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MATERIAL FROM THE EL CHICHON VOLCANO ABOVE SPAIN ON 3 MAY 1982—ONE MONTH AFTER THE ERUPTION

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Abstract—Stratospheric dust layers photographically observed in the altitude range 16–28 km from a balloon gondola floating at 36.6 km altitude on 3 May 1982 over southern France are identified as originating from the 4 April eruption of the Mexican El Chichon volcano. The identification is compatible with the zonal air motions leading to lidar detections over Japan, United States and Italy. The observations confirm the eastward motion of part of the injected material below 20 km altitude and the westward motion above this altitude. They imply a northward component of the meridional motion of the order of 20° (from 17°N to 37°N) in one turn around the Earth. The observation of scattered sunlight in blue and red light allows to deduce some optical properties of the aerosol, mainly those implied by the wavelength dependence of the scattering efficiency being highly variable, particularly above the Junge layer.

INTRODUCTION

On 9 April 1982, lidar soundings performed at the Mauna Loa Observatory (20°N, 156°W) revealed the presence at 25.8 km of an enhancement of the stratospheric dust concentration (*EOS*, 1982). A very large scattering ratio was observed (350) for the dust layer exhibiting a half width smaller than 1 km. Its origin was considered to be the 4 April eruption of the El Chichon volcano in southern Mexico (17°N, 93°W). On 18 April very thin layers with a vertical thickness of less than 1 km were detected at 16, 25.5 and 26.5 km during the continuous observations of stratospheric aerosol particles made at Kiyushu University (33°N, 130°E) in Japan (Hirono and Shibata, 1983). The authors have pointed out that such thin features are seen only when newly injected volcanic layers are present over their station. The scattering ratios observed at 1.06 μm ranged from 5 to 10 from 18 to 21 April. Hirono and Shibata have attributed them to the El Chichon eruption.

On 3 May 1982, D'Altoria and Visconti (1983) observed non-negligible scattering ratios at 0.589 μm by thin scattering layers notably at 27.8, 28.5 and 30 km altitude from L'Aquila (42°N, 13°E). On the same day, photographs of the Earth limb taken from a balloon gondola floating at 36 km altitude over southern France (44°N, 0.5°E) revealed the presence toward the South of few hundred meters thickness layers in the 23–28 km altitude region. Some characteristics of these layers are discussed with their possible origin from El Chichon as well as a strong layer observed at 16 km altitude. The enhancement of sulfur bearing compounds in spring 1982 at mid-latitude over Europe (44°N) from this volcano has been postulated by Arijs *et al.* (1983) and by Arnold and Bührke (1983) to explain an increase of sulfur containing negative ions up to 33 km altitude but particularly at 25 km. On the other hand, the tracking at mid-latitude of volcanic material newly injected in the tropical stratosphere sheds light on meridional transport of air in this atmospheric region.

OBSERVATIONS

The balloon borne photographic observation method has been described previously (Ackerman *et al.*, 1981). The method and the experimental conditions particular to the flight considered here will be given briefly. A solar azimuth controlled gondola equipped with eight motorized Hasselblad 70 mm film cameras was launched from the CNES range in Aire sur l'Adour on 3 May 1982. The horizontal optical axis of four cameras were directed at 180° from the optical axis of the other four and the gondola was rotated about its vertical axis by steps of 36° over 180° from the solar azimuth so that photographs of the Earth limb were taken over 360° in azimuth. The 80 mm focal length lenses of the cameras loaded with Kodak Plus X and IR 2424 films were fitted with optical filters centered at 0.44, 0.65 and 0.84 μm. Due to the limited dynamic range of the IR film the high altitude aerosol layers which will mostly be discussed here were not observed at 0.84 μm.

