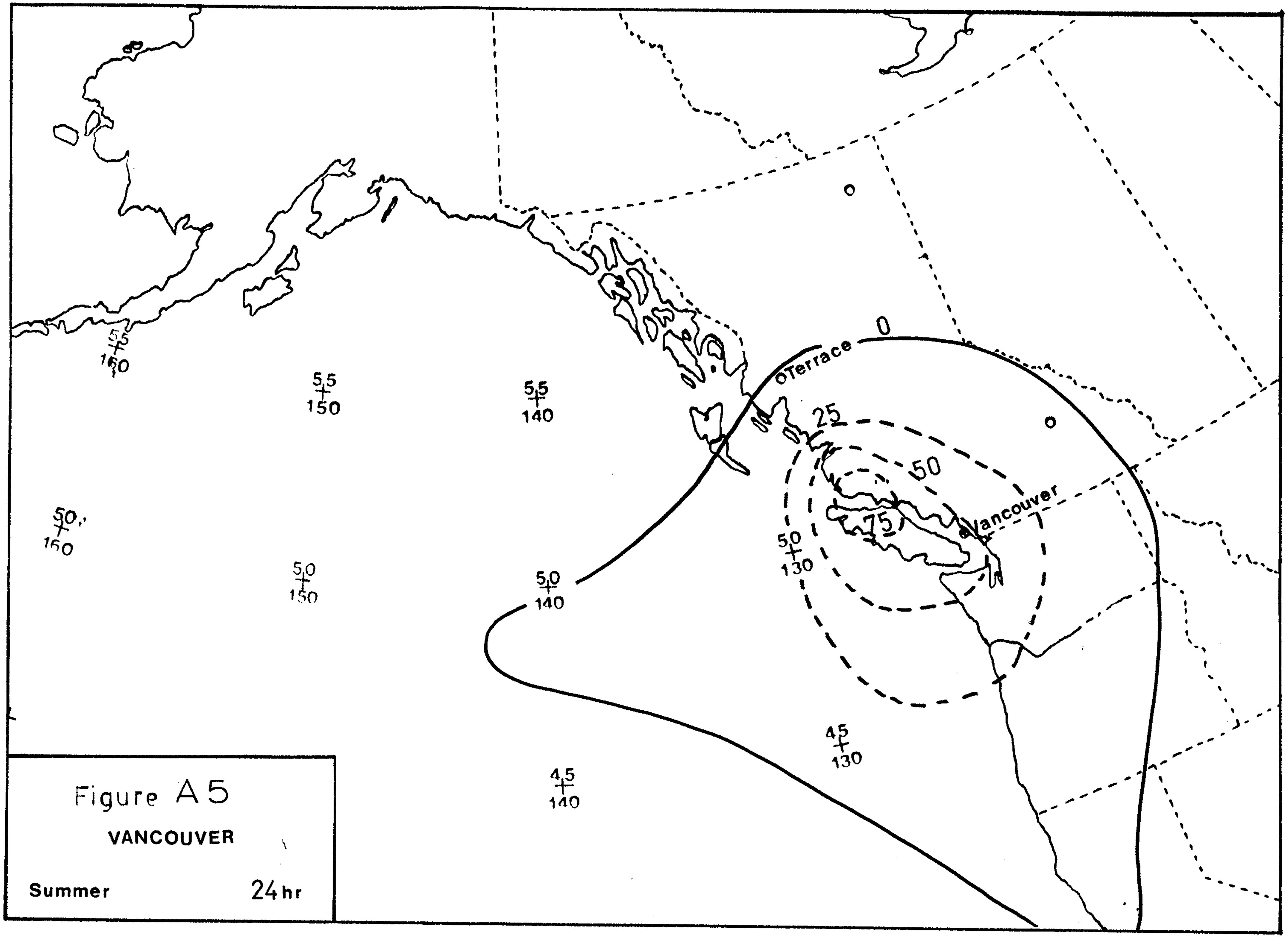


Figure A5
VANCOUVER
Summer 24hr

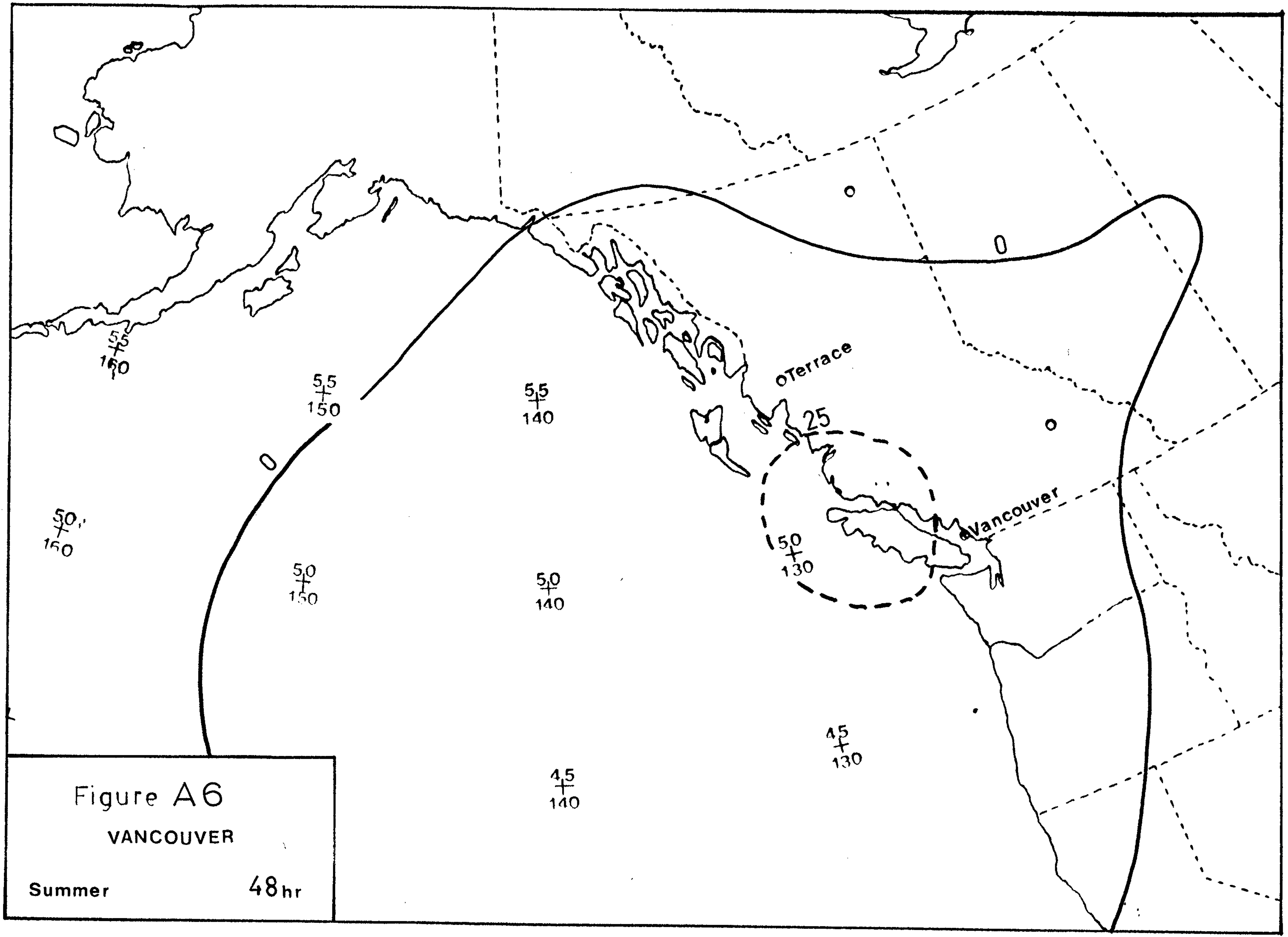


Figure A6
VANCOUVER
Summer 48hr

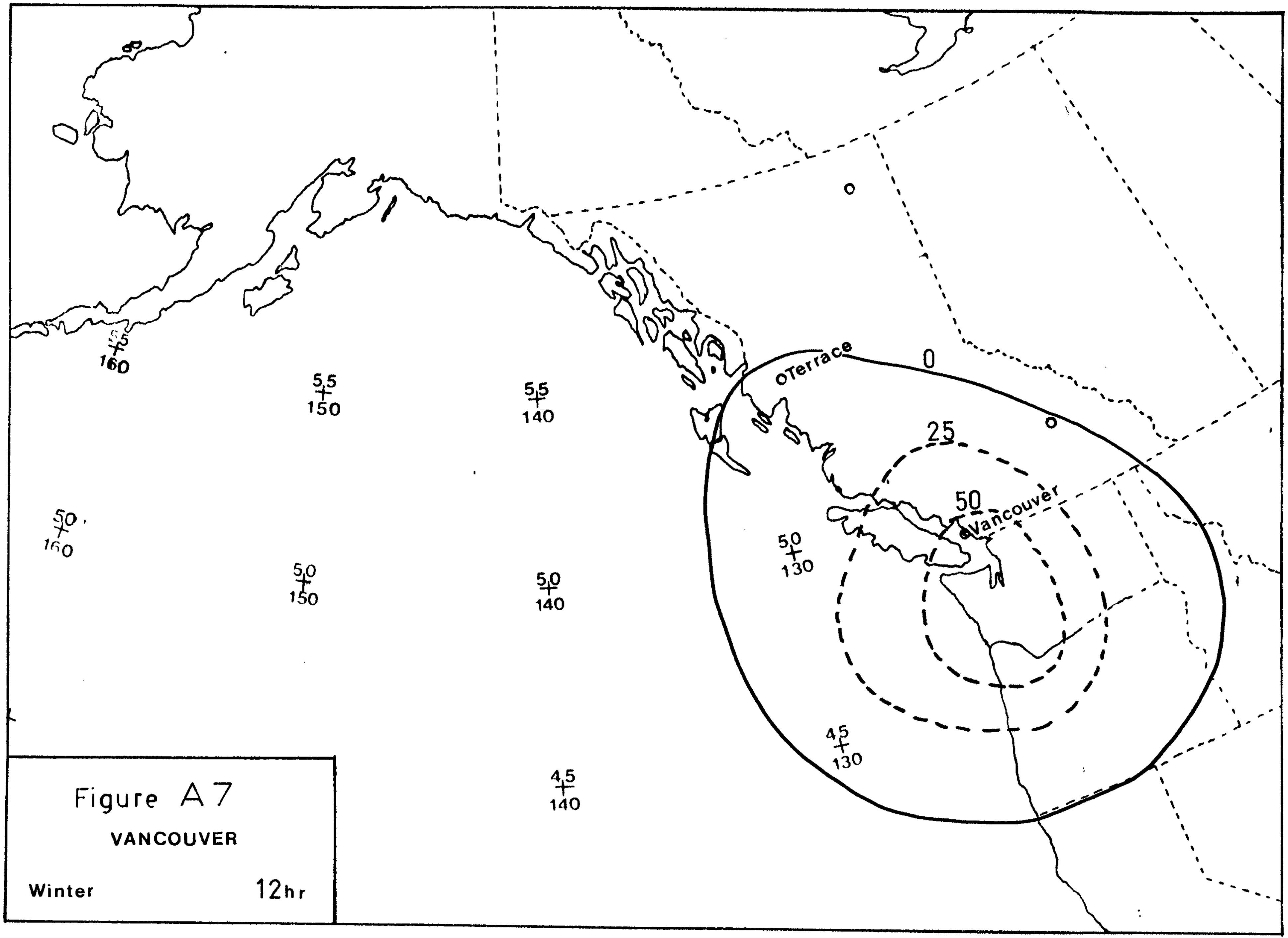


Figure A7
VANCOUVER
Winter 12hr

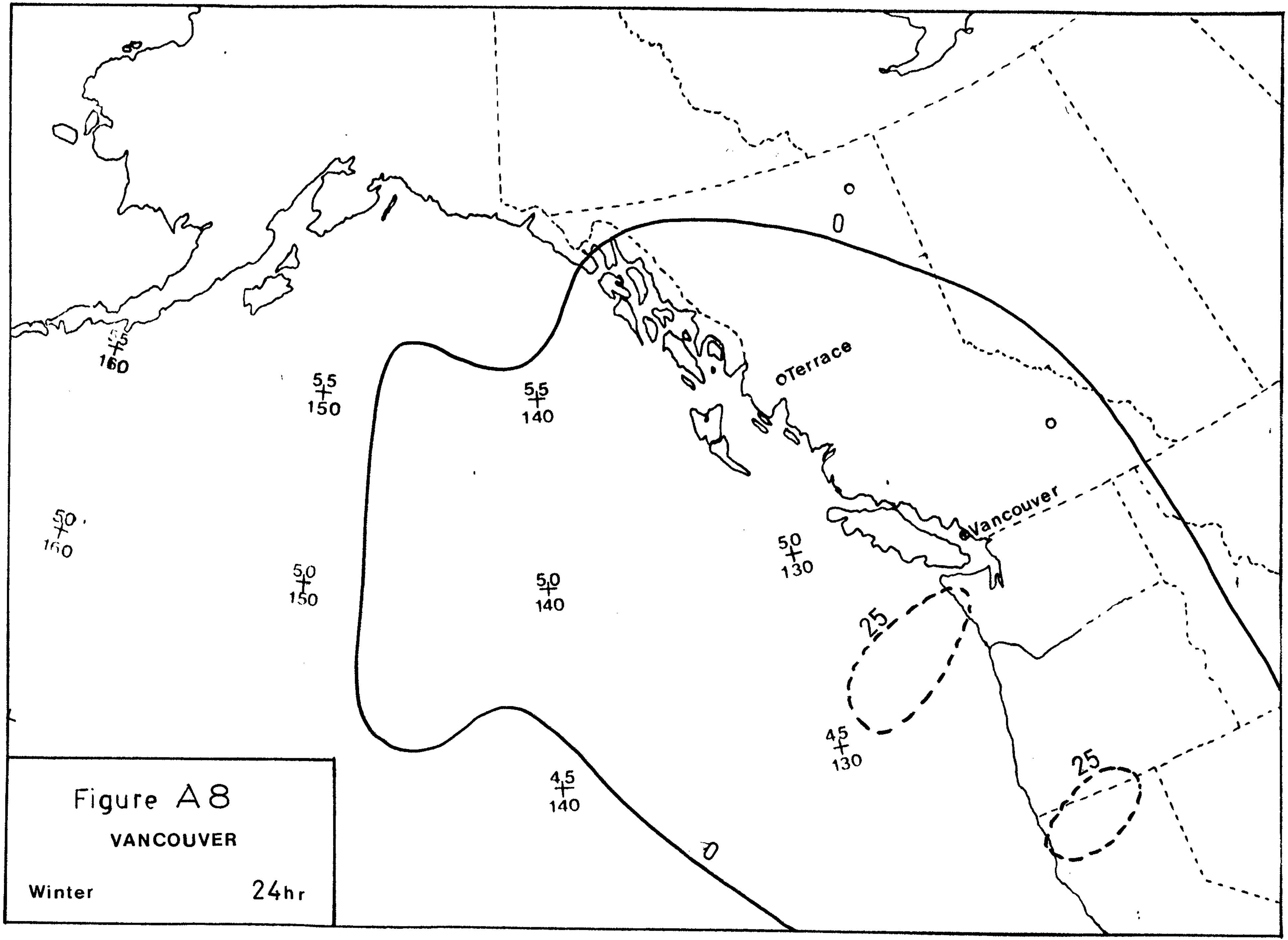
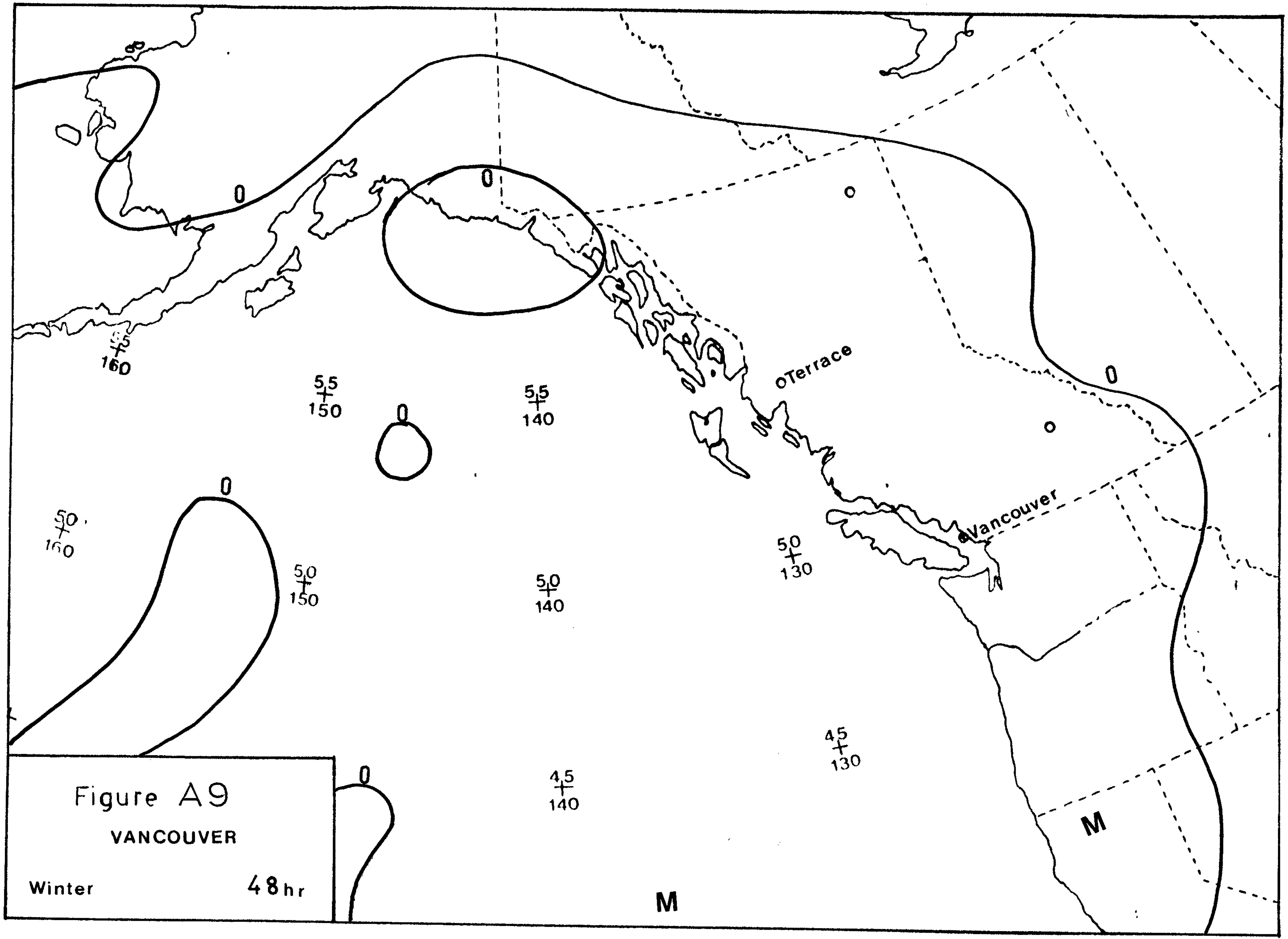


