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# THE LONG-RANGE TRAVEL AND DISPERSION OF THE PLUME FROM THE MOUNT ST HELENS VOLCANO.

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## ABSTRACT

The eruption of the Mount St Helens volcano on 18 May 1980 provided a unique opportunity to study long-range transport of airborne material in the upper troposphere. Forecast trajectories indicated that the major part of the debris would reach the eastern Atlantic around 30°N, and the Hercules aircraft of the Meteorological Research Flight was detached to Gibraltar to take samples of the plume. The results showed that the trajectories, based on the Meteorological Office 10-level forecast model, predicted the movement of the debris quite well. There was marked horizontal and vertical structure within the plume, and evidence that some segregation of particles of different size ranges had occurred. The total flux of material in the sampled volume was estimated to be of the order of half a megatonne.

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## 1. Introduction

The main eruption of the Mount St Helens volcano (46.2°N 122.2°W), which started at about 1530 GMT on 18 May 1980 and lasted for about eight hours, injected material into the atmosphere up to heights of at least 18 km (80 mb) and possibly 22 km (40 mb) (Danielsen, 1981). The plume was quickly distorted and split by vertical wind shear. The portion in the lower troposphere moved towards the east-northeast, while the material in the upper troposphere and lower stratosphere (up to about 100 mb) mostly travelled southeastwards and then eastwards across the United States of America. At the highest levels, from 100 mb to about 50 mb, the debris moved slowly southeastwards initially, but turned sharply to the north or northwest after a day or so.

Forecasts of the movement of the plume in the upper troposphere predicted that it would reach the eastern Atlantic in the vicinity of 30°N on 24 May. To make use of this unique opportunity to study the transport and dispersion of airborne material over distances of travel of several thousand kilometres, the C-130 Hercules aircraft of the Meteorological Research Flight was detached to Gibraltar on 23 May and from there carried out plume sampling flights on 24, 25 and 26 May.

## 2. The general synoptic situation

The general flow in the upper troposphere is illustrated in Fig 1, a composite 300 mb contour chart broadly following the eastward progress of the main plume from 18 to 24 May at that height (about 9 km). Strong flow around a deep low over the Aleutian Islands split into two branches shortly after crossing the north-western coast of the United States of America. The southern branch moved south-eastwards across the continent, then eastwards towards the Iberian peninsula and North Africa, while the northern part extended over Northern Canada and round a large-amplitude trough between Labrador and Greenland on its way to northwest Europe. Between the two strong flows were marked mid-latitude perturbations, one over Canada and Northern USA and the other over the northeast Atlantic.

From a subjective examination it seemed likely that most of the material injected into the upper troposphere would have moved quickly southeast and then east in the fairly strong southern flow, but a fraction may well have travelled either with the northern branch or in the slower oscillating flow of the perturbation over North America.

## 3. The trajectory analysis

Trajectory forecasts, based on the limited information available about the source and on a number of aircraft reports (mainly over the USA) were used to indicate the general area in which the aircraft should search for the plume. For operational convenience the past history of the trajectory was constructed using manually-drawn charts and the predictions were prepared by a numerical method applied to the output of the Meteorological Office 10-level forecast model (Burridge and Gadd, 1977).

After the sampling flights, post facto trajectories were computed in order to study the flow in more detail: these were derived entirely objectively. In the coarse-mesh version of the 10-level model, used in this study, data from most of the northern hemisphere were analysed every twelve hours, and prognoses calculated at six-hour intervals throughout the forecast period of 72 hours. It was not possible to compute trajectories based wholly on analyses, the nearest approach being the use of an analysis and the 6- and 12-hour prognoses to cover the 12-hour period from one base chart to the next. During trajectory computation linear interpolation was carried out with respect to time in the 6-hour interval between successive fields, and with respect to distance between grid-points (the grid-points form a square network on a polar stereographic projection: the separation varies with latitude, being 300 km at 60°N). Each six-hour element of a trajectory was calculated by a method of successive approximations not very different from that followed by a subjective analyst. The first estimate assumed that the wind at the position and time at the start of the element applied throughout the whole six hours. The second estimate divided the time-step into two parts, of three hours each, taking the wind at the trajectory location at the start and mid-point to hold for the two 3-hour steps. The process of halving the time step was continued until the vector difference between two successive estimates was less than a chosen small value.

The 10-level model is based on the primitive equations of motion, ie the calculated wind takes into account not only the geostrophic balance, but also isallobaric, inertial and curvature terms. Analyses and prognoses are available at the standard levels used in international exchanges (surface, 850, 700, 500, 300, 250, 200 and 100 mb). The 250 mb field, showing the flow at a height usually near the level of maximum wind over much of the temperate zone, is obtained from those at the other levels by fitting cubic splines to the profiles below and above that level. The flow at non-standard levels (eg 400 mb) is obtained by linear interpolation between adjacent standard levels.

