**GEORGIA INSTITUTE OF TECHNOLOGY**
**OFFICE OF CONTRACT ADMINISTRATION**
**SPONSORED PROJECT INITIATION**

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Project Director: Dr. Derek M. Cunnold

Sponsor: NASA-Langley Research Center; Hampton, VA 23665

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Date 10/11/83

Project No. G-35-657 School/~~Lab~~ Geo. Sci.

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Project Director(s) Dr. D.M. Cunnold GTRI/~~GIT~~

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Title: Ozone Transport in the Lower Stratosphere and the Ozone - $NO_2$ Relationship

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Grant/Contract Closeout Actions Remaining:

- [X] None
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G35-657

FINAL REPORT

# THE MOTION AND DISPERSION OF VOLCANIC EMISSIONS FROM LA SOUFRIERE INJECTED INTO THE STRATOSPHERE

By

D. Cunnold and M. Pitts

Under

NASA Grant NSG–1643

September 1980

**GEORGIA INSTITUTE OF TECHNOLOGY**

**SCHOOL OF GEOPHYSICAL SCIENCES**

**ATLANTA, GEORGIA 30332**

1980

# The motion and dispersion of volcanic emissions from La Soufriere injected into the stratosphere

by

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submitted under

NASA Grant NSG-1643 to Georgia Tech

entitled

Ozone transport in the lower stratosphere and the ozone-$NO_2$ relationship

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## 1. Introduction

Atmospheric particles resulting from the eruptions of the La Soufriere volcano in April, 1979 have been detected from GOES satellite photographs, from an airborne libar and probably by the SAGE satellite. In order to support the probable detection by SAGE, we decided to investigate the meteorological situation in the Eastern Caribbean at the time of these eruptions and to assess the likely motion and spreading of the emissions.

## 2. Cloud motion

Figure 1 indicates the location of radiosonde stations in the Caribbean which were sometimes providing data during mid-April, 1979. Note that La Soufriere is located in the Eastern Caribbean and that because the observed drifts as well as the prevailing winds in the lower stratosphere were eastward, the injected materials rapidly moved into a region where wind observations were extremely sparse. For this reason, we decided it was inappropriate to perform a sophisticated trajectory analysis. A large scale analysis seemed to offer the best estimate of the trajectory of the cloud across the Atlantic; the standard maps (and tapes), which are obtainable from NOAA, provide the basis for such an analysis.

We have obtained the temperature and geopotential height maps at all the standard meteorological levels from Jim Laver at NOAA for April, 1979. Separate maps exist, on the 65x65 grid, for the Northern and Southern Hemispheres. Below 100 mb the data consists of an optimal interpolation of a combination of both satellite (temperature) and radiosonde measurements (see Smith, et al., 1979). Above 100 mb in the Northern Hemisphere, only radiosonde data has been used (although at and above 10 mb, where radiosonde data is non-existant, satellite data has been used).

Eruptions from La Soufriere occurred on April 13, 14, 17, 22, and 26. Several of these appeared to penetrate the stratosphere (Krueger, private communication, 1980). In particular, airborne lidar observations indicate that the eruption at 2105Z on April 17th reached 18 km. The largest of these eruptions occurred on April 13th and 17th. SAGE made observations in this latitude region on April 23rd and 24th. Possible trajectories of material at 70 mb from the April 17th eruption and from the eruption at 2100Z on April 13th are shown in Figure 2. These trajectories were calculated assuming the material remained on the 70 mb surface and using winds which were derived geostrophically from the NOAA geopotential height maps. Because this approach to trajectory analysis could lead to substantial errors at the latitude of La Soufriere (13°N), several tests have been performed to assess our confidence in the trajectories given in Figure 2.

The airborne lidar observations indicate that at 0Z on April 19th a "cloud" of particles existed at 12°N, 62°W (roughly 200 km southwest of La Soufriere) at 18 km altitude. Smaller concentrations were also observed at 16 and 17 km altitude at roughly this time at approximately 10°N, 58°W (Figure 3). Even allowing for the fact that the diameter of the cloud was probably of order 1000 km at that time (see the discussion on dispersion), the lidar observation at 18 km seems to be inconsistant with the geostrophic trajectory of Figure 2. The closest radiosonde station to La Soufriere is Trinidad; the winds observed there at this time in April are shown in Figure 4. We note that over Trinidad on April 18th the winds at 70 mb were observed to be light and variable. In contrast to this, the winds deduced geostrophically from the NOAA maps were approximately a factor of 2 stronger and persistently from the northwest (Figure 5). We do not find this disagreement particularly discouraging because the NOAA maps are only produced once per day and emphasize the larger scale features of the motion field. Nevertheless, the geostrophic trajectory appears to overestimate the initial speed of the cloud at 70 mb. Therefore, in view of the lightness and apparent variability of the winds over Trinidad, we are unable to establish the initial motion of the cloud with any degree of confidence.

The cloud motion at 100 mb also suggest a limitation of the geostrophic analysis. Both the radiosonde observations and the geostrophically-derived winds indicate a flow in the southeasterly direction. The Trinidad radiosonde suggests a speed of approximately 15 knots. The airborne lidar observations as well as GOES pictures of the motion of the cloud in the upper troposphere are consistent with such a flow. Again, however, the geostrophic wind speed is substantially too large.

In order to further investigate this apparent discrepancy, we have compared the geostrophically-derived winds against radiosonde observations at several Caribbean locations. To statistically summarize this intercomparison, we have divided the locations into two groups:

19°N>latitude>16°N (stations 78526, 78861, 78866, 78897)

and 13.1°N>latitude>10°N (stations 78954, 78970, 78988).

The results for the period April 15 to April 21 are shown in Table 1, where we have excluded wind speeds of less than 5 knots from the directional comparison. The results indicate acceptable agreement in the 16-19° latitude range but that the geostrophic wind appears to overestimate the wind speed by a factor of roughly two in the 10-13° latitude range.