Figure A8

VANCOUVER

Winter 24hr



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VANCOUVER
Winter 48 hr

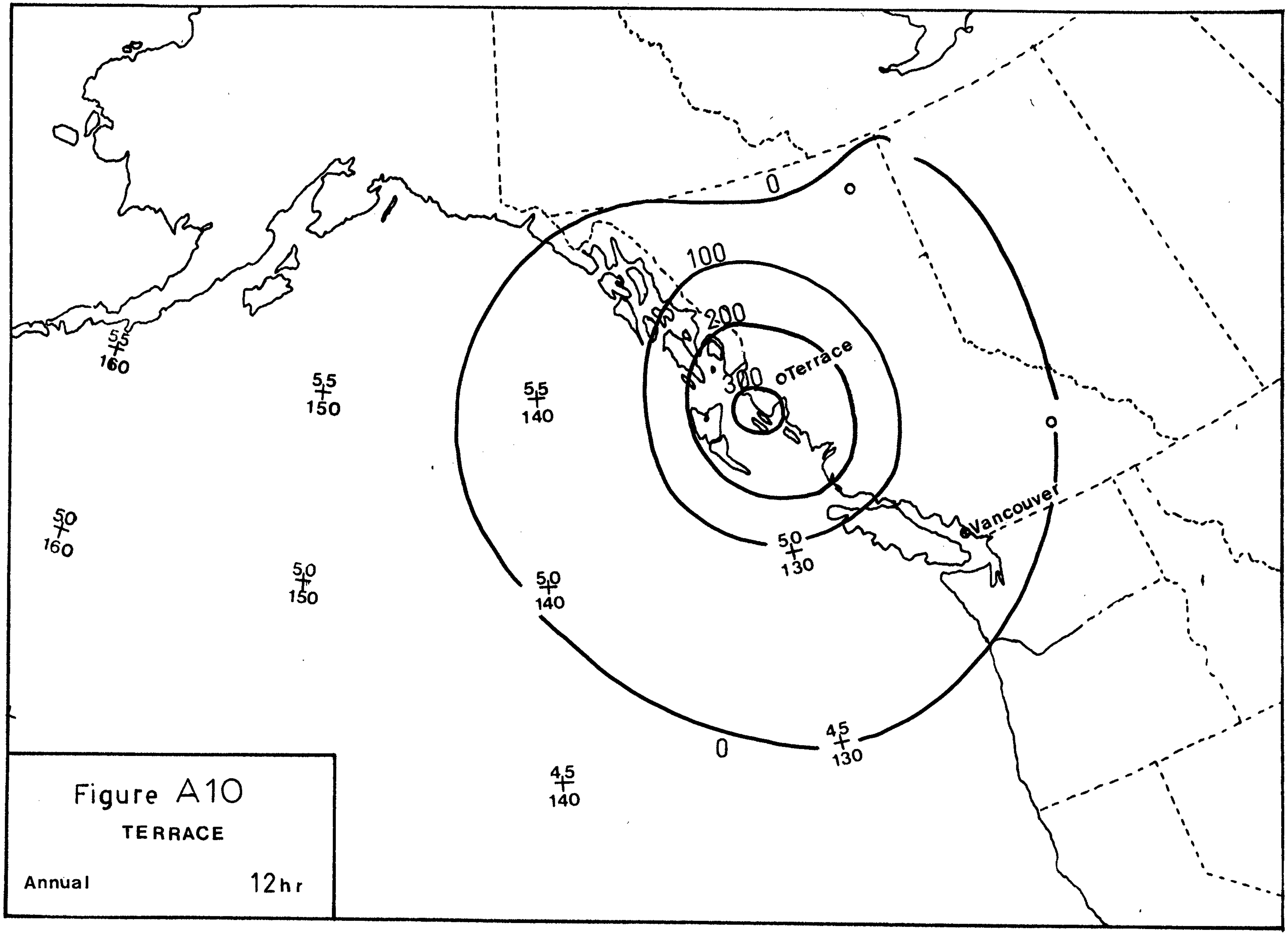
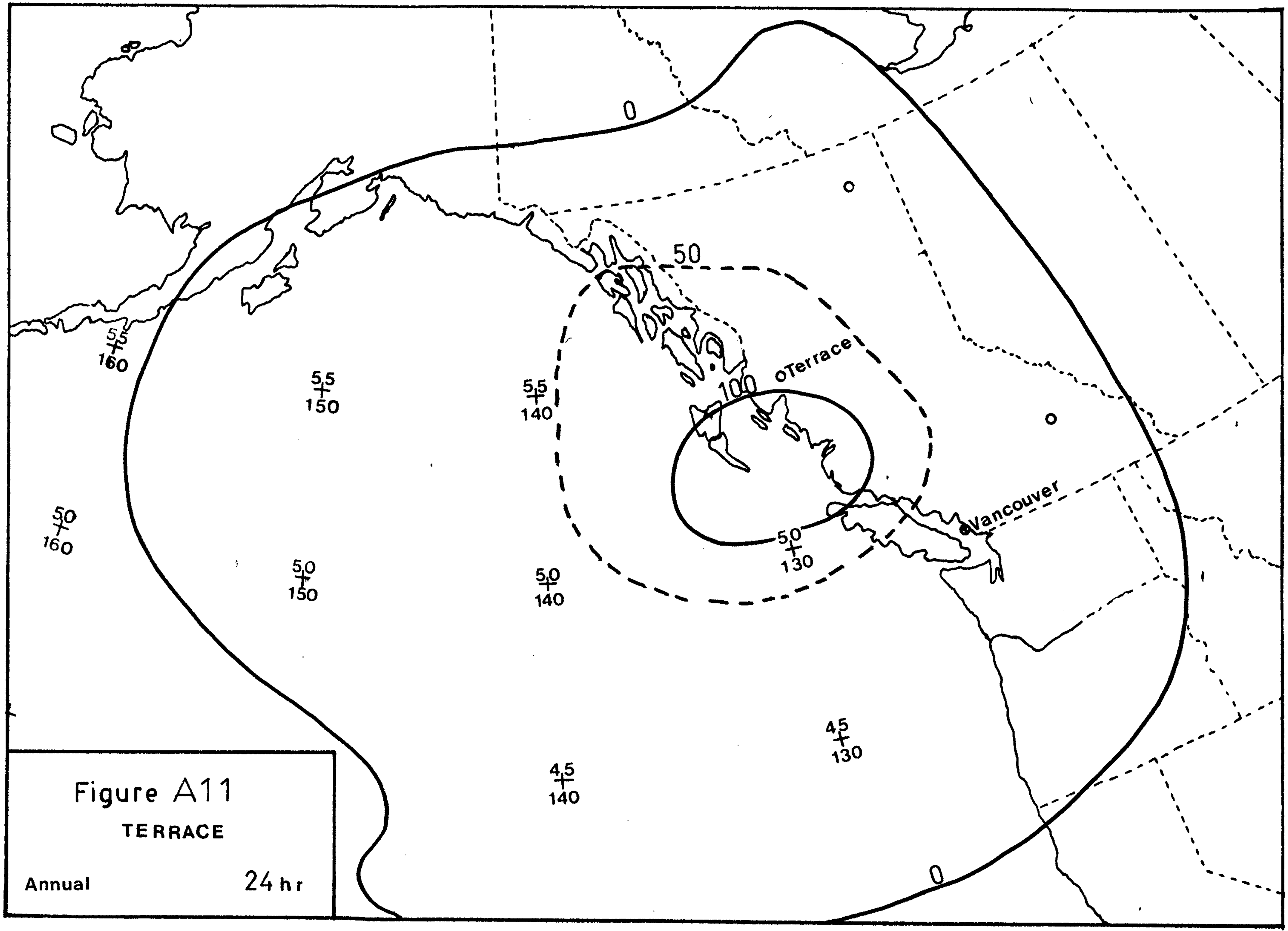