Trajectories were calculated at 500, 400, 300, 250 and 200 mb from the position of the volcano itself and from points one degree to the north, south, east and west, starting at 1600 GMT 18 May. The main results for the 300 and 250 mb levels are shown in Fig 2. The shaded areas contain the end-points, at given times, of the bulk of these trajectories: they do not necessarily indicate the size of the cloud resulting from small and mesoscale dispersion, but will also reflect an artificial spread brought about by errors in the meteorological fields and in the trajectory calculations. The results confirm the subjective impression that most of the material would be expected to follow the southern route: the analysis agrees quite well with the observed forward edge of the cloud over eastern North America (eg McCormick, 1980). 300 mb trajectories started from 2° to 5° north of the volcano (not shown) followed the more northerly route towards northwest Europe: sightings of debris were reported over East Anglia and the Wash, England at 35,000 ft (~ 10 km) at about 1100 GMT on 25 May, and over Southern Scandinavia (Meixner, et al, 1981), in reasonable agreement with these trajectories. At lower levels (400 and 500 mb) many of the trajectories became caught up in the trough-ridge system over North America, delaying their eastward movement.

Trajectories at 400 to 200 mb were also initiated at 6-hour intervals over an 18-hour period after the main event: all reached the eastern Atlantic between latitudes 27°N and 36°N at times ranging from late on the 23 May to late on 24 May.

4. <u>The Hercules sampling flights</u>

On the basis of the forecast trajectories the Hercules aircraft of the Meteorological Research Flight was detached to Gibraltar on 23 May, and from there carried out sampling flights over the eastern Atlantic on the following three days between latitudes 25°N and 37°N. In addition to the usual meteorological instrumentation (Nicholls, 1978) the Hercules carried three instruments for sampling particulate matter, namely:

a. A standard 1957 type Pollak (CN) counter (Metnieks and Pollak, 1959) was used to make spot measurements of the concentration of Aitken nuclei at intervals of two minutes throughout each flight, giving a spatial resolution of about ten kilometres. The efficiency of the instrument is greatest for particles of radius $\geqslant 0.01\ \mu m$ (Sinclair, 1982). The absolute accuracy in normal use is stated to be about $\pm$ 16 per cent when the concentration of Aitken nuclei lies within the range 100-500 000 $cm^{-3}$ (Podzimek et al, 1981). However, at the low temperatures and pressures encountered at the flight levels (8 to 10 km) the measured concentrations could be up to 30 per cent too low (Pollak and Metnieks, 1960, 1961).

b. A CCN (cloud condensation nucleus) counter of the thermal-gradient diffusion chamber type was used for particles of radius greater than 0.1 μm (Kitchen and Stirland, 1981). The sampling inlet was not designed for isokinetic flow, and some particles would be lost, so the measurements must be regarded as little more than qualitative. The instrument was run at a high supersaturation (4 per cent) to obtain condensation on all particles and not just those active at normal atmospheric supersaturations. However, in spite of these shortcomings, the observations serve to substantiate the variations in particle concentration observed by the Pollak counter. Samples were taken every few minutes.

c. A modified Knollenberg ASSP (Axially Scattering Symmetric Probe) (Ryder 1976) was used to measure particles with radii in the range 1-15 μm. The instrument is intended for the study of cloud droplet spectra, so the measurement of dry, irregularly-shaped aerosol particles must be regarded as largely qualitative. The sampling period was 50 seconds, equivalent to a horizontal distance of 5 km, and care was taken to note times when the measurements may have been within cirrus cloud.

The objectives of the flights were as follows:

i. to locate the plume in order to verify the trajectory predictions;

ii. to study the horizontal and vertical structure of the plume;

iii. to examine the distribution of particle sizes of the material in the plume;

iv. to assess the flux of material in the plume.

The flight plan aimed to locate the plume by flying perpendicular to the wind direction in the area indicated by the trajectories, and, when the plume had been located, to carry out a number of traverses, extending the whole width of the plume if possible. Observations were made in the upper troposphere as the flow was stronger and less complex than at other levels, providing the earliest opportunity to sample the plume, and probably keeping to a minimum any complications resulting from vertical exchange processes (eg convection, sedimentation).

Fig 3 shows the flight pattern for the first sampling day, 24 May, in which the track of the aircraft has been displaced to show the approximate air positions at 1300 GMT. Shaded areas show the regions of high CN counts ($>$ 5000 $cm^{-3}$) inferred from these measurements, while Fig 4 shows a plot of the variation of CN, CCN and N (radius $> 1\ \mu m$) particles. The location on the aircraft track can be identified by the letters along the top of Fig 4, which correspond with those of Fig 3. Most of the samples were taken at a height of 8.9 km (310 mb), except before 1145 GMT (about 8 km, 350 mb) and after 1615 GMT (9.5 km, 285 mb).