Because of this lack of agreement we have investigated whether any improvement on the geostrophic approximation might be possible. In particular

$$u = u_g - \frac{1}{2\Omega\sin\phi}\ \frac{dv}{dt}$$

and $$v = v_g + \frac{1}{2\Omega\sin\phi}\ \frac{du}{dt}$$

where $u_g$ and $v_g$ are the geostrophic velocity components, $2\Omega\sin\phi$ is the Coriolis force and $\frac{d}{dt}$ indicates rate of change along the particle trajectory. Unfortunately, this correction to the geostrophic velocity appears to be substantial (~ 50%) in the 10-13° latitude range. We have attempted to use trajectories based on the $u_g$ and $v_g$ to update u and v but, because of the size of the correction, this approach is found not to be useful. We conclude that the contributions of ageostrophic motions may explain the differences between radiosonde winds and geostrophic motions but a sophisticated model would be required to further evaluate and correct for these differences.

In addition to the geostrophic approximation, the assumption that material is transported on the 70 mb surface represents a significant limitation on the trajectory analysis. Isentropic transport of an air parcel is almost certainly a better approximation. However, because of the already apparent limitations of the geostrophic approximation and because the global geopotential height maps are only available at the standard meteorological levels, it did not seem worthwhile to correct for isentropic transport. Figure 6 shows the temperature structure at 70 mb. on April 18. Not unexpectedly, temperature is higher to the North (throughout this period). Air parcels following the trajectories shown in Figure 2 would warm, based on the temperature maps for this period. Isentropically, the maps imply that the air parcels would be sinking through approximately 1-1/2 km. The geopotential maps at 100 mb for this period suggest an increasingly rapid transport as the air sinks. Significantly, however, the winds at 100 mb are also directed toward the northeast; a correction for isentropic transport would therefore almost certainly not alter the directional tendencies of the trajectories.

We conclude therefore that the trajectories given in Figure 2 are quite unreliable. Nevertheless, it is clear from the geopotential maps for this period (see, for example, Figure 7) that a geostrophic tendency to transport material in a southeasterly direction followed by transport to the northeast persisted throughout this period. Furthermore, we should recall that the mean direction for geostrophic motion was not very different from that observed by the radiosonde network. Beyond 16°N good agreement with geostrophic motion was found. The tendency for overestimation of wind speeds at approximately 13° latitude is compensated by the tendency for air parcels to sink and speed up as they move northward. We thus regard Figure 2 as a reasonable estimate of the trajectories.

## 3. Cloud spreading

In order to assess the observability of the volcanic clouds we must estimate not only the motion of the center of mass but also the dispersion of the cloud. Because of the shortage of radiosonde stations east of La Soufriere and because of uncertainty in the adequacy of the geostrophic approximation at that latitude, we decided to estimate cloud dispersion using a climatological data set. A procedure for calculating the dispersion of a cloud prior to its reaching the scale of the large scale circulation has been assembled by Justus and Mani (1978) (also described in Mani, 1977). The half width of the cloud is solved as a function of time by numerical integration based upon prescribed vertical shears of the horizontal wind, vertical stability viscosity, turbulent length scales, initial cloud size, and a heat transfer parameter. Most of these parameters are provided by a climatological, monthly-varying model of the atmosphere. This model is limited, unfortunately, to latitudes higher than 20°N and we have, therefore, calculated the dispersion at 20° latitude instead of at lower altitudes. A typical result is shown in Figure 8. The radius of the cloud after one day is predicted to be approximately 500 km. This may be compared against observations summarized by Bauer (1972) which exhibit a range of 10-200 km after one day (see Figure 9). GOES pictures of the spreading of the volcanic clouds from La Soufriere indicate that in the upper troposphere (≈ 100 mb?) the radius is of order 100 km after three hours. This suggests that the Justus and Mani result may be appropriate and that the expansion rate may be on the high side of the range given by Bauer. After approximately one day the cloud having reached the synoptic scale in size probably expands more slowly (approximately as $t^{1/2}$) as indicated by the change in gradient in Figure 8. Based on these results, we estimate that after five days the cloud has a radius (to half-concentration) of roughly 1000 km and of 1400 km after ten days.

## 4. Conclusions

Figure 10 shows the location of SAGE observations of scattering layers for the period April 23 to 28. Summarizing the results on cloud motion and spreading we also present on this figure possible locations and sizes of stratospheric clouds from La Soufriere eruptions on April 13 and 17. When we allow for the initial apparent overestimation of velocities by the geostrophic approximation, we can conclude that it is not an unreasonable hypothesis that SAGE observed aerosols from the April 17 eruption over the mid-Atlantic (approximately 35°W) on April 25 to April 28 and that aerosols from the April 13 eruption were observed on April 23 and 24 over West Africa. Observed layers in the vicinity of the volcano on April 23 and 24 most likely result from the April 22 eruption.

## References

Bauer, E., 1973: Dispersion of tracers in the stratosphere. Proc. Second Conference on CIAP, November 1972. U.S. Department of Transportation Report DOT-TSC-OST-73-4, April, 1973, pp. 254-261.

Justus, C.G., and K.K. Mani, 1978: A model for the simulation of turbulent and eddy diffusion processes at heights of 0-65 km. Pageoph, 117, 513-530, 1978/79.

Mani, K.K., 1977: A model for turbulent diffusion in the atmosphere. Georgia Institute of Technology Thesis, School of Aerospace Engineering, August, 1977.

Smith, W.L., H.M. Woolf, C.M. Hayden, D.A. Wark, and L.M. McMillin, 1979: The Tiros-N operational vertical sounder. Bull. Amer. Met. Soc., 60, 1177-1187.

TABLE 1: Comparison of radiosonde observations with geostrophically derived winds

| Latitude Range of Stations(°N) | Number of Stations | Number of Observations | Observed Speed (Knots) | Observed Direction (Deg. E of N) | Geostrophic Speed - Observed Speed(Knots) With 1σ Error Bars | Geostrophic Direction - Observed Direction(°) With 1σ Error Bars |
|---|---|---|---|---|---|---|
| 16.27 - 18.43 | 4 | 15 | 17 ± 8 | 294 ± 29 | 4 ± 8 | -10 ± 18 |
| 10.58 - 13.07 | 3 | 13 | 13 ± 8 | 263 ± 57 | 13 ± 14 | 18 ± 53 |

Figure 1. Location of radiosonde stations in the Caribbean.