Figure A10
TERRACE
Annual 12hr



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TERRACE
Annual 24 hr

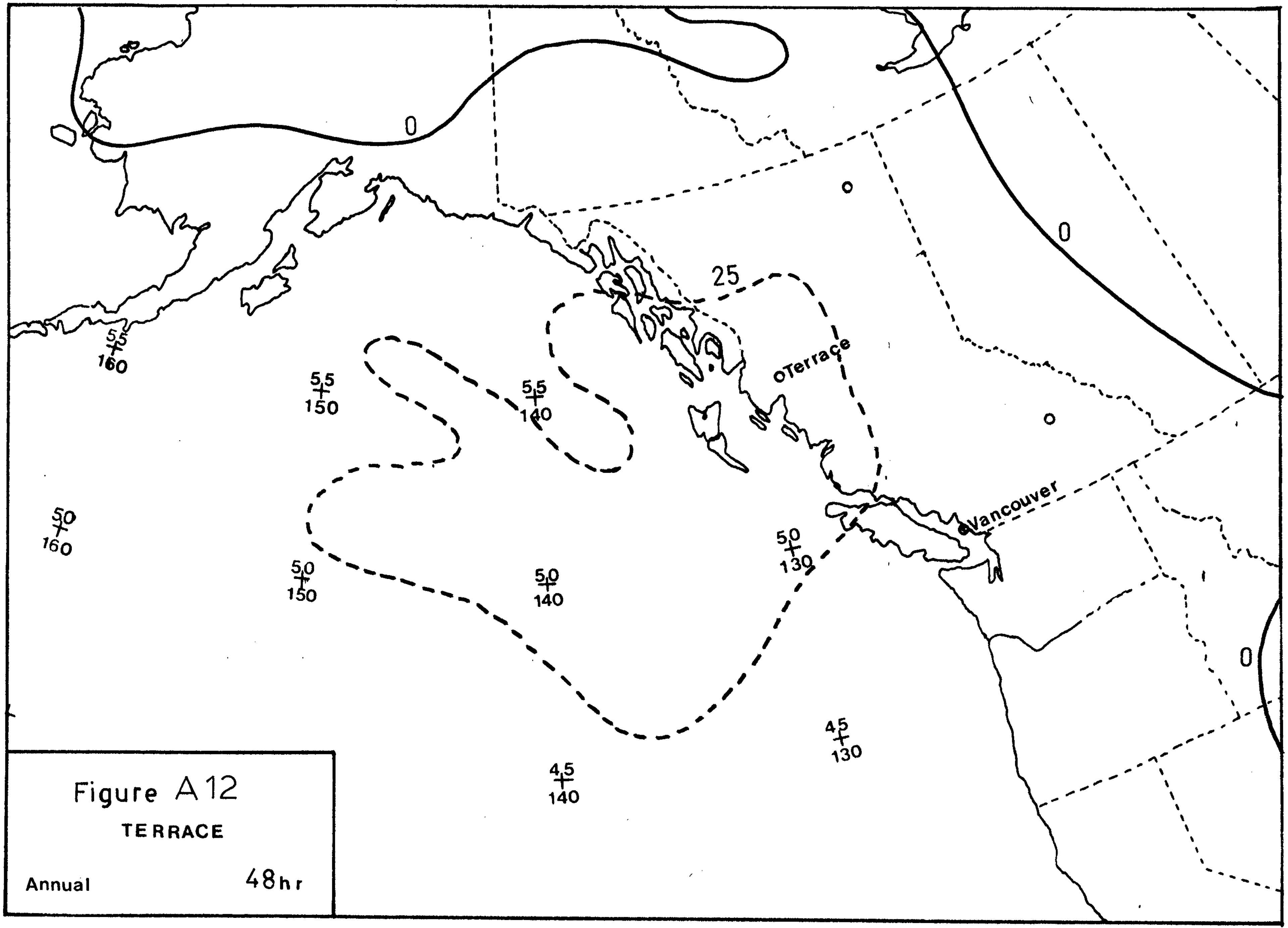

Figure A12

TERRACE

Annual 48hr

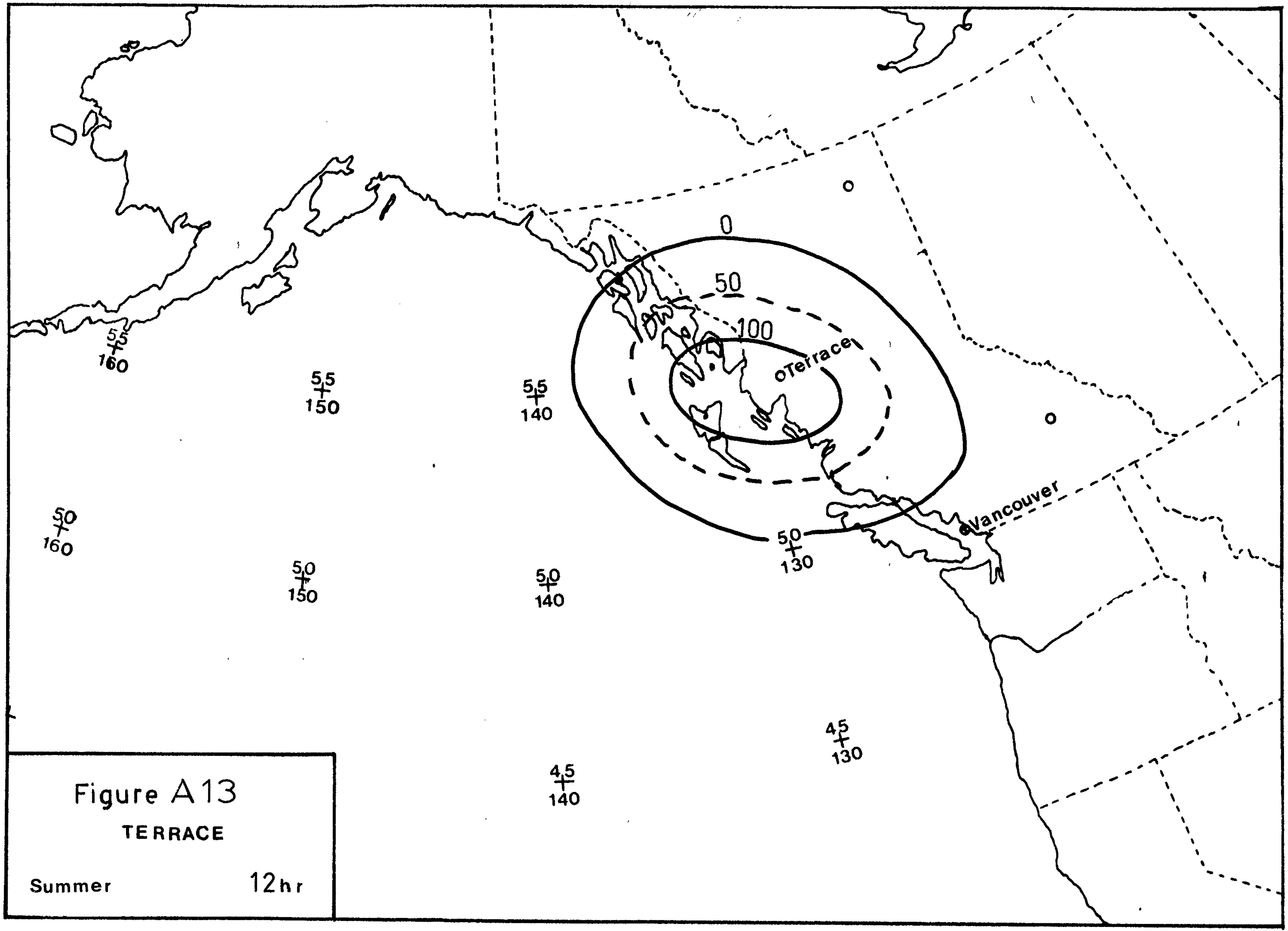

Figure A13

TERRACE

Summer 12hr

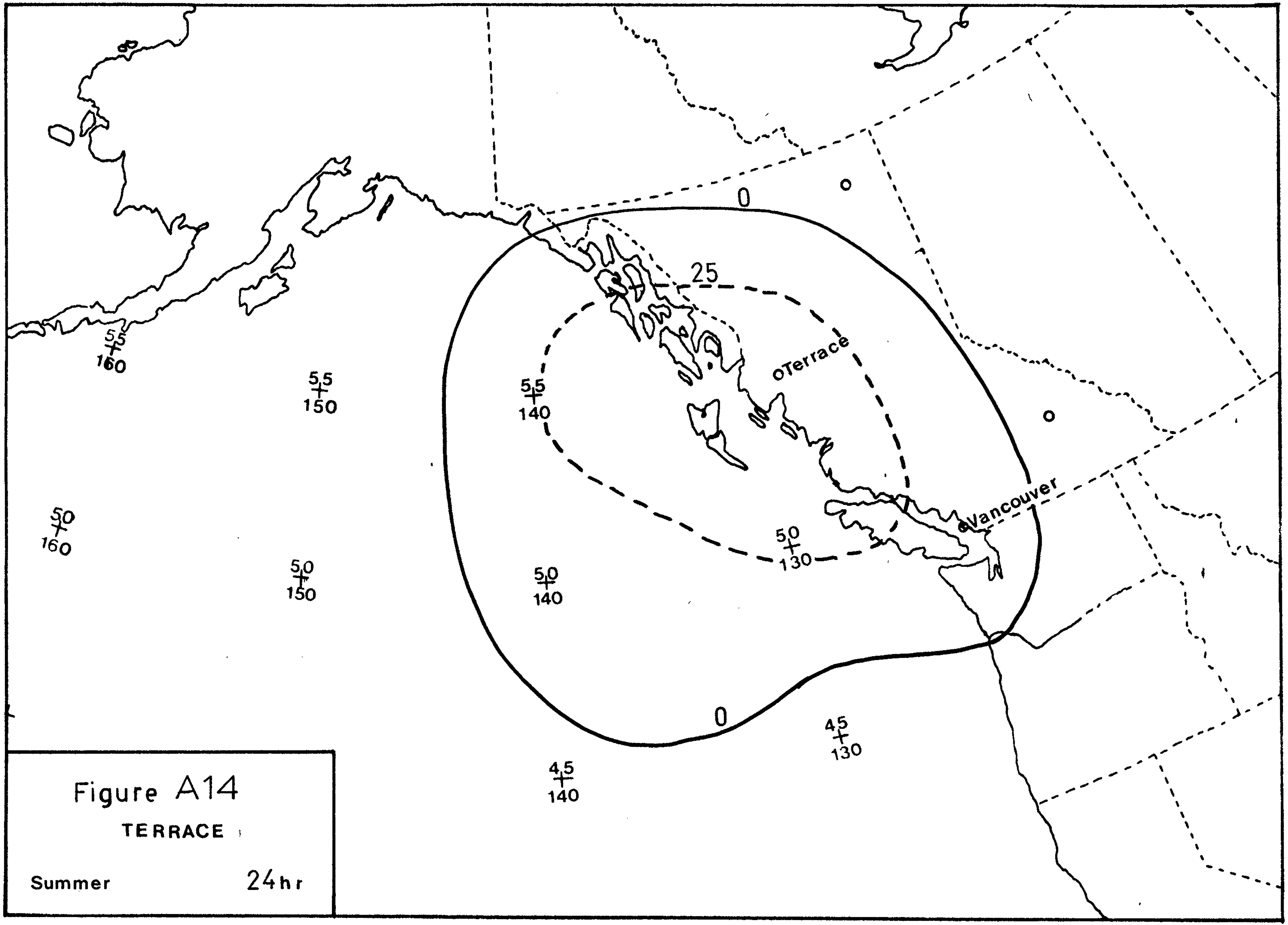

Figure A14

TERRACE

Summer 24hr