Records from all three instruments show generally low levels with several peaks. The CN trace shows most variability, with a "background" level typical of the upper troposphere, of the order of 50–3000 $cm^{-3}$, and peaks rising above this to 20000 to 30000 $cm^{-3}$. On 25 and 26 May the CN observations show similar features (but with on isolated peak rising to nearly 80 000 $cm^{-3}$ on the 26th): the CCN and large particle concentrations, however, did not rise above background level on those days. On all the days, the regions of higher concentration extended typically about 50-200 km along the aircraft track.

Few measurements are available for comparison. From admittedly rather limited experience of nucleus measurements at such heights over the previous two years, such concentrations appear to be abnormally high, more typical of the continental boundary layer than the upper troposphere. In transit to Gibraltar on 23 May and during the return to the United Kingdom on 27 May the observed concentrations of CN in upper tropospheric haze layers occasionally approached, for brief periods, the maxima measured on the experimental flights. However, about a month later, on 23 June 1980, sampling carried out in apparently similar haze layers over the Atlantic near 50°N 20°W yielded a maximum CN count of only 3600 $cm^{-3}$. In the experiment reported by Flyger et al (1976) the maximum CN concentration at heights of 3–4 km over the North Atlantic and Greenland was about 10,000 $cm^{-3}$, well below those observed at the much greater heights near Gibraltar.

Visual observations from the aircraft, as well as the instrumental data, indicate that the volcanic dust cloud was fragmented and thinly layered on all three sampling days. Differences among the particle counts of the three instruments, and from one day to another, suggest that some sedimentation of larger particles had probably occurred. On 24 May, the peak concentrations sometimes occur simultaneously on all three instruments, whereas at other times marked peaks are present in only one or two of the size ranges. Furthermore the Knollenberg ASSP showed a distinct change in the large particle count and size between the first day and the remaining two days, as shown in the following table:-

| Date (May 1980) | Nmax ($cm^{-3}$) | $\overline{R}$ ($\mu m$) |
|---|---|---|
| 24 | 8.7 | 3.9 |
| 25 | 0.5 | 1.4 |
| 26 | 0.5 | 1.4 |

Nmax is the maximum concentration of particles of radius $> 1 \mu m$ sampled by the ASSP in a 50-second period in clear air at altitudes $> 8$ km. $\overline{R}$ is the mean radius of particles sampled by the ASSP in clear air at altitudes $> 8$ km.

The peak concentration, Nmax, on the first day is more than an order of magnitude greater than that observed on the second and third days; the mean radius also shows a significant decrease by the second day, although the values of $\overline{R}$ are subject to some uncertainty if the aerosol particles are irregularly shaped. According to Stokes' Law, the terminal velocity of a spherical particle of density 2 g $cm^{-3}$ at a height of 10km is about 3.5 x $10^{-4}$ m $s^{-1}$ for particles of 1 $\mu$m radius and about an order of magnitude greater for particles for 3 $\mu$m radius. Over six to eight days of travel the larger particles could have fallen about 2 km and the smaller ones by only 200 m or so. The upper regions of the plume would have been depleted of the largest particles, leaving the concentration of particles of radius less than 1 $\mu$m virtually unchanged.

Fragmentation of the plume is apparent from Fig 3, with patches of high CN concentration about 150 to 250 km across, and clearer air between. Whether this represents a true horizontal distribution or whether the vertical structure has a dominant effect is a question which cannot be answered with the available data. The time-averaged widths of the observed portion of the plume on the three days were 450, 1000 and 650 km respectively: on no occasion was clear air sampled on both sides of the plume, so these values must be regarded as minimum widths. The observations of total plume width are not inconsistent with estimates given by Heffter (1965) of dispersion over large distances of travel.

It is possible to make an order-of-magnitude estimate of the maximum flux of material integrated over the plume cross-section on 24 May. Assuming the volume mean radius, $\bar{r}$, of each class of particle as given in the first column of the following table and assessing the mean concentration of particles in each range from the data shown in Fig 4, the weight of matter in unit volume may be calculated.

| Particle type | $\bar{r}$ ($\mu$m) | Mass* of Particle (g) | Number of Particles/m$^3$ | Mass* of Particles/m$^3$ (g) |
|---|---|---|---|---|
| CN | 0.05 | $10^{-15}$ | $6 \times 10^{9}$ | $6 \times 10^{-6}$ |
| CCN | 0.5 | $10^{-12}$ | $10^{8}$ | $10^{-4}$ |
| N | 3.0 | $2 \times 10^{-10}$ | $2.5 \times 10^{5}$ | $5 \times 10^{-5}$ |

*Assuming density = 2 g/cm$^3$, typical of light lava. (Smithsonian Physical Tables, Ninth Edition, 1954: Table 282).

If the plume width is taken to be 1000 km and its depth 2 km, then for a wind speed of 20 m s$^{-1}$ the total ~~flux~~ amount of material crossing longitude 10°W on 24 May would be about 0.5 megatonne. On the remaining two days, the contribution from the N and CCN particles was very much less, and the mass flux was reduced by one or two orders of magnitude.