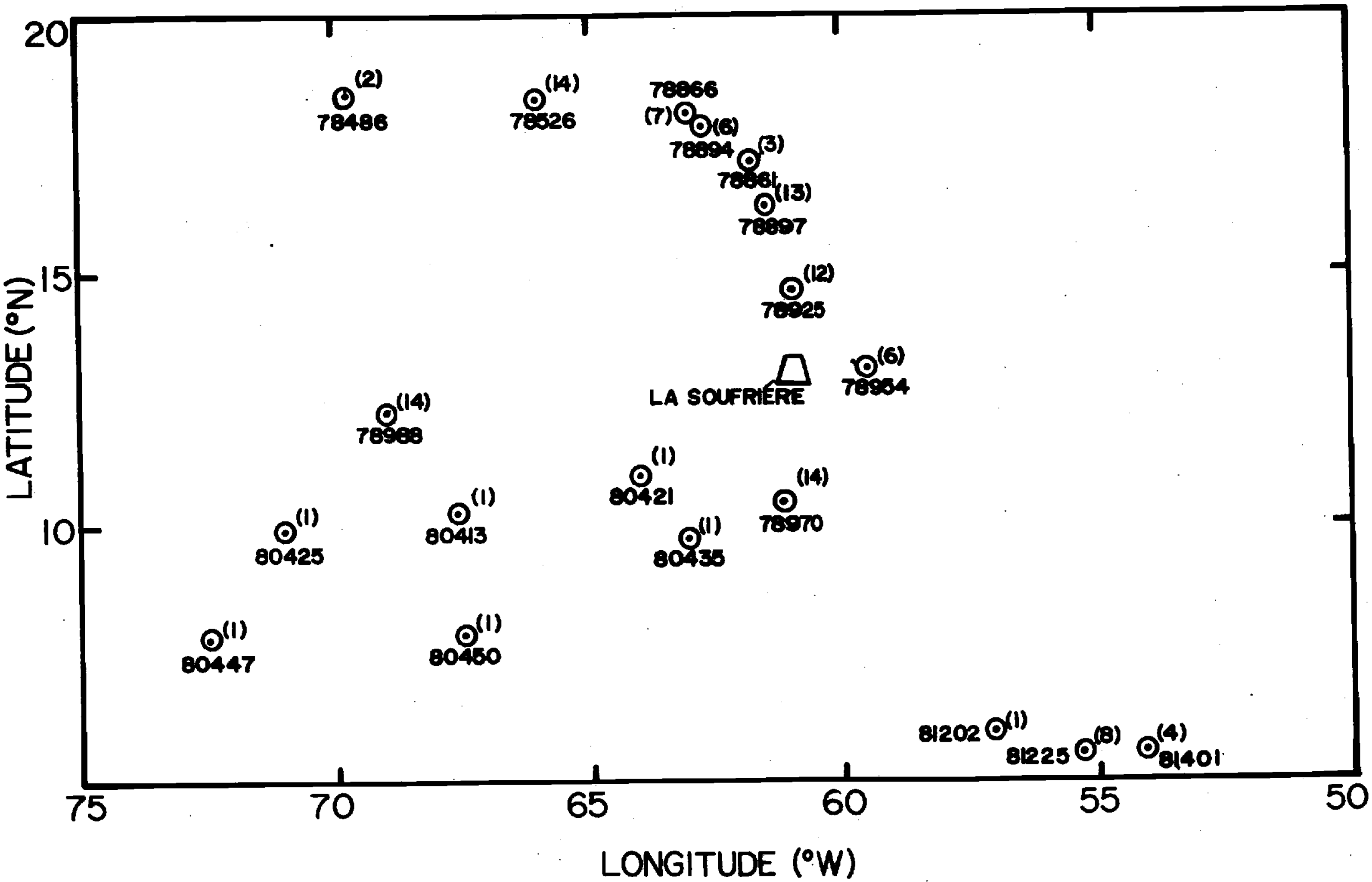

Figure 2. Calculated trajectories of stratospheric air parcels starting at 2100Z on April 13 and 17. Trajectories are based on winds geostrophically-derived from global geopotential height maps.