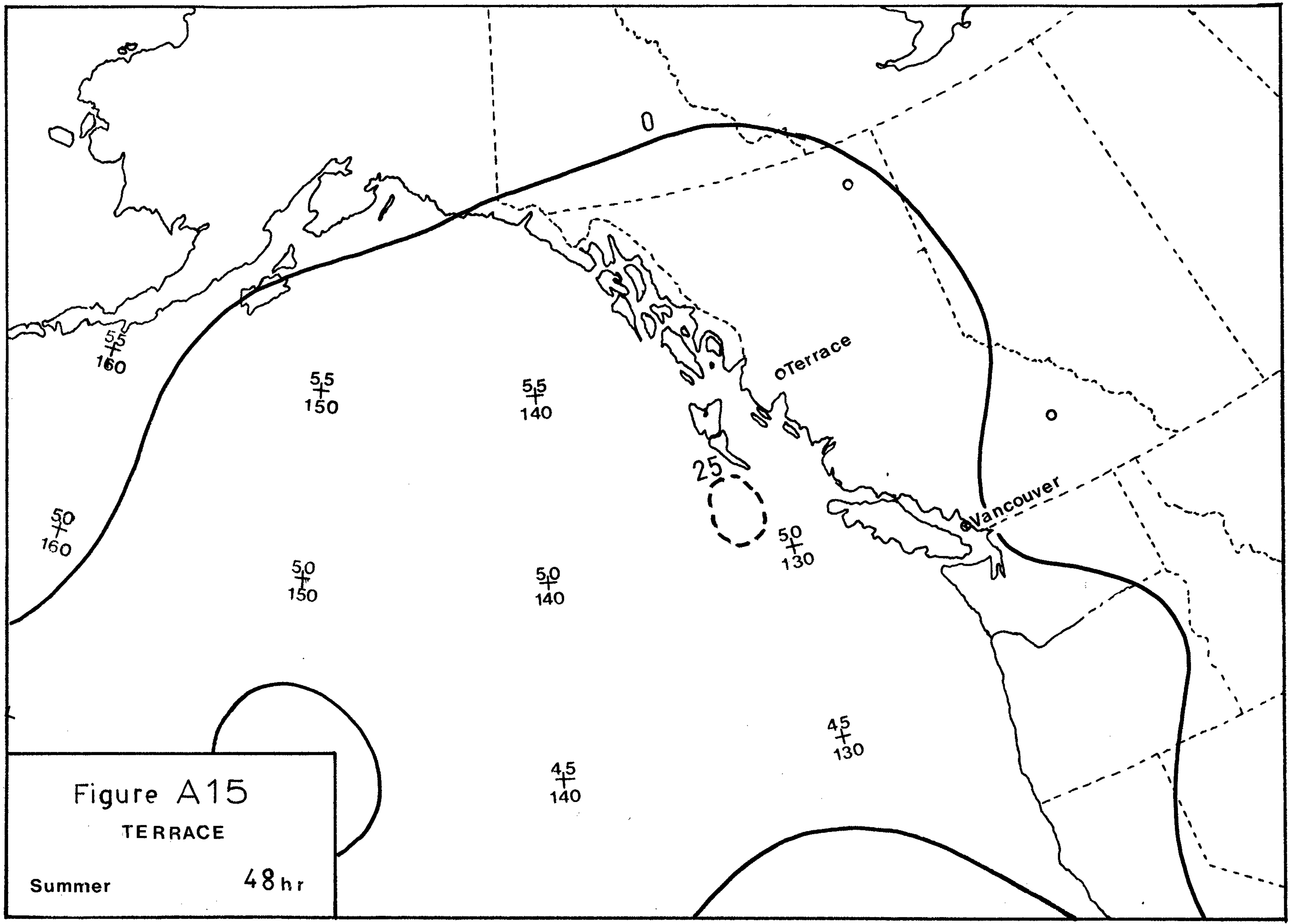

Figure A15

TERRACE

Summer 48 hr

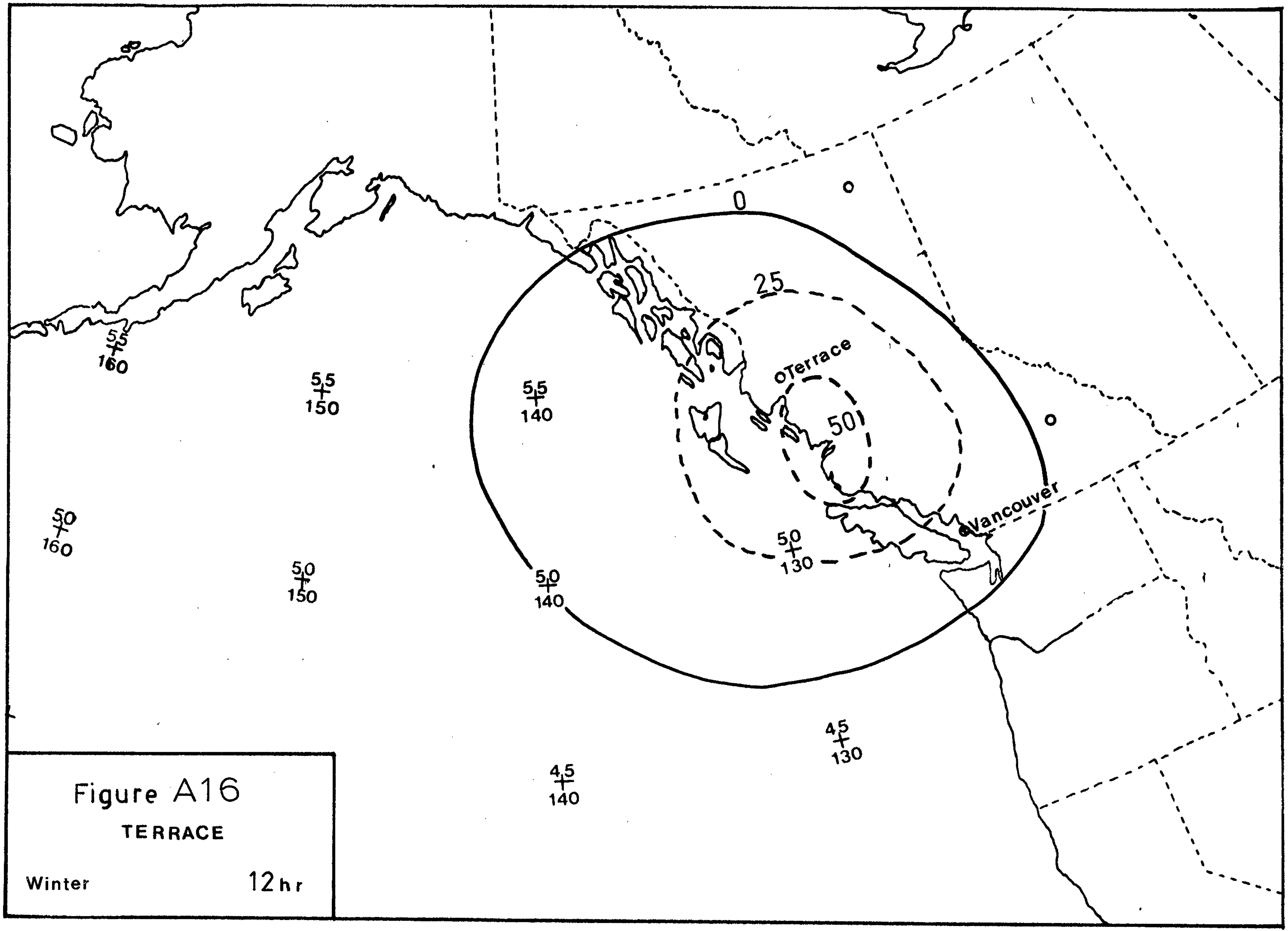

Figure A16

TERRACE

Winter 12 hr

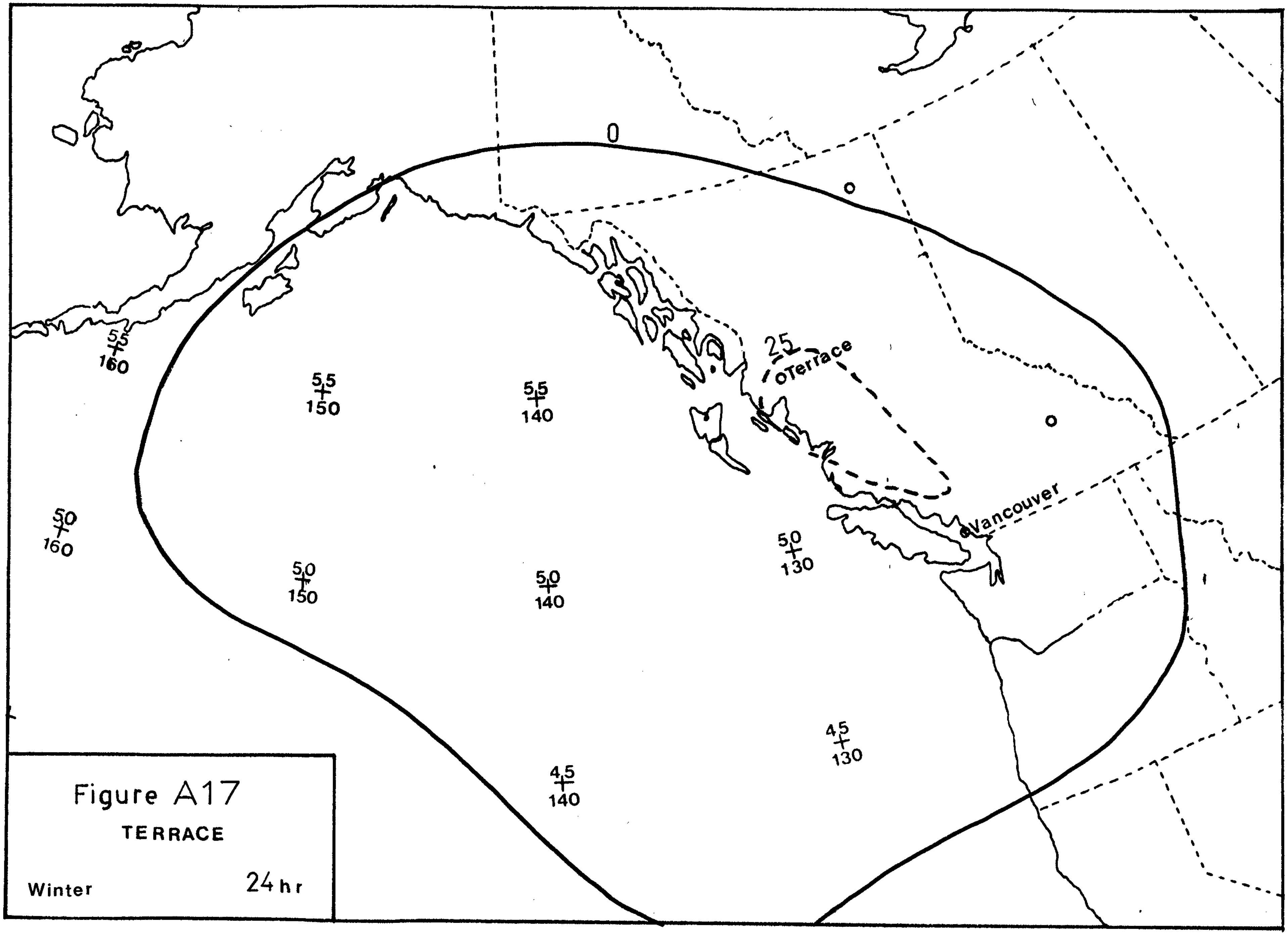

Figure A17

TERRACE

Winter 24 hr

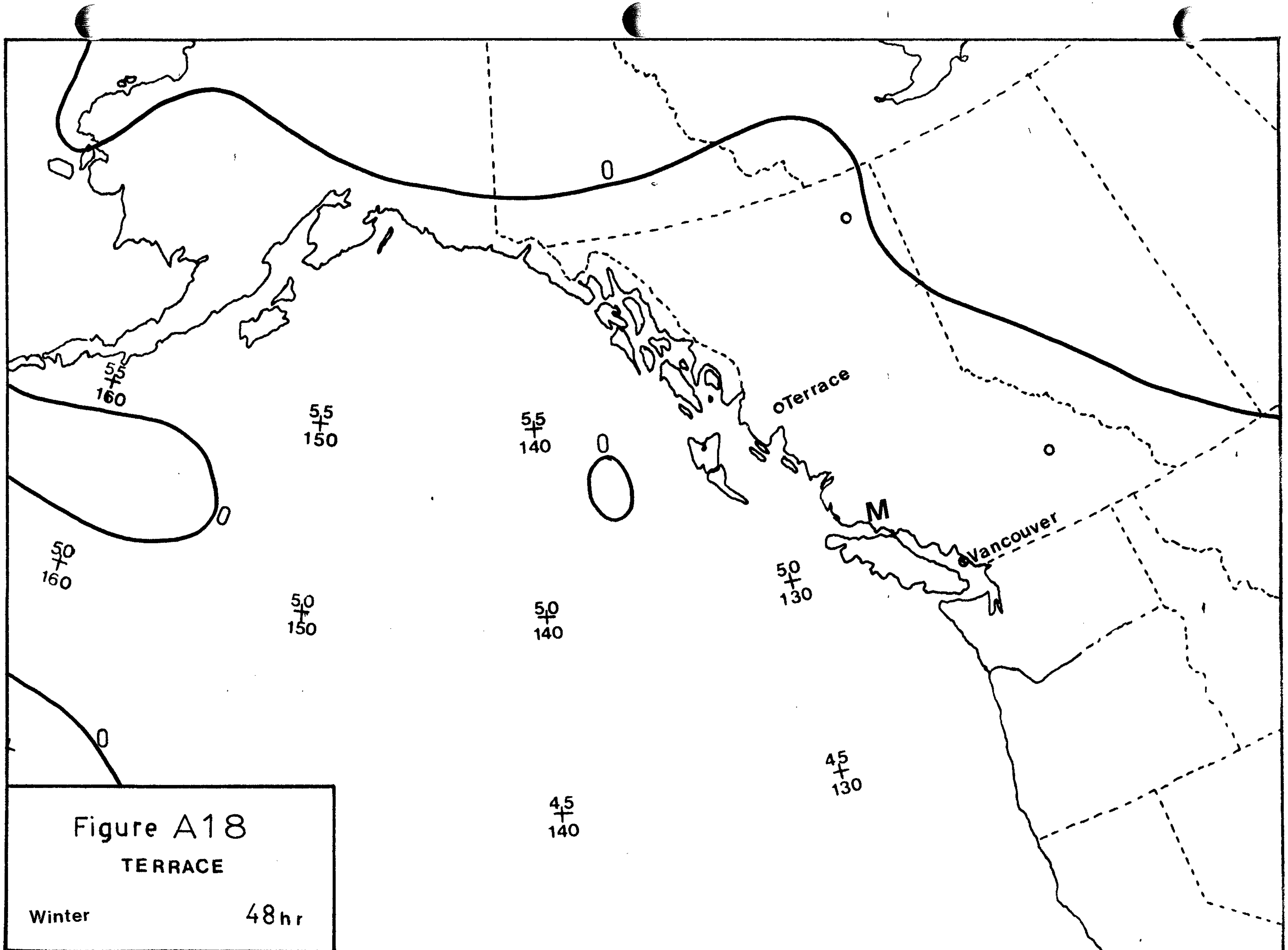

Figure A18
TERRACE
Winter 48hr

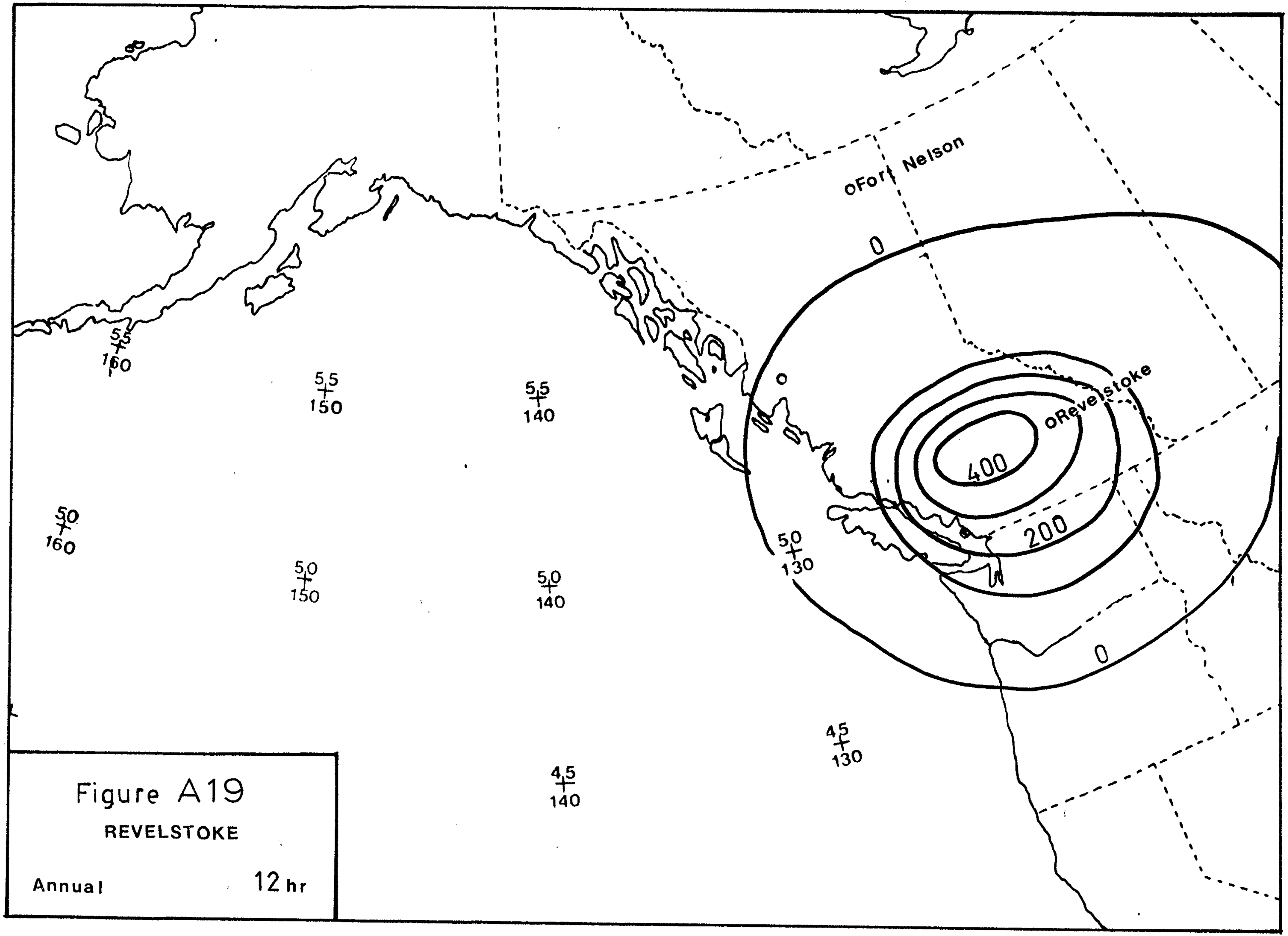