## 5. Discussion

The evidence supports the hypothesis that some of airborne material from the Mount St Helens eruption crossed the Atlantic at about 30 N and was sampled by the Hercules on 24, 25 and 26 May 1980. Concentrations of particles in all the observed size ranges were well above those which have been measured in the troposphere on other occasions. In particular, the presence of 'giant' particles (radius $>$ 1 $\mu$m) at heights of 10 km or so cannot readily be explained other than by volcanic action: in addition, such particles have an appreciable terminal velocity (about 300 m a day) and this limits the time of injection to well within a month of the sampling date.

The majority of the trajectories reached the eastern Atlantic in the vicinity of 25-35°N late on 23 or early on 24 May, suggesting that the observed debris formed the major part of the cloud which crossed the Atlantic at that time. There were also one or two isolated reports from northwest Europe (Meixner et al, 1981), which confirmed the track suggested by trajectories started from positions two to five degrees north of the volcano. A complete comparison between the forecast and the post facto trajectories is not possible, since the forecast trajectories were for operational reasons based on U.S. aircraft reports and forecasts of positions over eastern North America and the western Atlantic. The two sets of trajectories, however, showed very similar speeds of movement over the eastern Atlantic.

Nor can a strict comparison between the winds implied by the trajectories and those measured by the Hercules aircraft be carried out - the 250 mb tracks had passed through the sampling area by 24 May and the 300 mb trajectories were well to the south. However, the 300 mb trajectory speeds on 24 May were about 20-25 m $s^{-1}$ at first, very similar to the aircraft winds: later in the day the trajectory winds increased to 30 m $s^{-1}$, while the aircraft winds increased rather more, to about 35 m $s^{-1}$. The overall conclusion is that both the forecast and the post facto trajectories provided good indications of the paths taken by the debris and its speed of movement over distances of travel of 10 000 km or so.

If the object had been to use the aircraft data and back-trajectory analysis to locate the source and/or time of eruption, the outcome may not have been quite so successful. Back trajectories from positions of high CN counts on 24 May passed very close to the source only a few hours after the main eruption started (see Fig 5). Those for 25 May were close to the source but indicated a time of origin some two days later than the main eruption, while the back-trajectories for 26 May were scattered over a range of latitudes. Variations in timing may have been caused by horizontal variations in wind speed within the generally strong flow, differences which would probably have been smoothed out by the coarse-mesh meteorological analyses and forecasts; or it may have been that some of the material was delayed in the meridional flow over northern USA before being caught up in the stronger flow to the south. A possible cause of the scatter in the tracks for the final sampling day is that relatively small errors in latitude over the Atlantic may have led to the trajectory becoming involved in the mid-latitude perturbation over the USA, with marked variations in the meridional component of flow.

## 6. Conclusions

The general picture that emerges suggests that a substantial fraction of the airborne debris moved quickly towards the eastern Atlantic between about 25°N and 35°N. The leading edge of the plume probably arrived in the area late on 23 May, but the passage was spread over a considerable time, three days or more, partly because of horizontal variations in wind speed within the strong flow, and possibly partly a result of matter being delayed for a time over the USA before being caught up in the stronger flow. Flux calculations suggest that about half a megatonne of debris may have been contained within the portion of the plume that was sampled: this was probably rather less than 0.1 per cent of the total airborne material, estimated to be about 0.3 to 0.6 $km^3$ of magma (Newell, 1983), most of which was deposited within a few hundred kilometres of the source. The plume showed marked horizontal and vertical inhomogeneity, possibly resulting from horizontal meso-scale eddies and vertical stability. The variation of particle size distribution with time may have been a consequence of sedimentation or of changes in the nature of the source in the days after the initial eruption.

The trajectories, based on the Meteorological Office ten-level numerical weather prediction model, enabled the plume to be located quickly in the sampling flights, and also explained certain features of the spread of material, notably the delay of some material over the USA and the reports of possible volcanic debris over northwest Europe.

Acknowledgements

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## FIGURES

Fig 1 Composite chart at 300 mb following the trajectories.

Fig 2 Estimated positions of cloud at 1600 GMT on given dates.

Fig 3 Hercules sampling flight of 24 May 1980.

Fig 4 Particulate concentrations measured on flight of 24 May 1980.

Fig 5 Back-trajectories from positions of high particle counts on sampling flight of 24 May 1980.