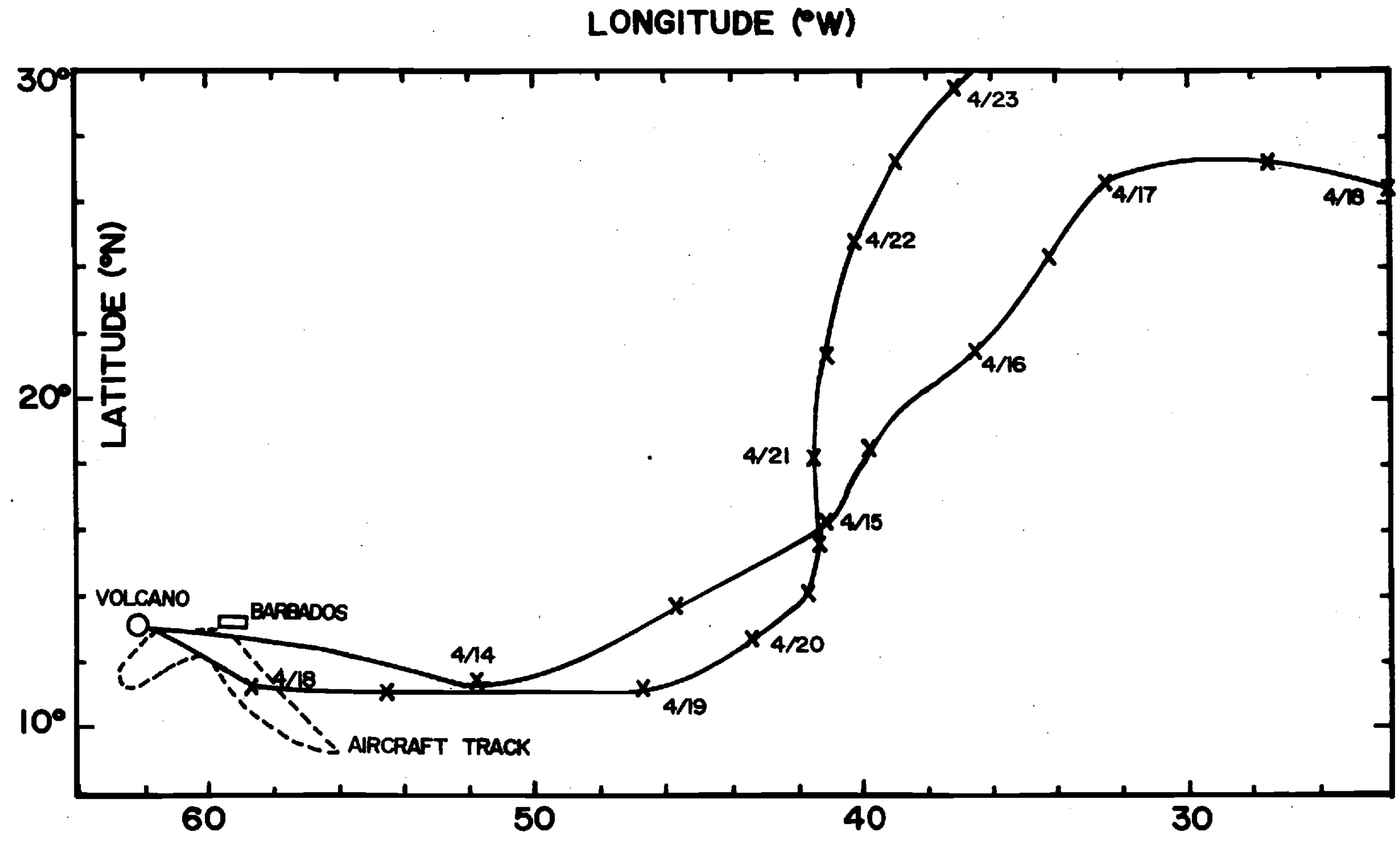

Figure 3. Airborne lidar observations of stratospheric aerosols at 0Z on April 19. Observed scattering ratios exceeding unity are indicated for four altitudes along the aircraft track.

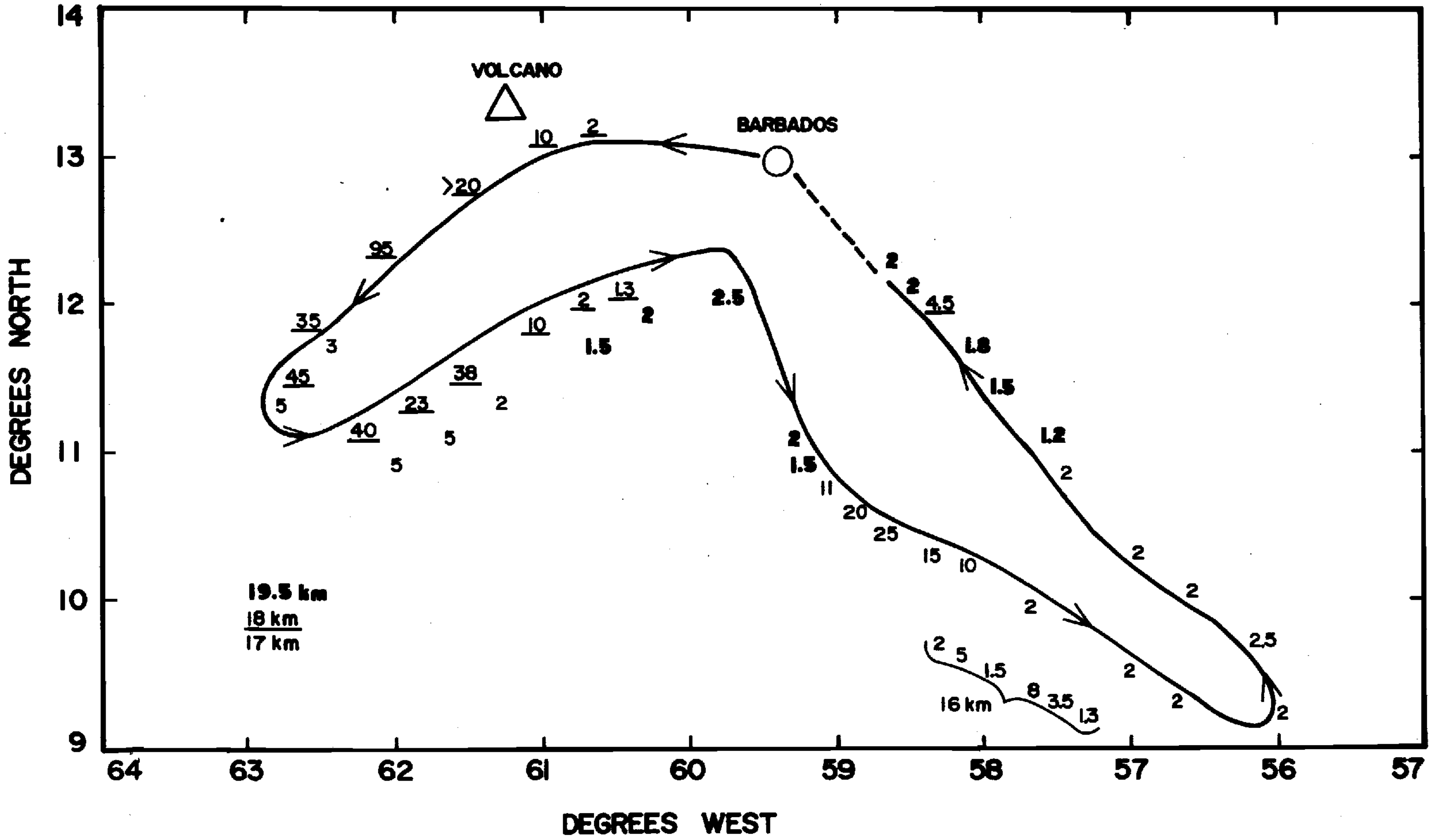

Figure 4. Rawinsonde observations at Trinidad (78970) for the period April 15-21, 1979.