Figure A19
REVELSTOKE
Annual 12 hr

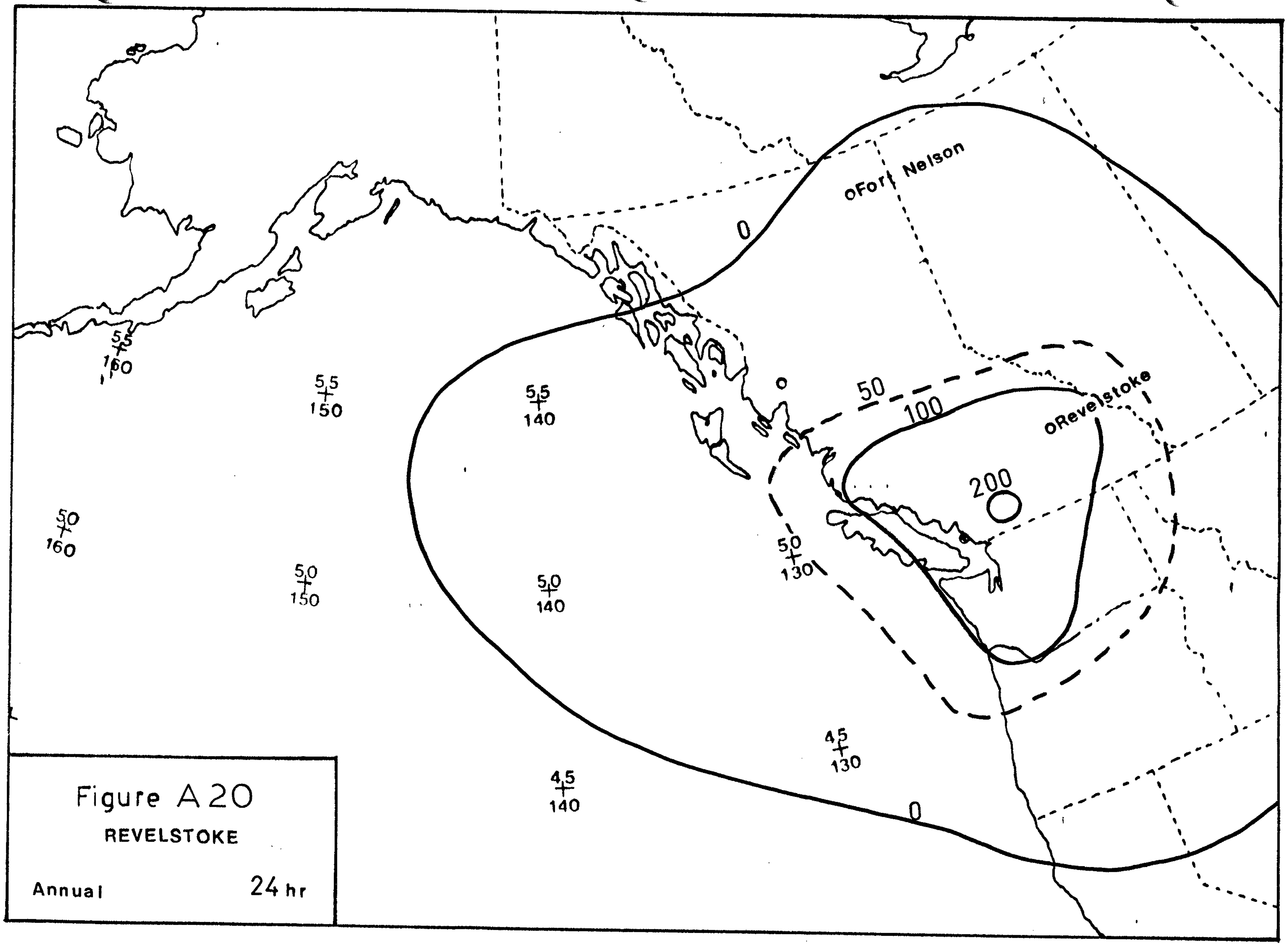

Figure A20

REVELSTOKE

Annual 24 hr

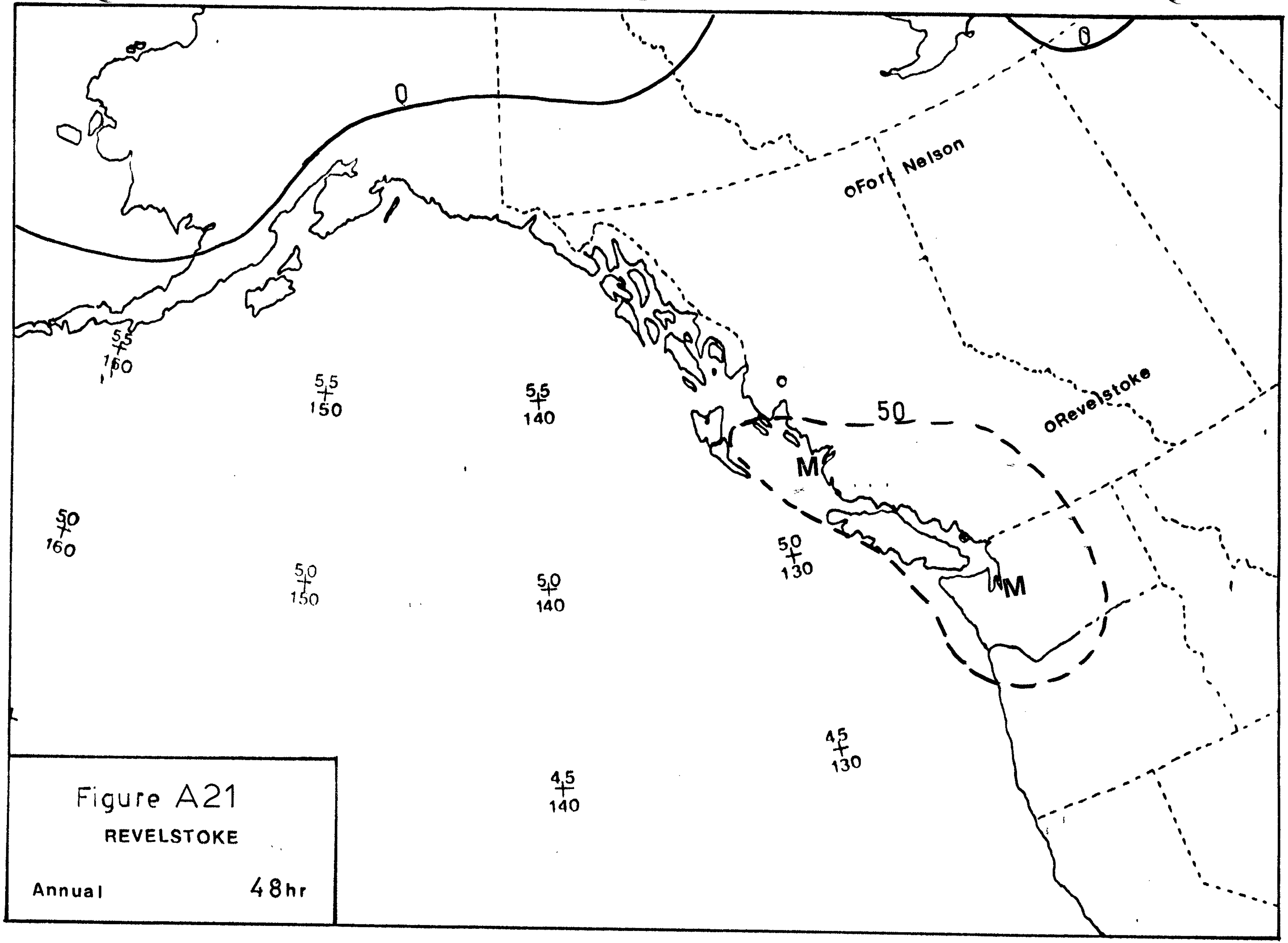

Figure A21
REVELSTOKE

Annual 48hr

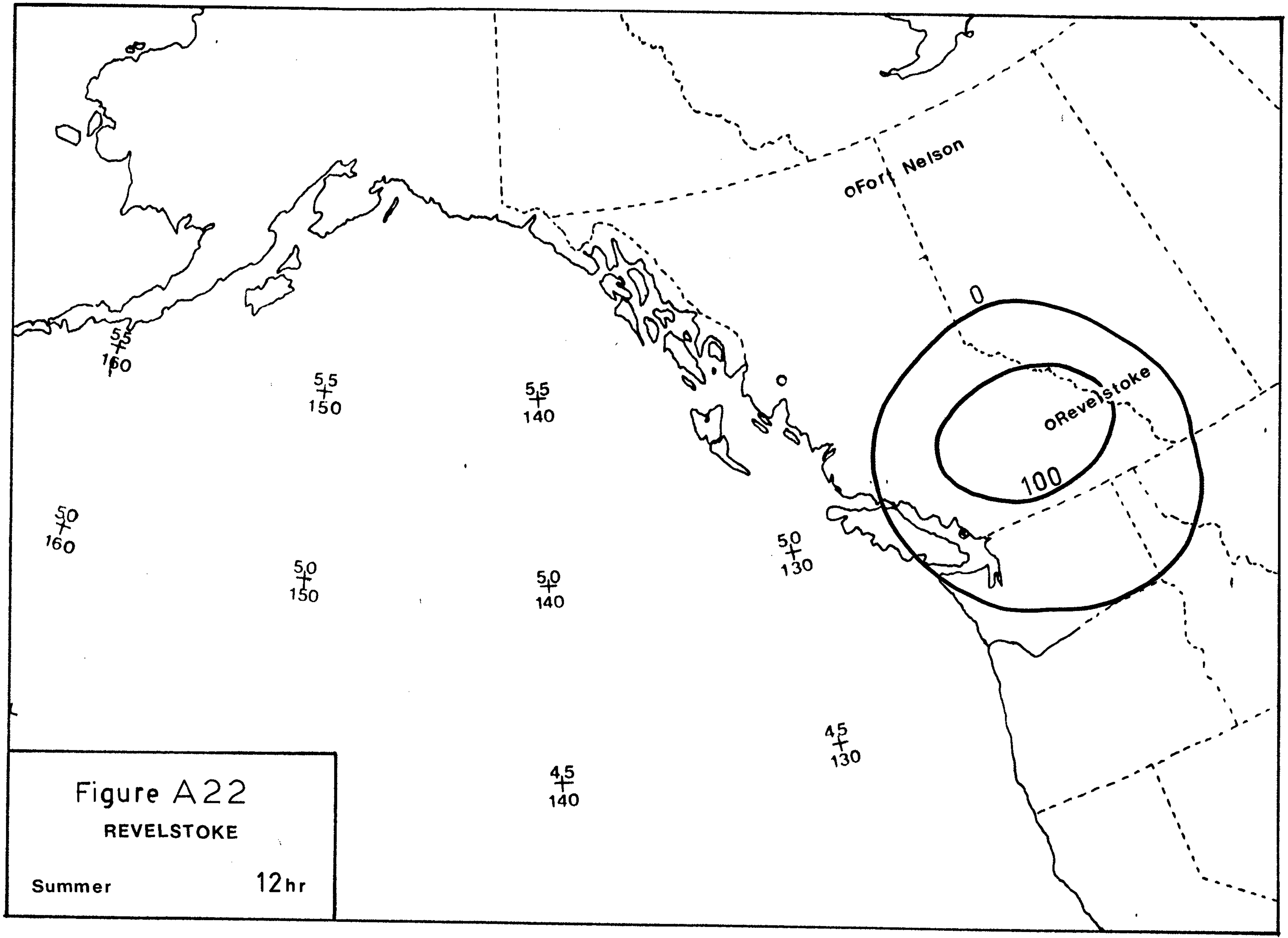

Figure A22

REVELSTOKE

Summer 12hr

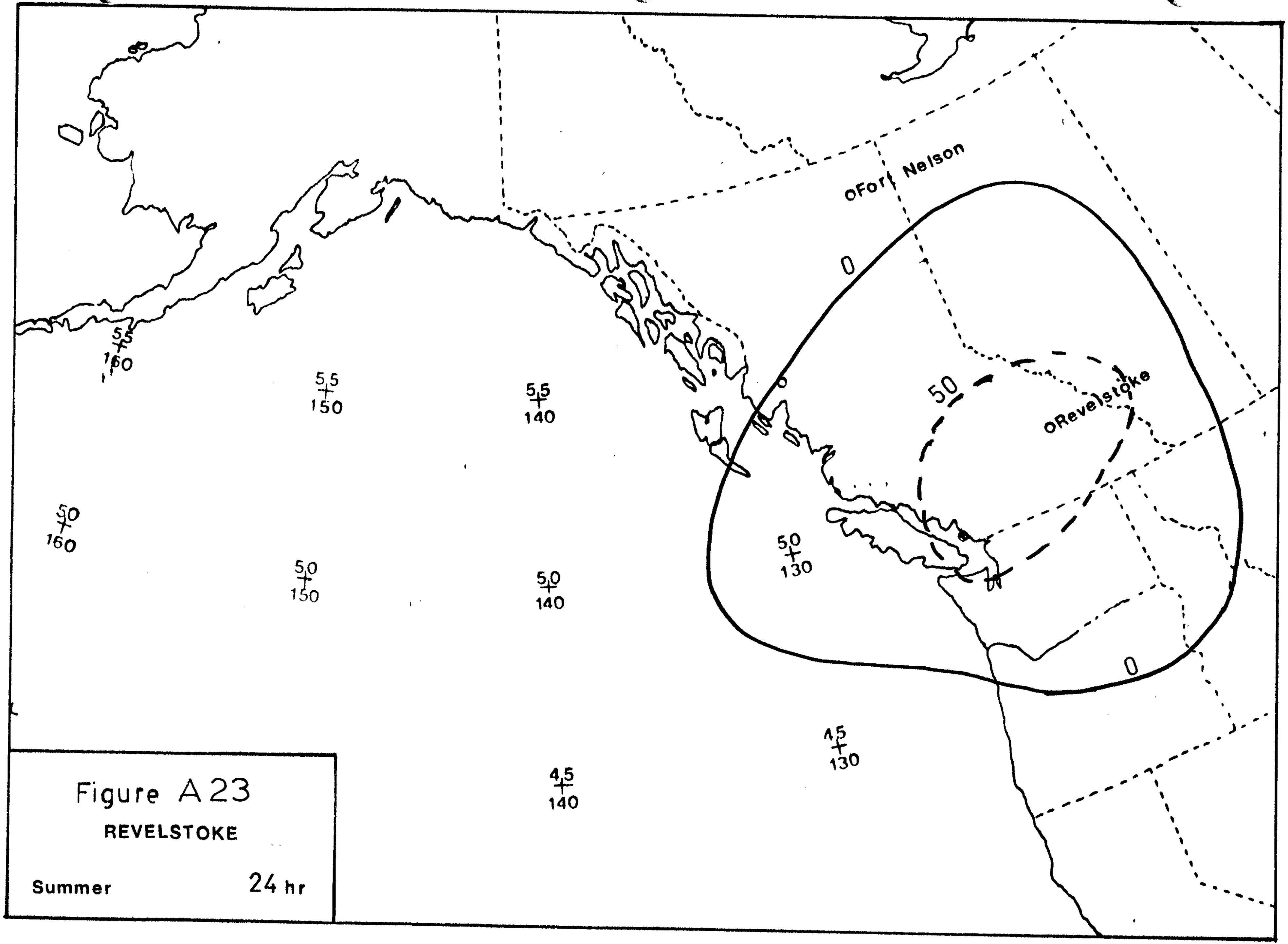

Figure A23

REVELSTOKE

Summer 24 hr