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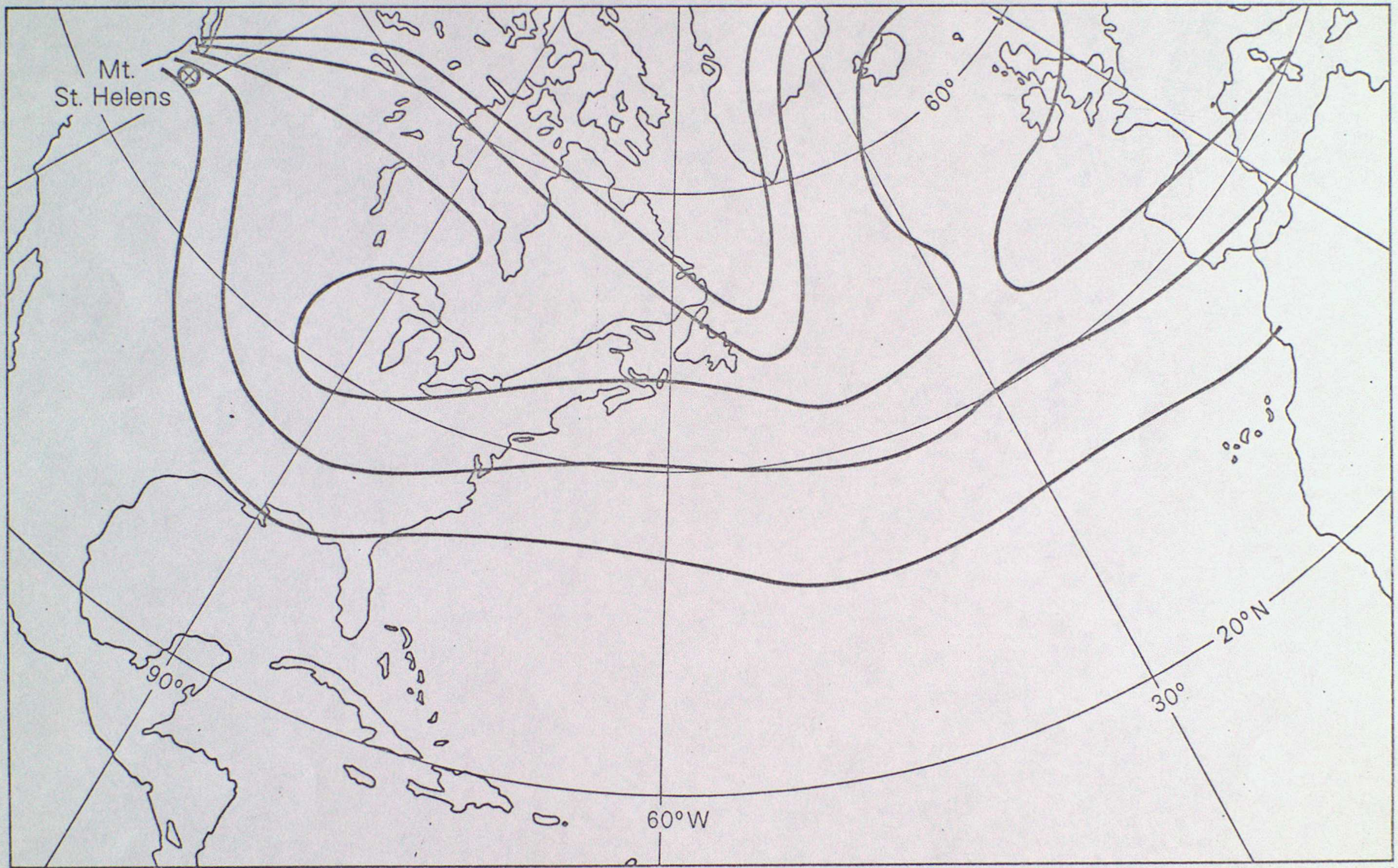