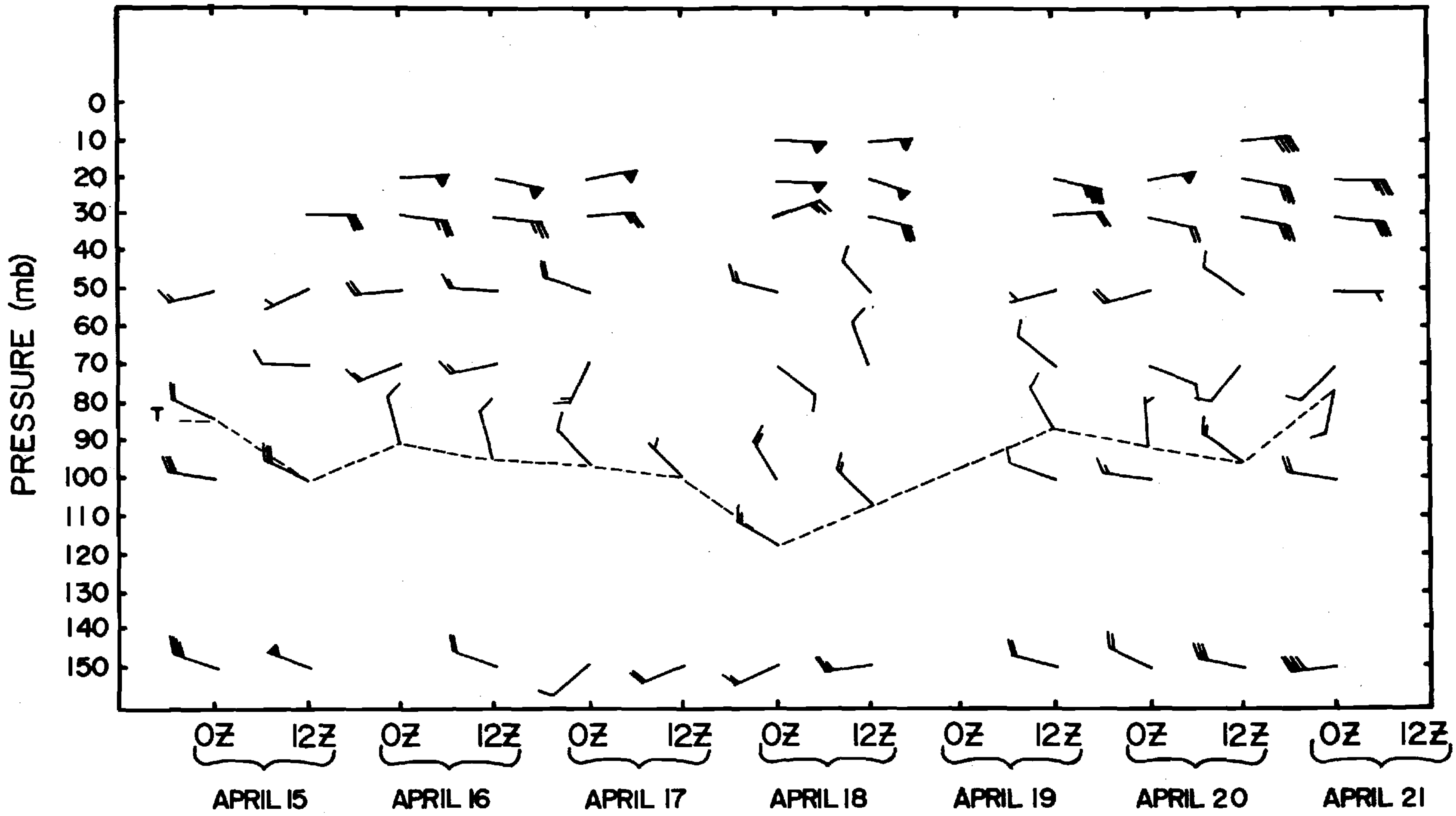

Figure 5. Geostrophically-calculated winds over Trinidad for the period April 15-21, 1979.