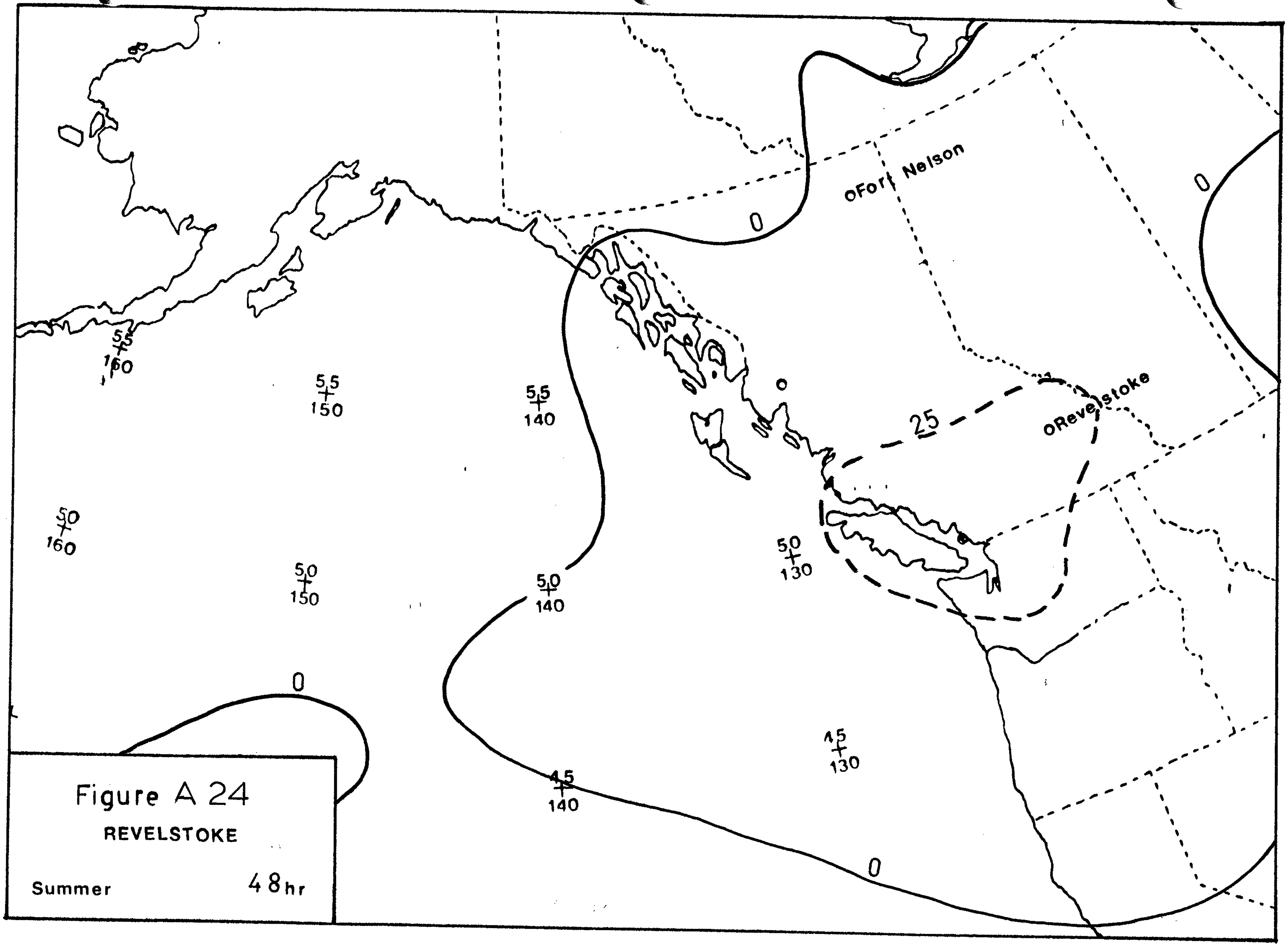

Figure A 24

REVELSTOKE

Summer 48hr

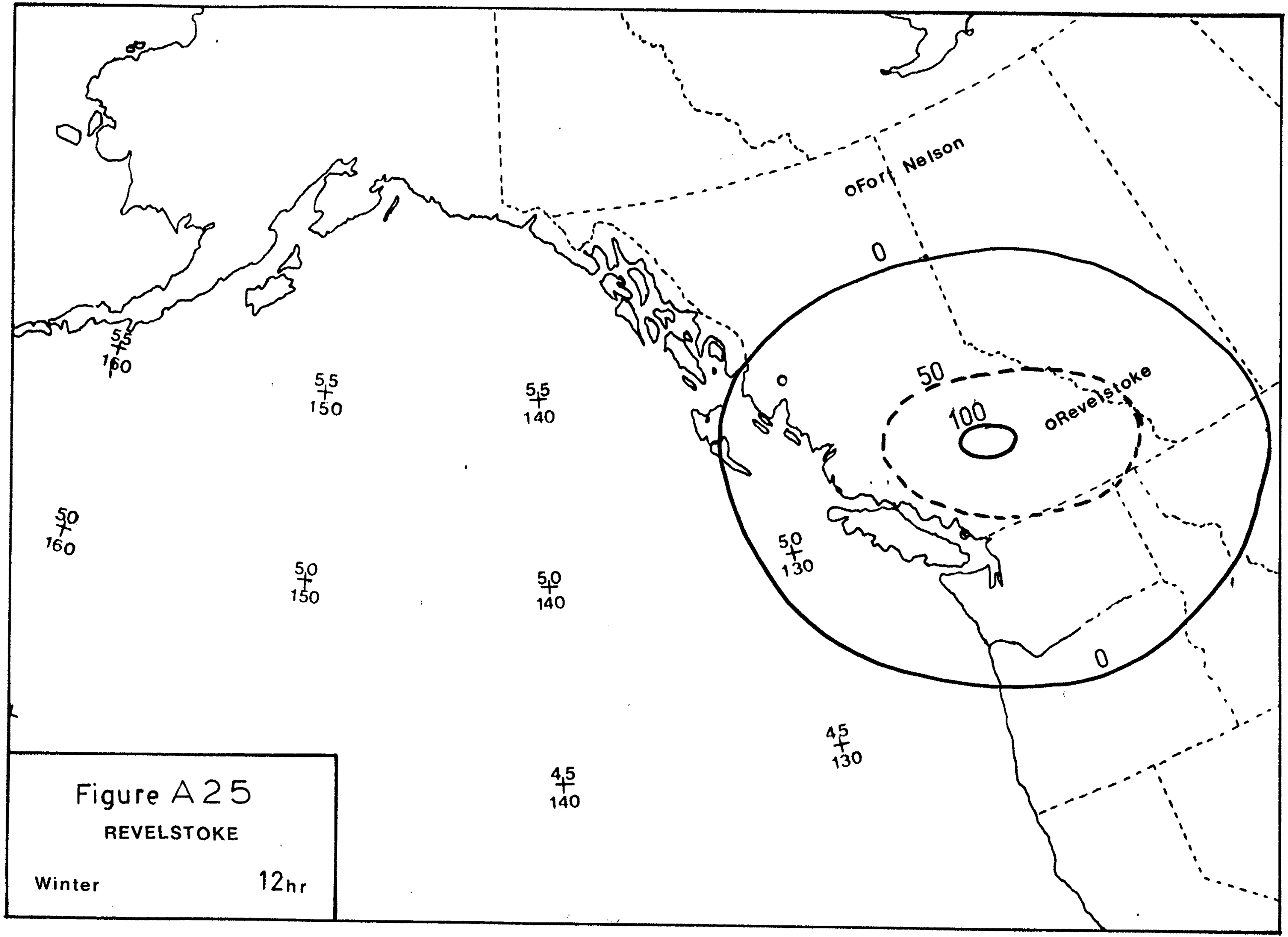

Figure A25

REVELSTOKE

Winter 12hr

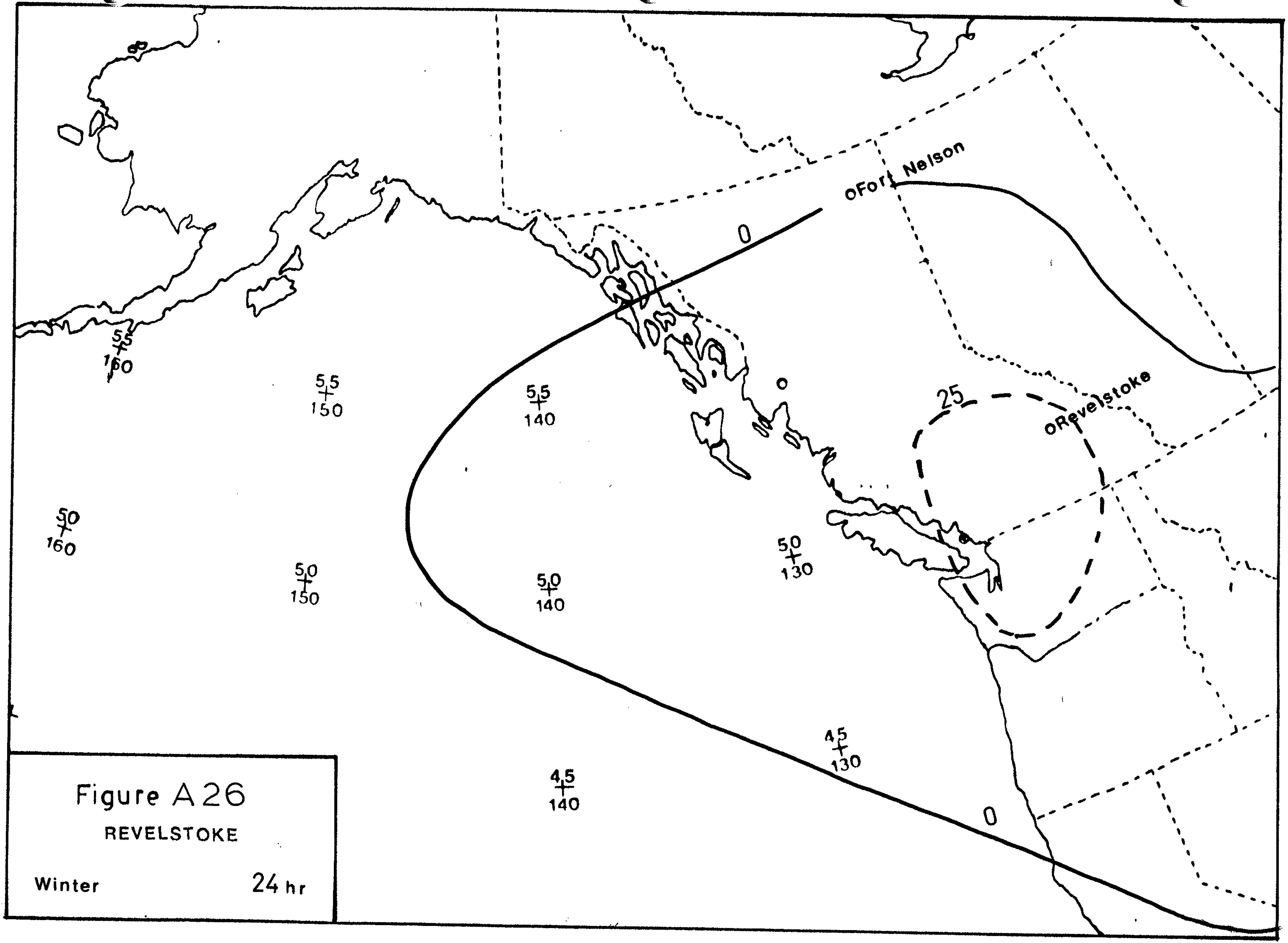

Figure A26
REVELSTOKE
Winter 24 hr

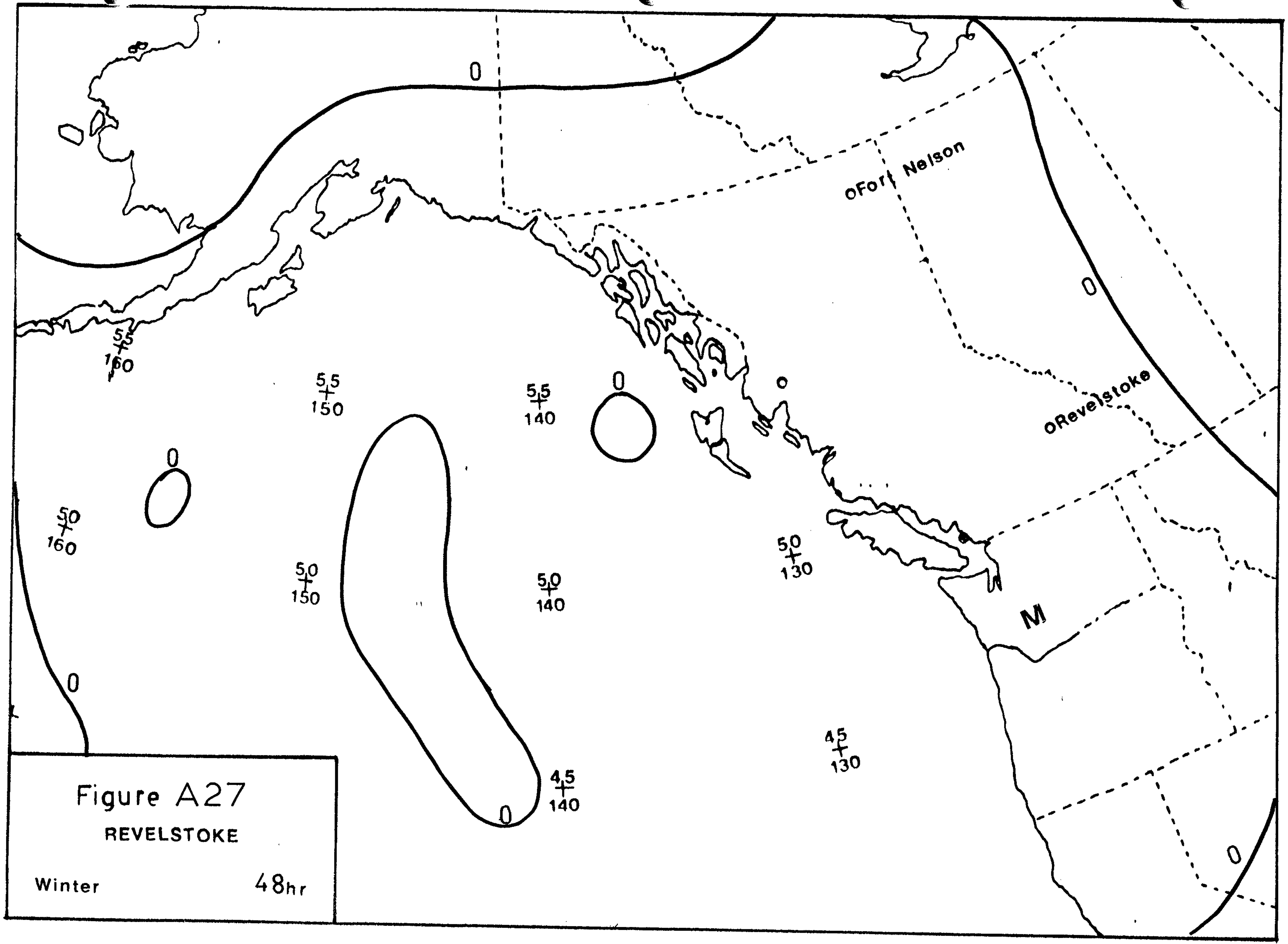

Figure A27
REVELSTOKE
Winter 48hr

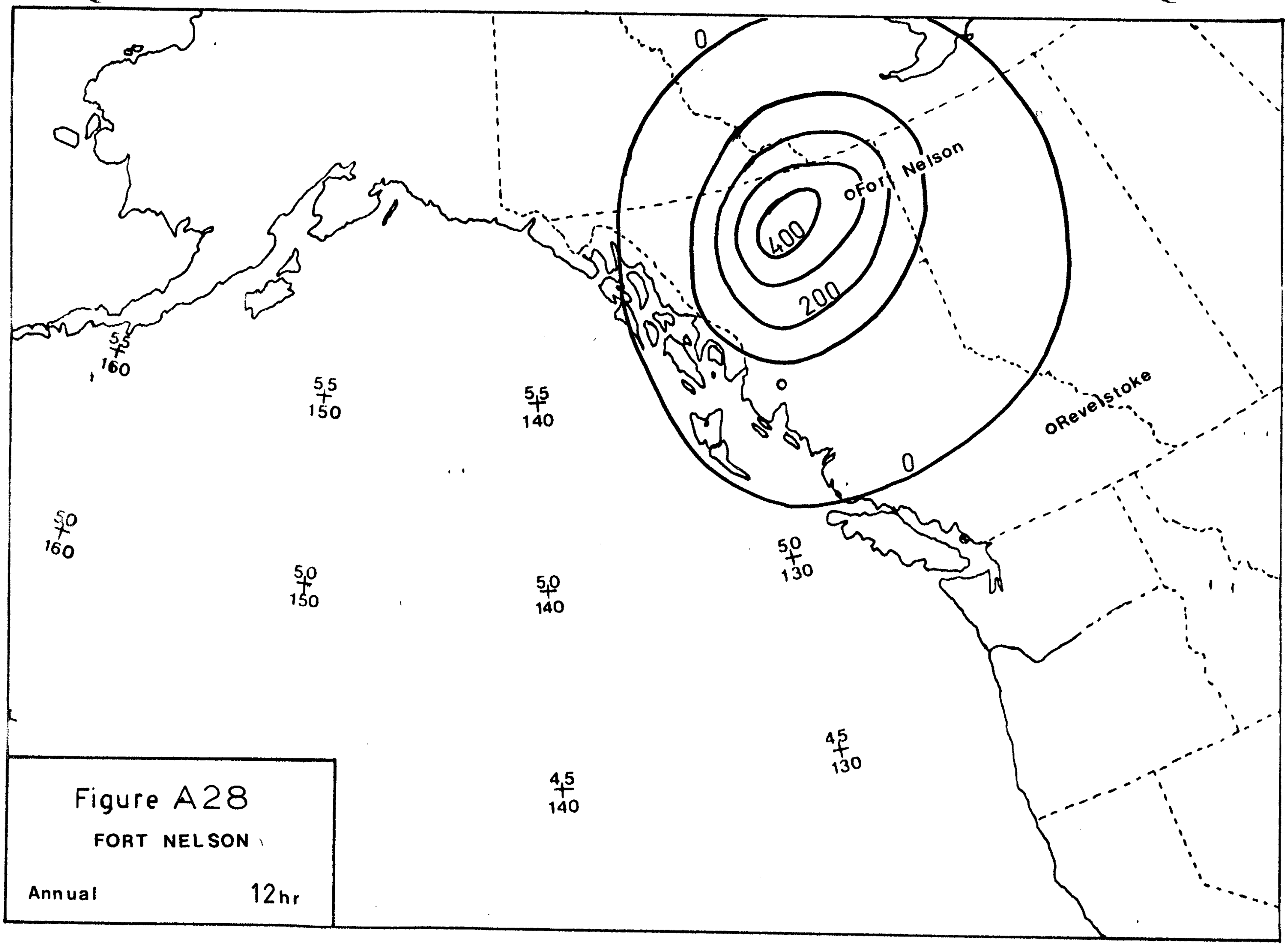