FIG 1

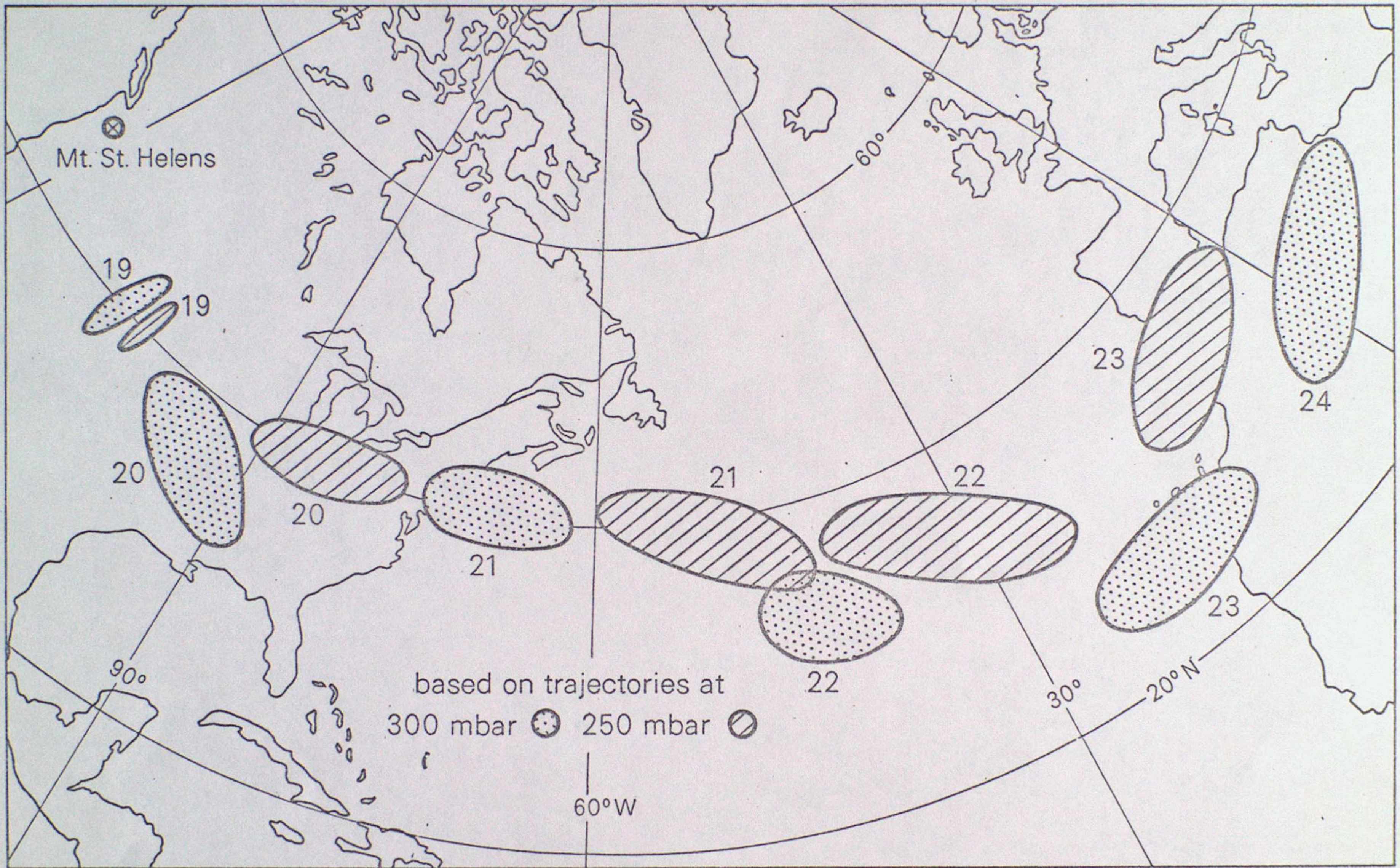

Mt. St. Helens
19
19
20
20
21
21
22
22
23
23
24
60°
30°
20°N
90°
60°W
based on trajectories at
300 mbar 250 mbar