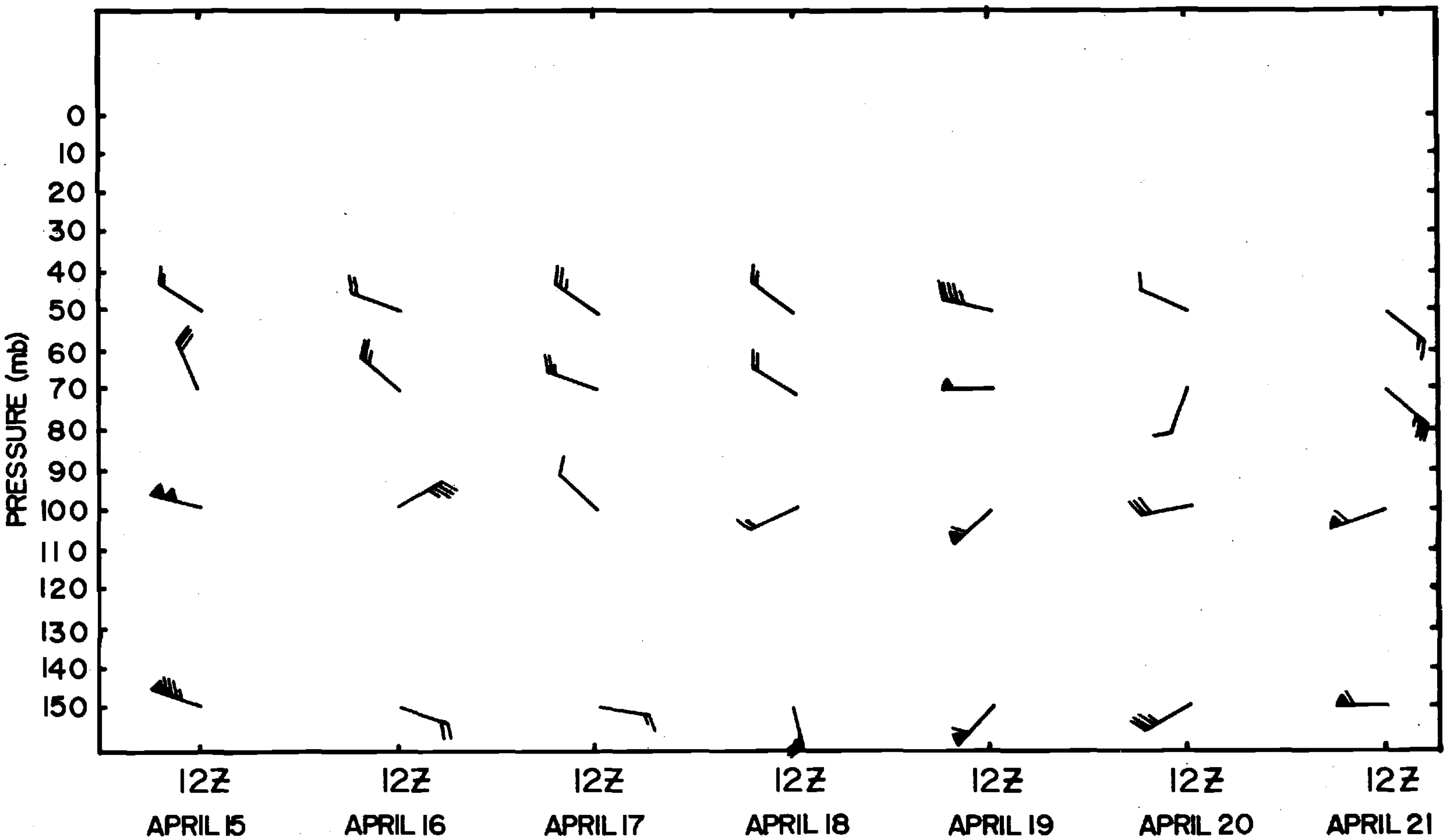

Figure 6. The 70 mb temperature field in the vicinity of La Soufriere on April 18 at 12Z..

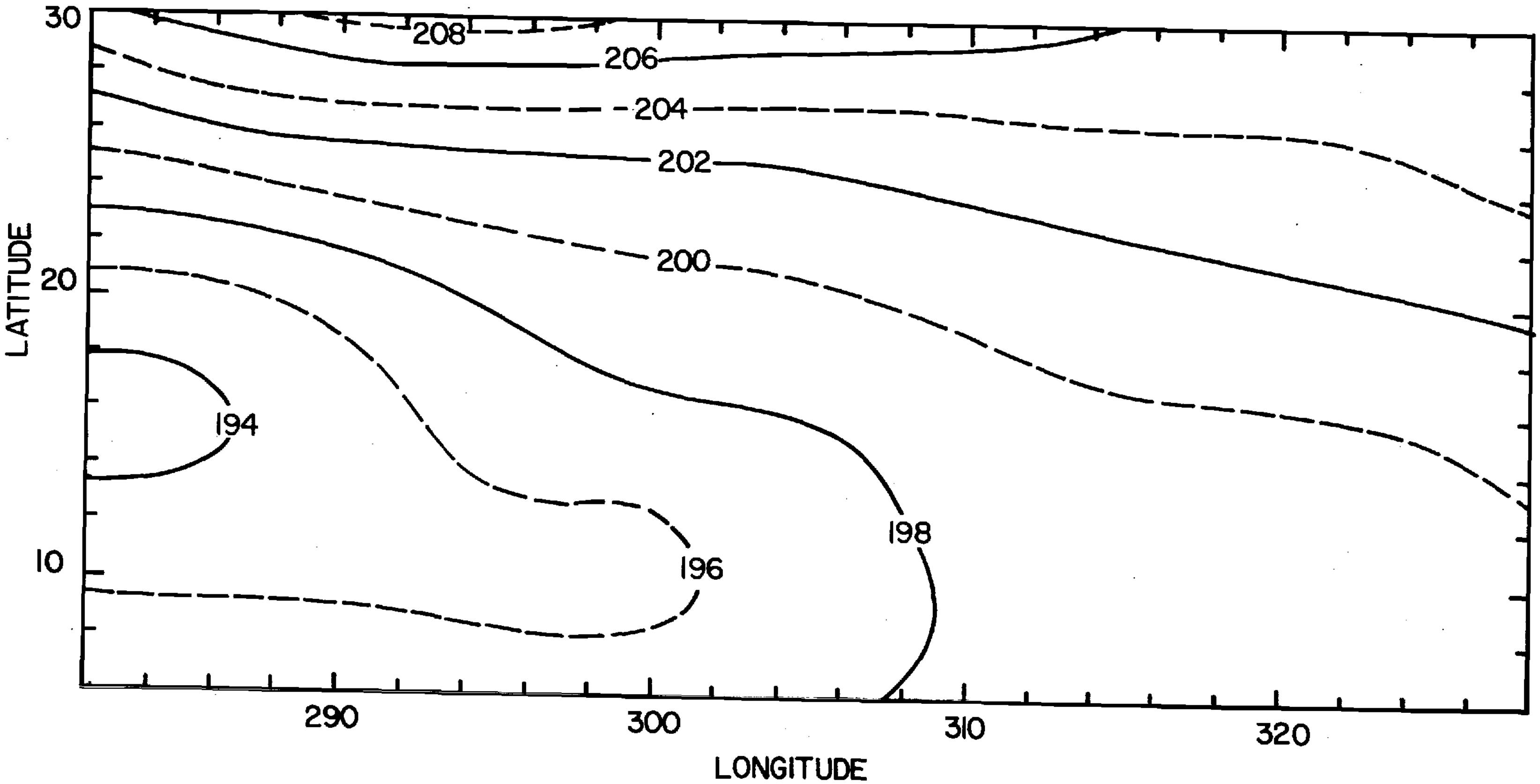

Figure 7. Geopotential maps in the vicinity of La Soufriere at 12Z on April 14 (a) and April 18 (b). Units are meters above 18 km.