Figure A28

FORT NELSON

Annual 12hr

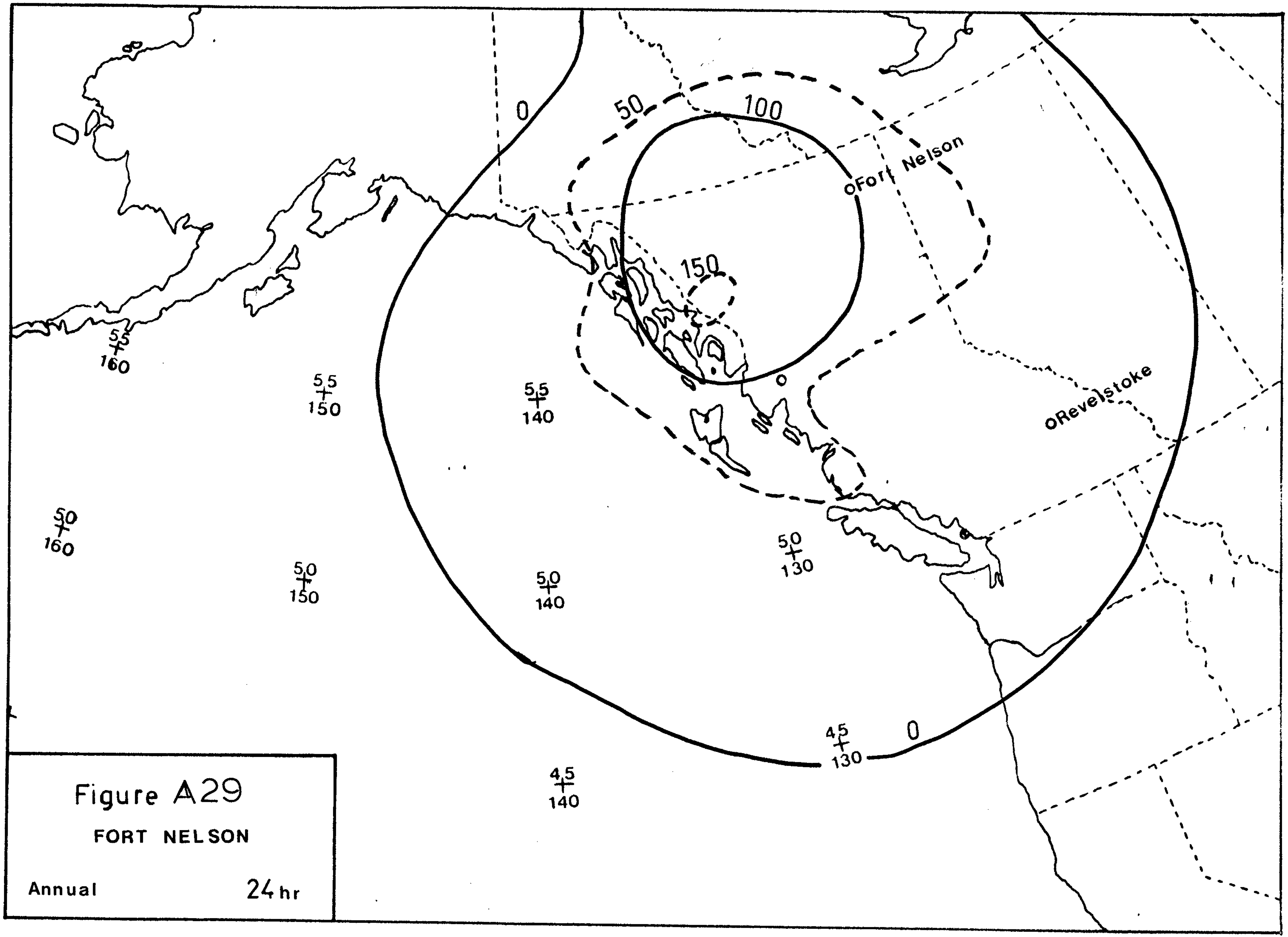

Figure A29
FORT NELSON
Annual 24 hr

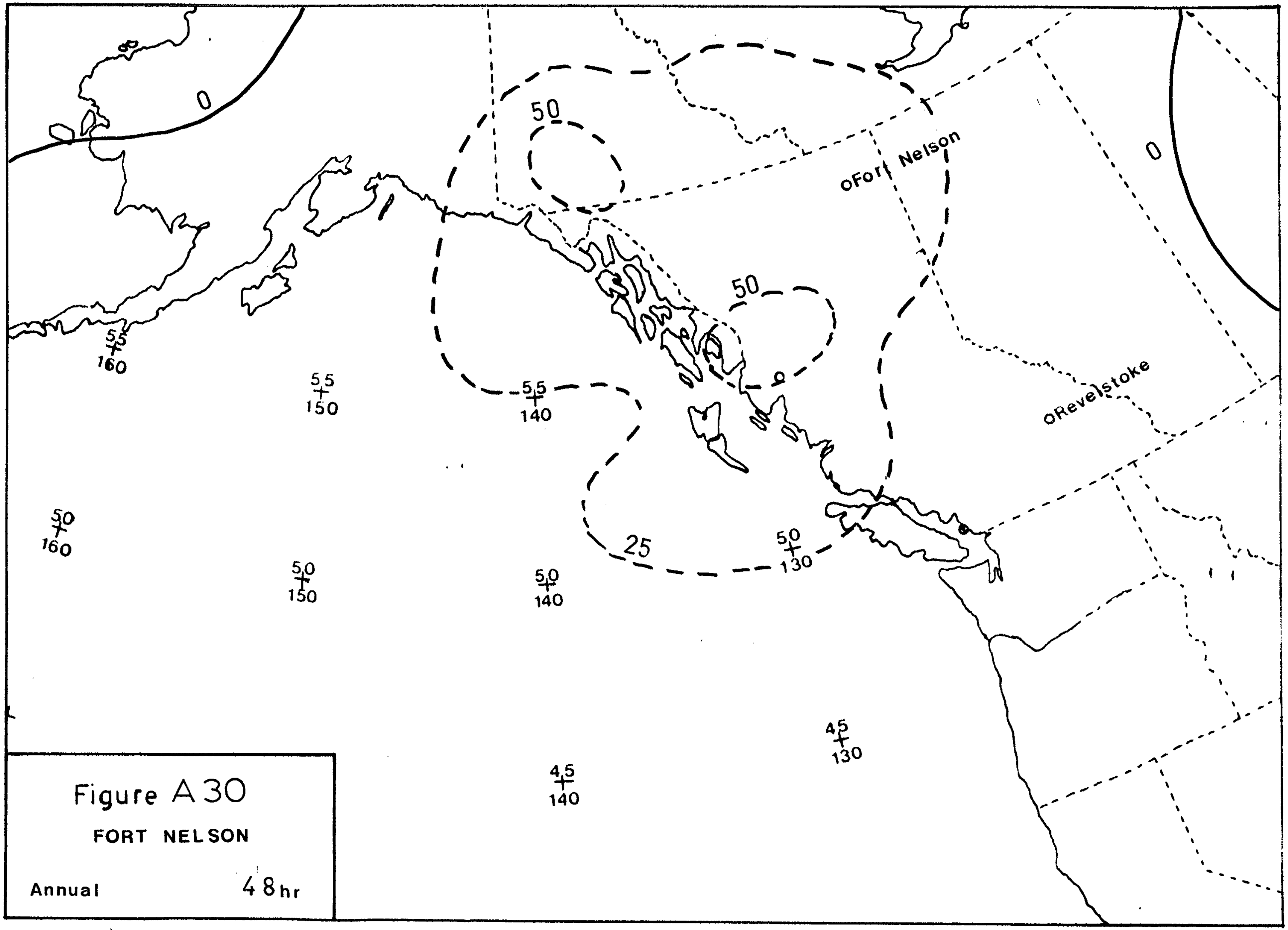

Figure A30

FORT NELSON

Annual 48hr

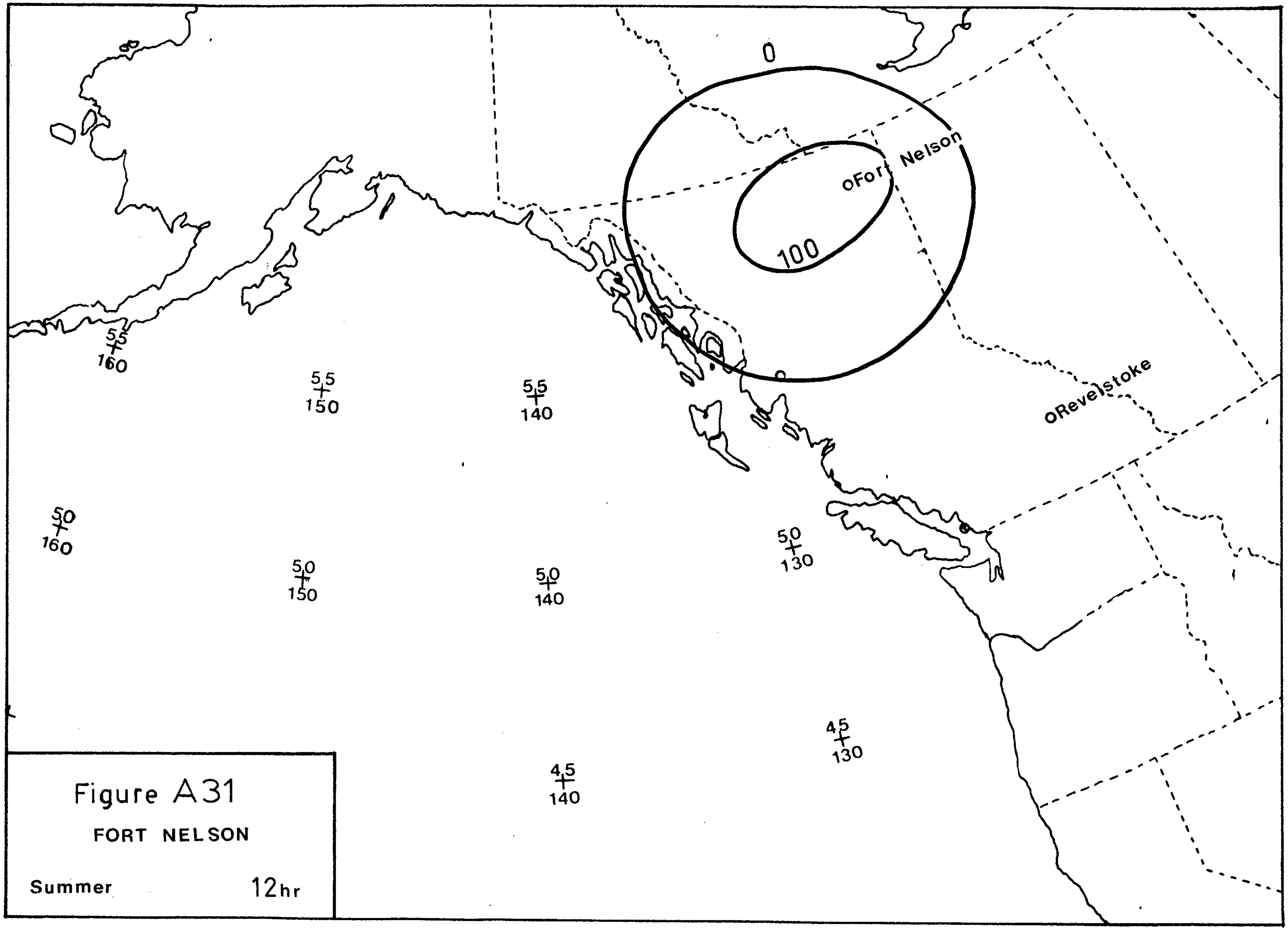

Figure A31
FORT NELSON
Summer 12hr

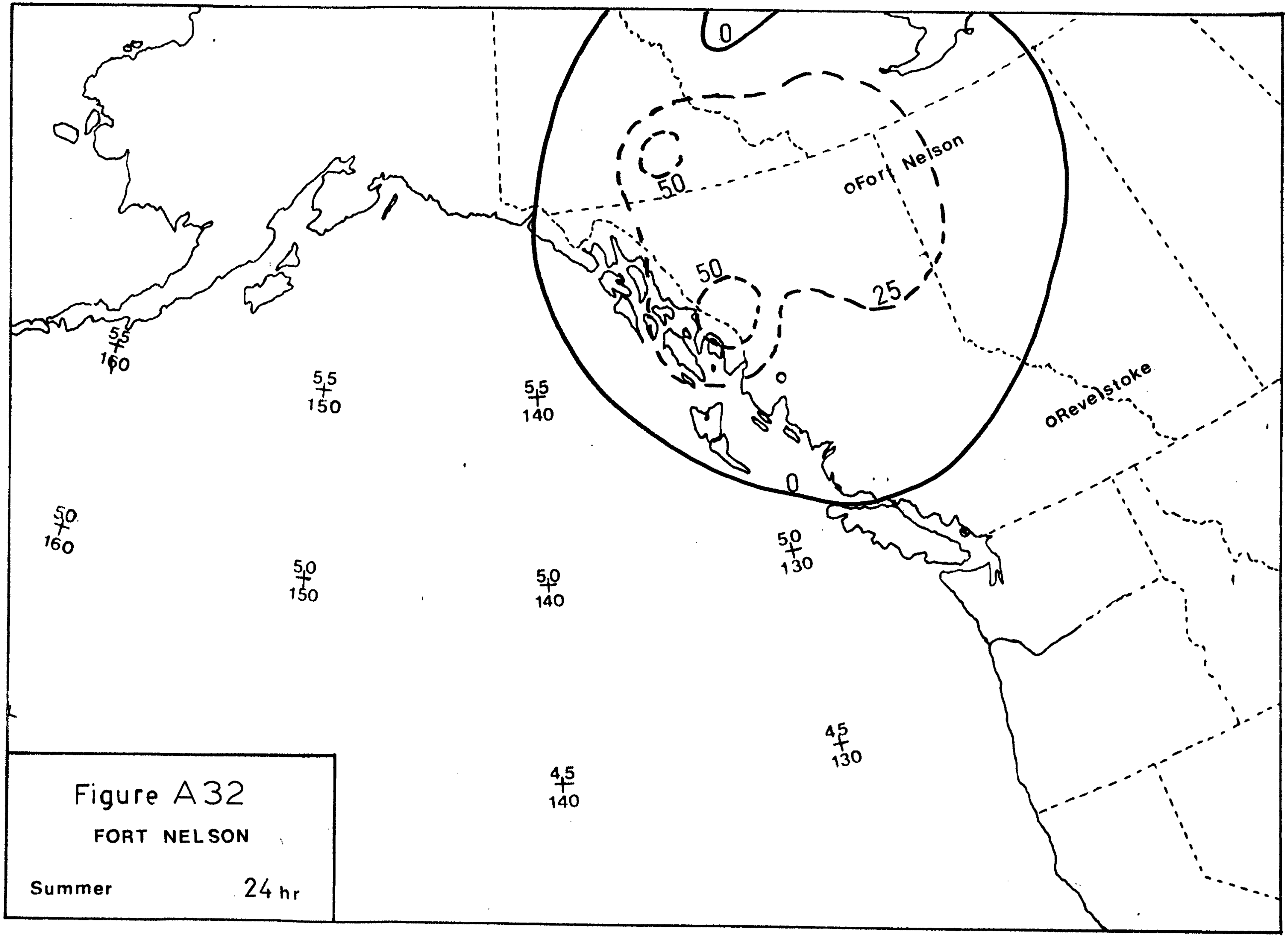

Figure A32