FIG 2

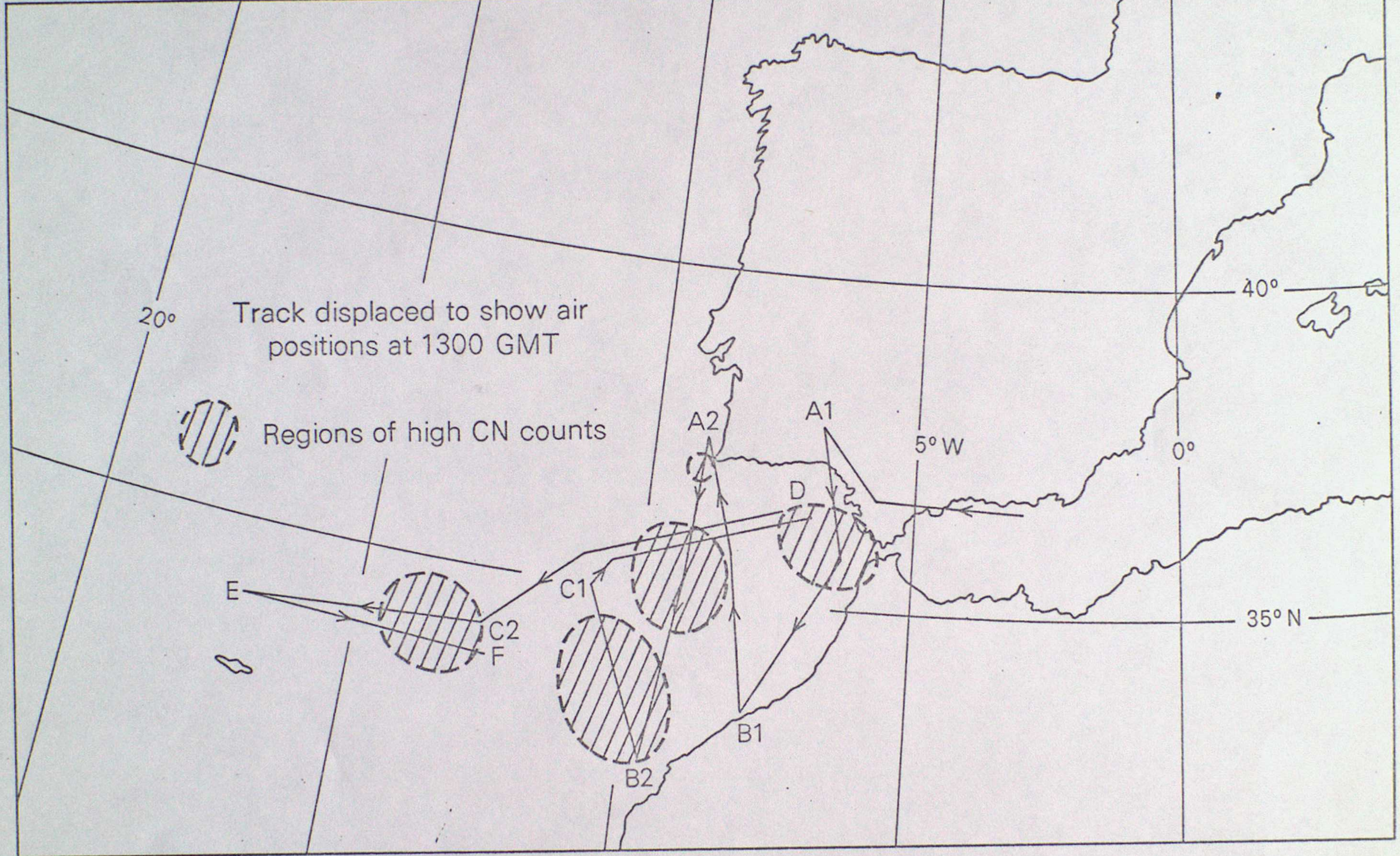
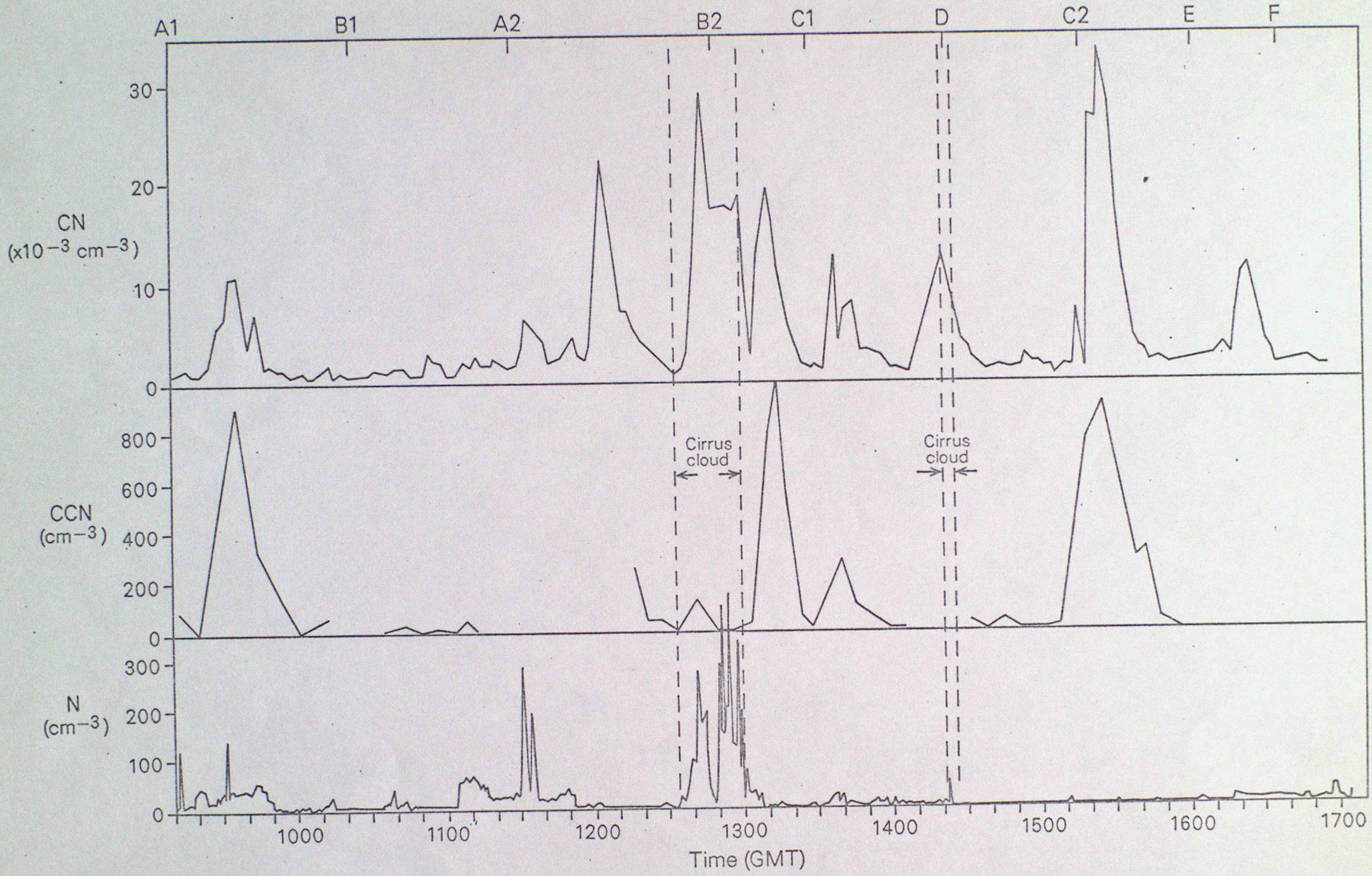