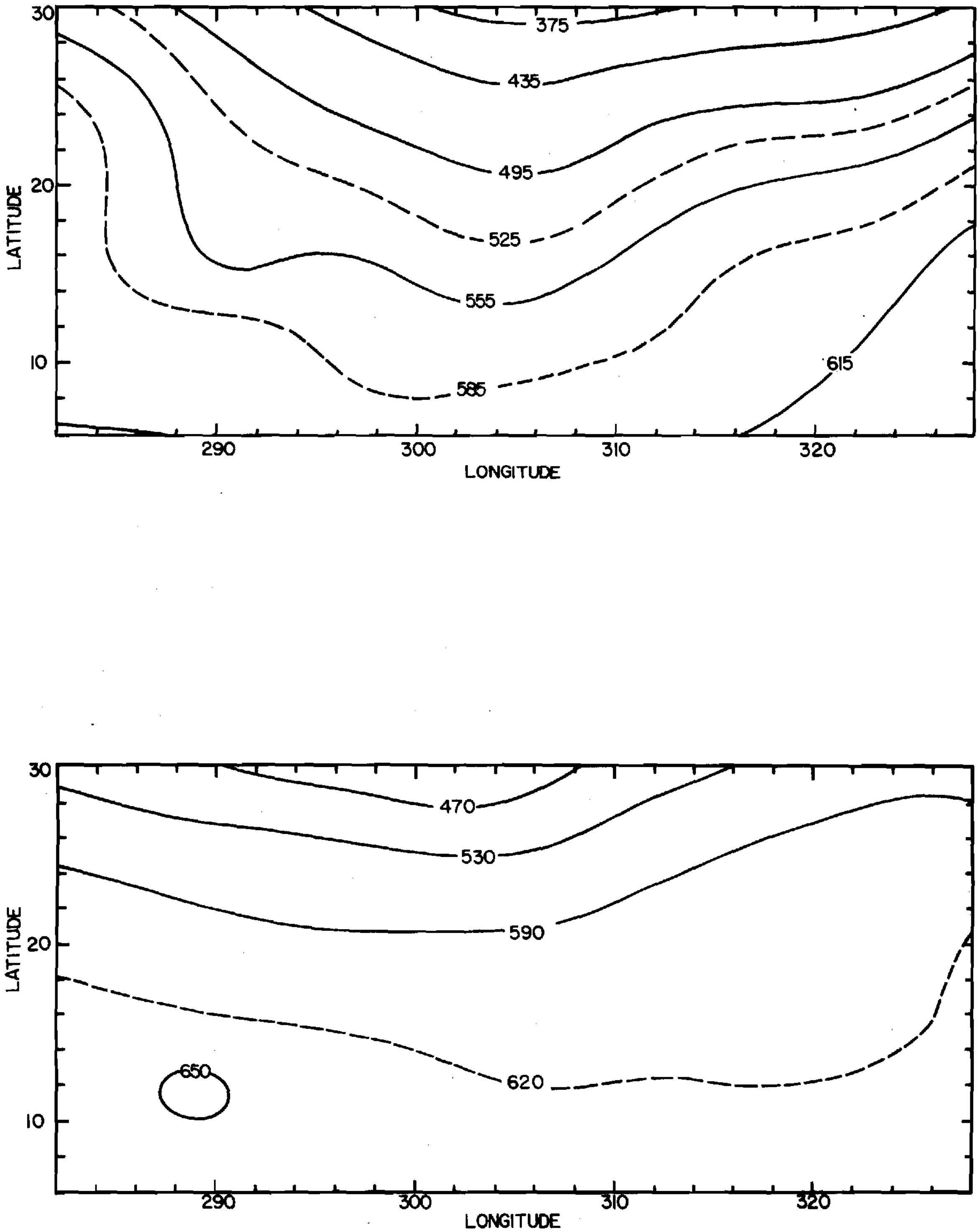

Figure 8. Dispersion of a cloud at 18.5 km and 20°N predicted by the model of Justus and Mani (1978). The x direction is East-West.