FORT NELSON

Summer 24 hr

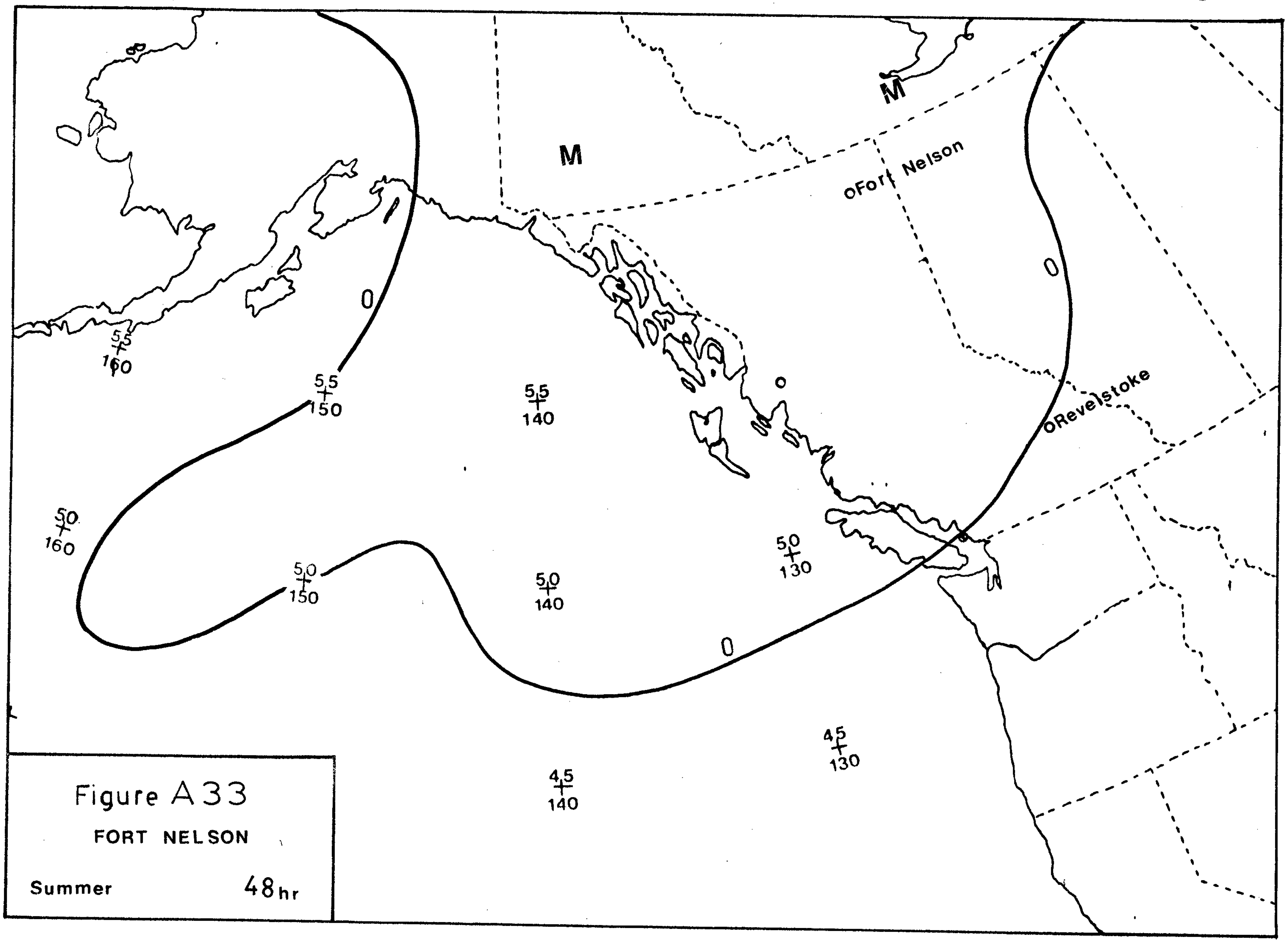

Figure A33
FORT NELSON
Summer 48hr

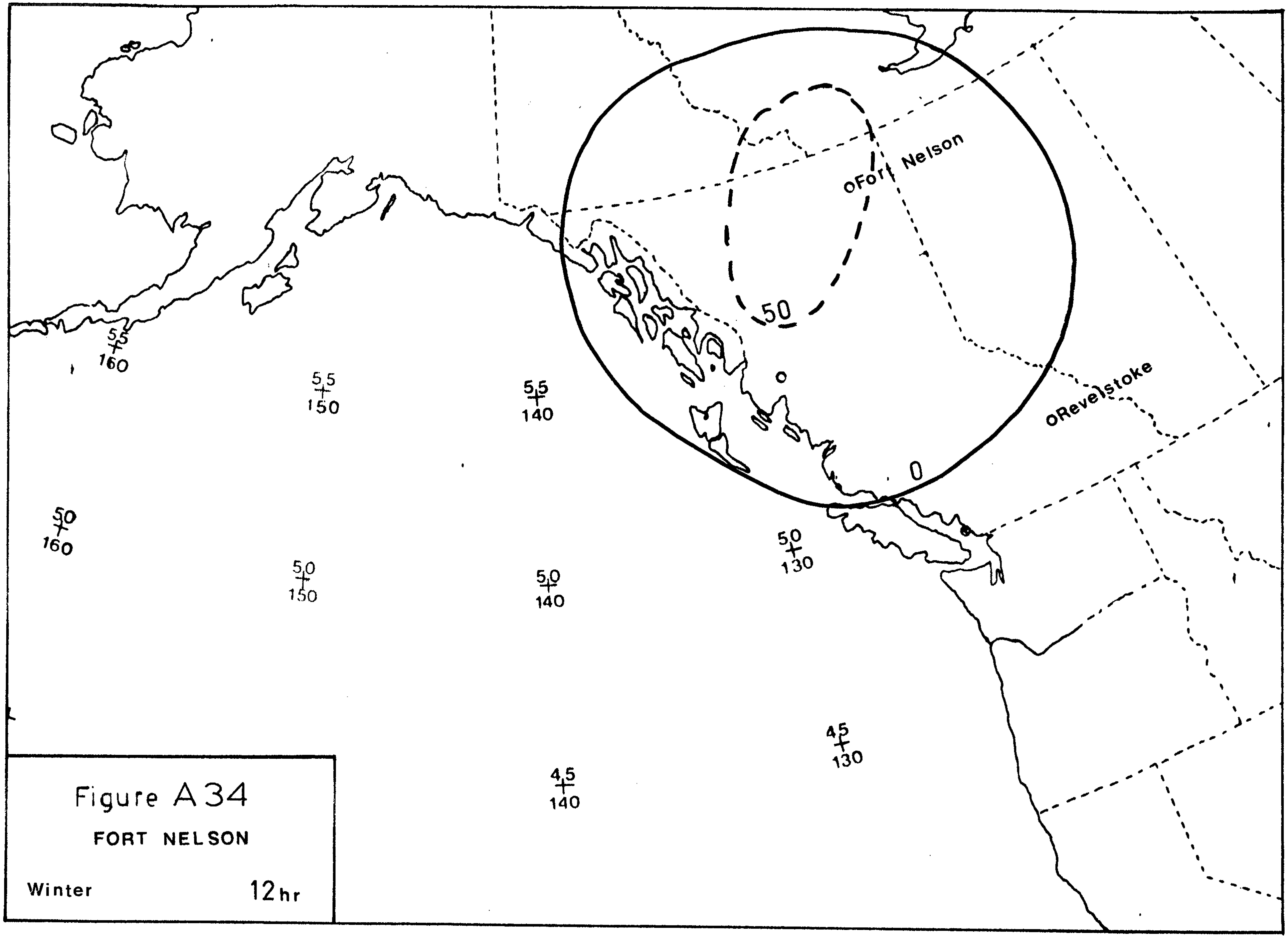

Figure A34

FORT NELSON

Winter 12 hr

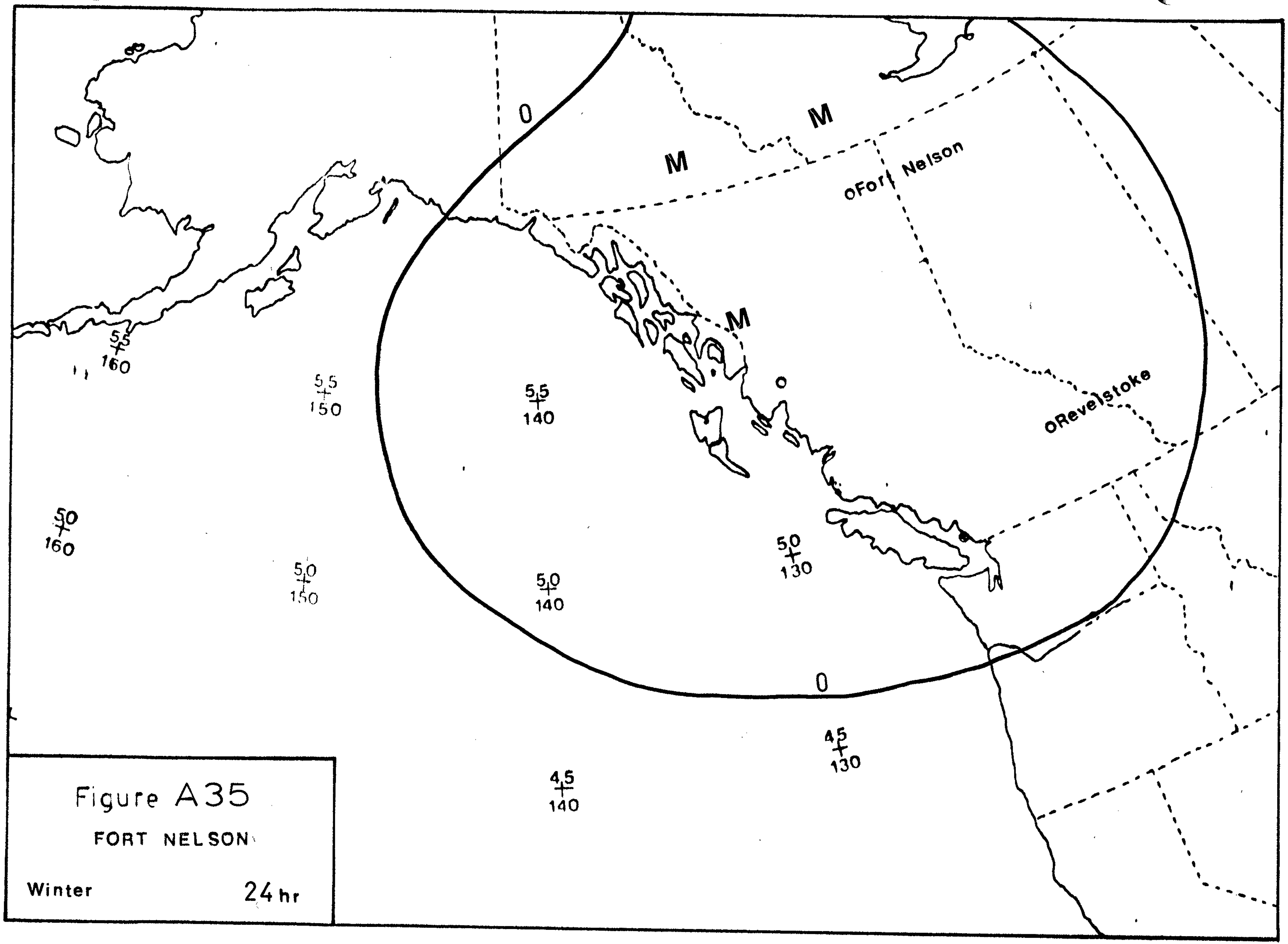

Figure A35

FORT NELSON

Winter 24 hr

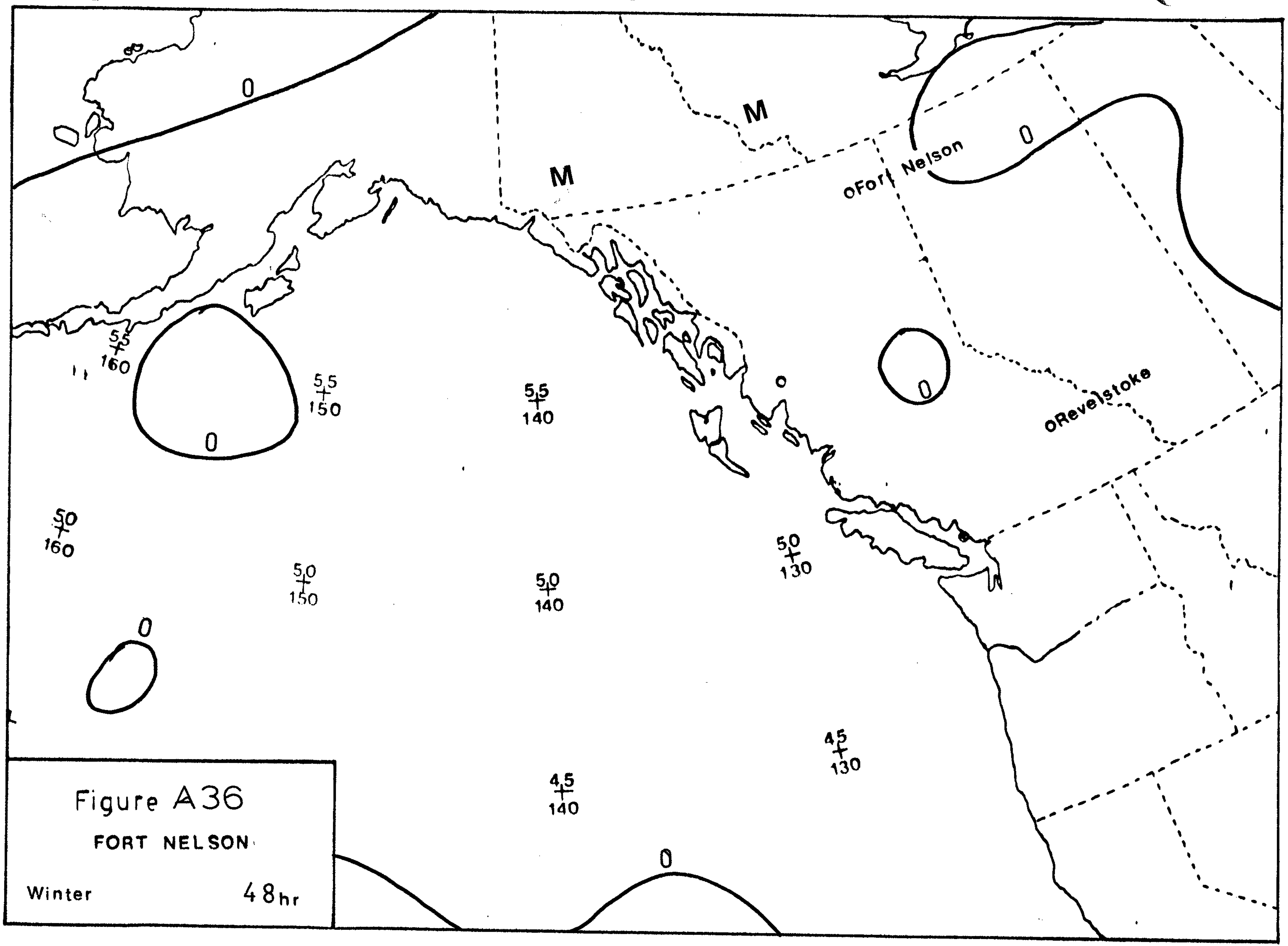

Figure A36

FORT NELSON

Winter 48hr