20°
Track displaced to show air positions at 1300 GMT
Regions of high CN counts
40°
35° N
5° W
0°
A1
A2
B1
B2
C1
C2
D
E
F

FIG 3



A1
B1
A2
B2
C1
D
C2
E
F
CN
(x10⁻³ cm⁻³)
30
20
10
0
CCN
(cm⁻³)
800
600
400
200
0
N
(cm⁻³)
300
200
100
0
Cirrus cloud
Cirrus cloud
1000
1100
1200
1300
1400
1500
1600
1700
Time (GMT)


FIG 4

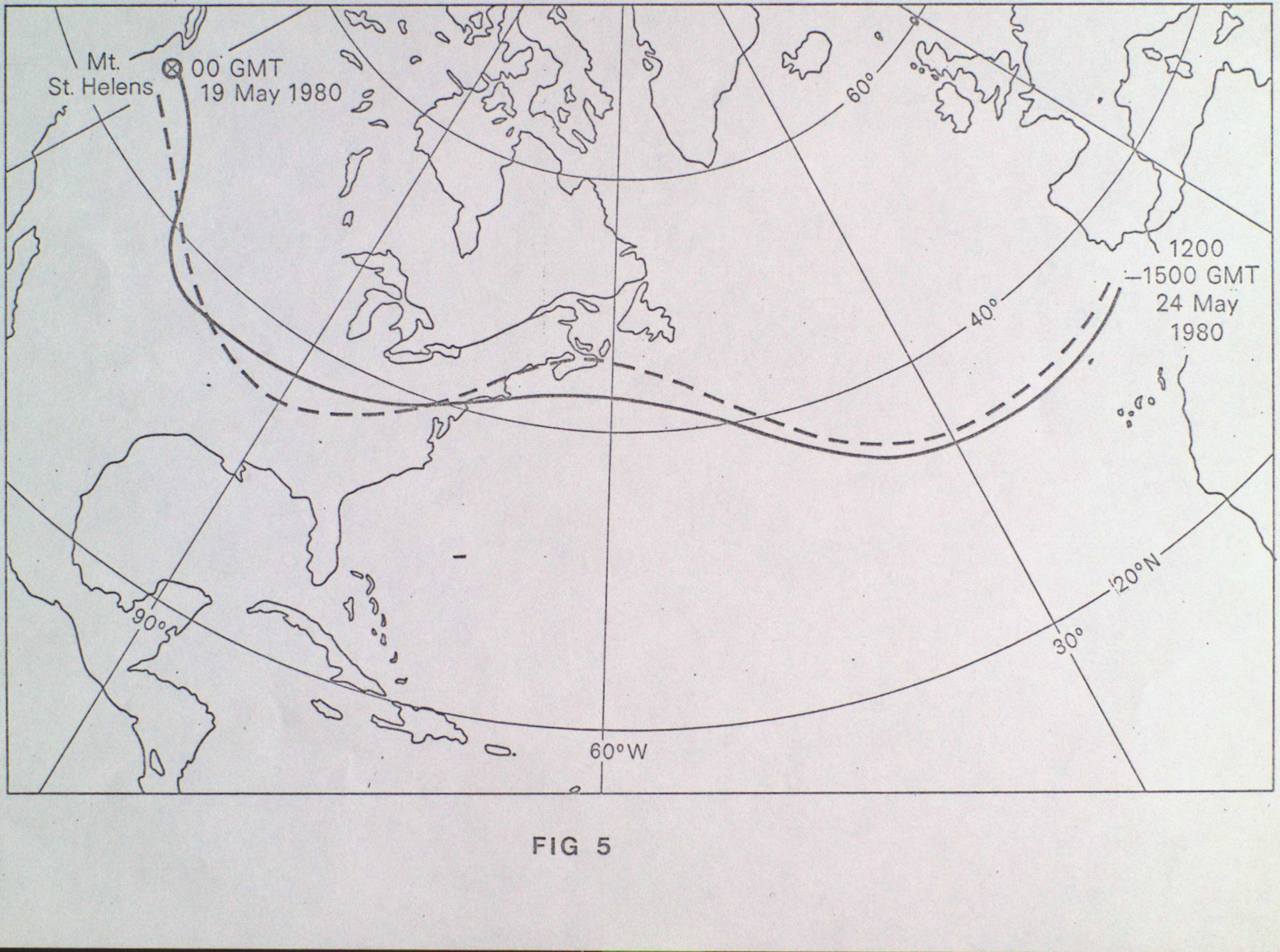

Mt.
St. Helens
00 GMT
19 May 1980
1200
–1500 GMT
24 May
1980
60°
40°
20°N
30°
90°
60°W

FIG 5