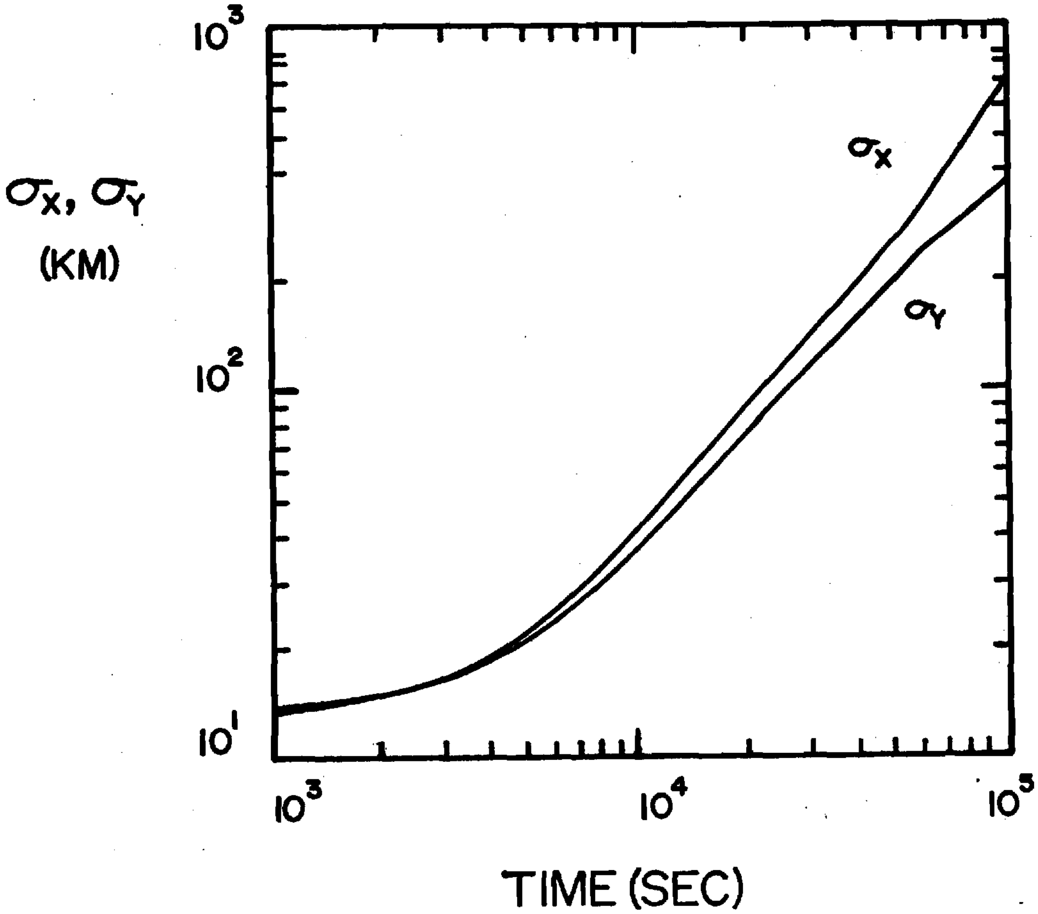

Figure 9. Observed cloud dispersions compiled by Bauer (1973).

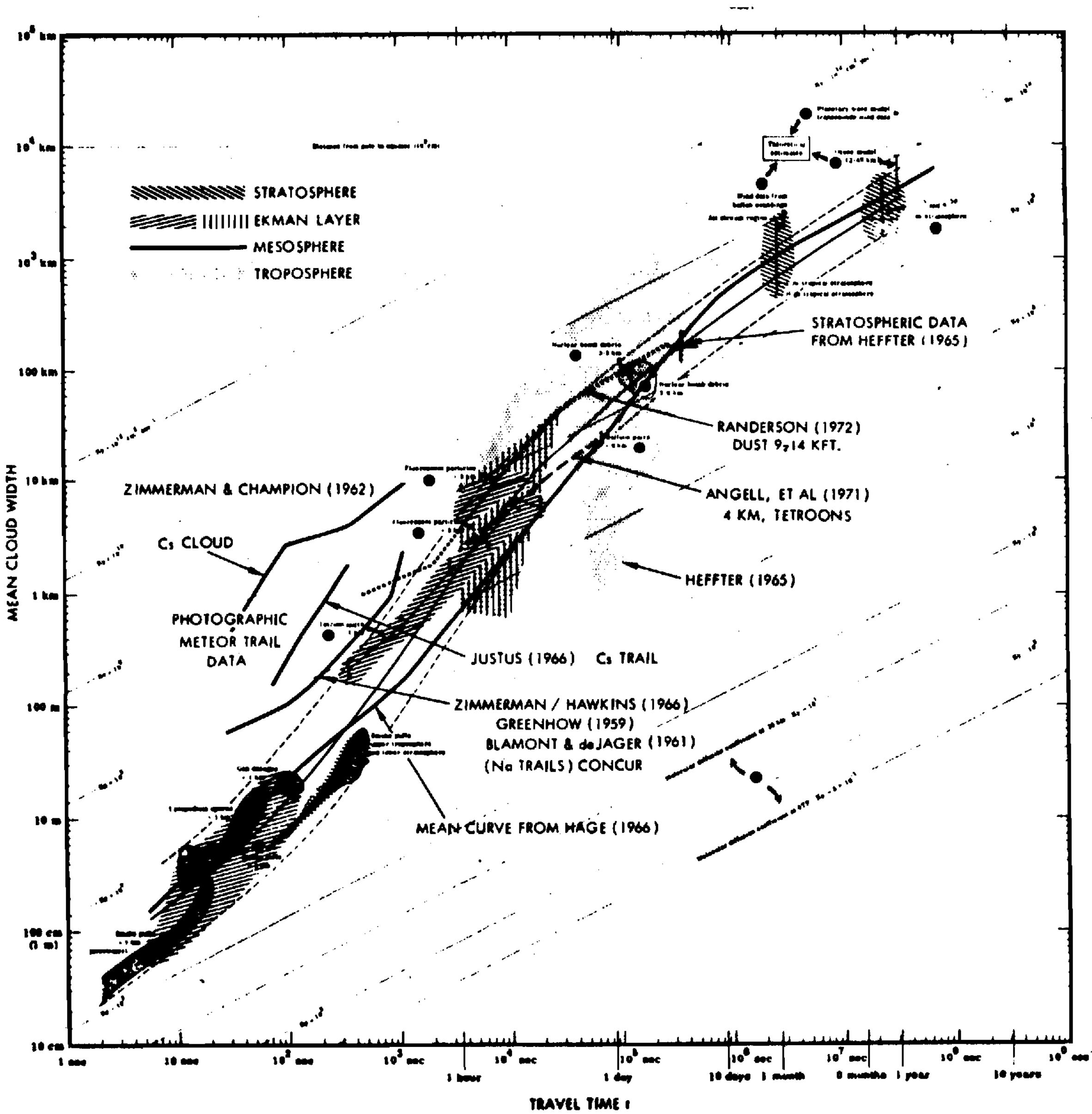

Figure 10. The locations of SAGE observations of anomalously high scattering ratios for the period April 23-28(circles). Dates of individual observations are shown on the ordinate. Estimated locations and cloud half-widths on April 23-24 for injection from La Soufriere on April 13 and 17 are indicated by dashed ellipses.