The data reported here were obtained from two photographic shots of the cameras which scanned the southern part of the Earth limb from 36.6 km altitude, 44°N and 0.5°E. From the two shots taken at 17.58 and 18.09 G.M.T. the radiance observed at 31 and 149° from the solar azimuth was analysed in detail. Since the solar elevation angle was equal to 9.5°, the scattering angles, θ, at the 25 km tangent altitude were respectively 33 and 148°. The variation of θ over the covered altitude range is negligibly small. Figure 1 shows the geographic location of the line of sight tangent points at 27 km altitude for the centers of the fields of view of the photographs. They are located at a latitude close to the latitude of L'Aquila at which lidar data were obtained on the same day. Figure 2 shows prints of a narrow vertical strip of the atmospheric limb on which the thin layering is readily observed at various tangent altitudes. The observed radiance of the sunlit atmosphere integrated over the line of sight has been inverted by altitude steps of 100 m taking ozone and Rayleigh extinction into account leading to the radiance, R_θ, per unit length on the optical path vs altitude in units of solar radiance, $R_\odot$, at the wavelength λ,

$$(R_\theta/R_\odot)_\lambda = A(n_A\sigma_A + n_M\sigma_M)_{\theta,\lambda} \quad (1)$$

where A is a geometric factor equal to 6.79×10^{-5} and n_A and n_M are the "number" of aerosol and air particles respectively and σ_A and σ_M are the differential scattering cross sections of the aerosol and of air at the scattering angle θ.

Since the scattering angles have been chosen almost symmetrically from $\theta = 90°$,

$$(\sigma_M)_{33°} = (\sigma_M)_{148°} \quad (2)$$

may be written and the ratio of (1) at the two scattering angles leads to

$$R(33\text{–}148)_\lambda \equiv (R_{33}/R_{148})_\lambda = 1 + [(n_A\sigma_A)_\lambda/(n_M\sigma_M)_\lambda]_{33} \quad (3)$$

since practically no vertical structure is observed at the large scattering angle indicating that the observed vertical structure of the aerosol is essentially due to forward scattering predominant over back scattering which, as a first approximation, may be neglected.

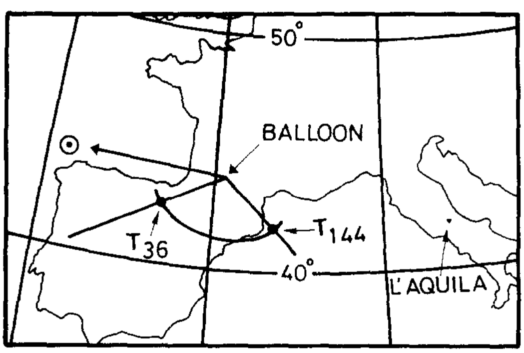

FIG. 1. GEOGRAPHIC POSITION OF THE BALLOON AT THE TIME OF OBSERVATION AND 36.6 km ALTITUDE.
The solar direction is shown as well as the location of the points (T_{36} and T_{144}) of closest approach to the Earth surface of the line of sight 36° and 144° from the Sun in azimuth and 3° below the horizontal. This corresponds to 27 km altitude. The position of L'Aquila is also shown.

DISCUSSION

The vertical distribution of $R(33\text{–}148)_\lambda$ is shown in Fig. 3 for $\lambda = 0.44$ μm and for $\lambda = 0.65$ μm. The thin layers visible on Fig. 3 at 22.9, 24.3, 25.2 and 28 km altitude appear clearly in both red and blue color. The lower part of the broad maximum, centered at 18.3 km and most probably corresponding to the usual Junge layer, is overwhelmed by a strong 1 km thick layer centered at 16 km altitude and exhibiting some vertical structure.

El Chichon origin of the thin layers

Following the argument of Hirono and Shibata (1983) according to which sharply defined thin layers occur when newly injected volcanic material is present in the stratosphere leads to search for a candidate volcano to have produced the ones observed here. El Chichon is the obvious one. It has, however, to be examined if the likeliness of this assumption is compatible with the zonal circulation of the initial cloud and with the possibility of meridional transport of minute samples of it from 17°N to 42°N in about 1 month. Hirono and Shibata (1983) have come to the conclusion that the layers observed for the first time, as weather permitted, on 18 April 1982, were brought over Kyushu from the East above 21 km altitude and from the West below this level in such a way that all layers observed arrived quasi simultaneously above the lidar station. On the other hand, new aerosols layers, all below 20 km altitude, were observed over NASA Langley Research Center (37°N, 73°W) on 29 April (Labitzke *et al.*, 1983). Figure 4 shows the amplitudes of the zonal motions which, if they persisted brought the El Chichon material at the longitude of the balloon observations on 3 May also simultaneously for the upper and lower altitudes. It should be noticed that westward for the first travel around the Earth and eastward when the second travel has started Kyushu is in both cases about half way from El Chichon to the Greenwich meridian.

If the northern component of the transport of thin air layers has brought them 16° towards the North over

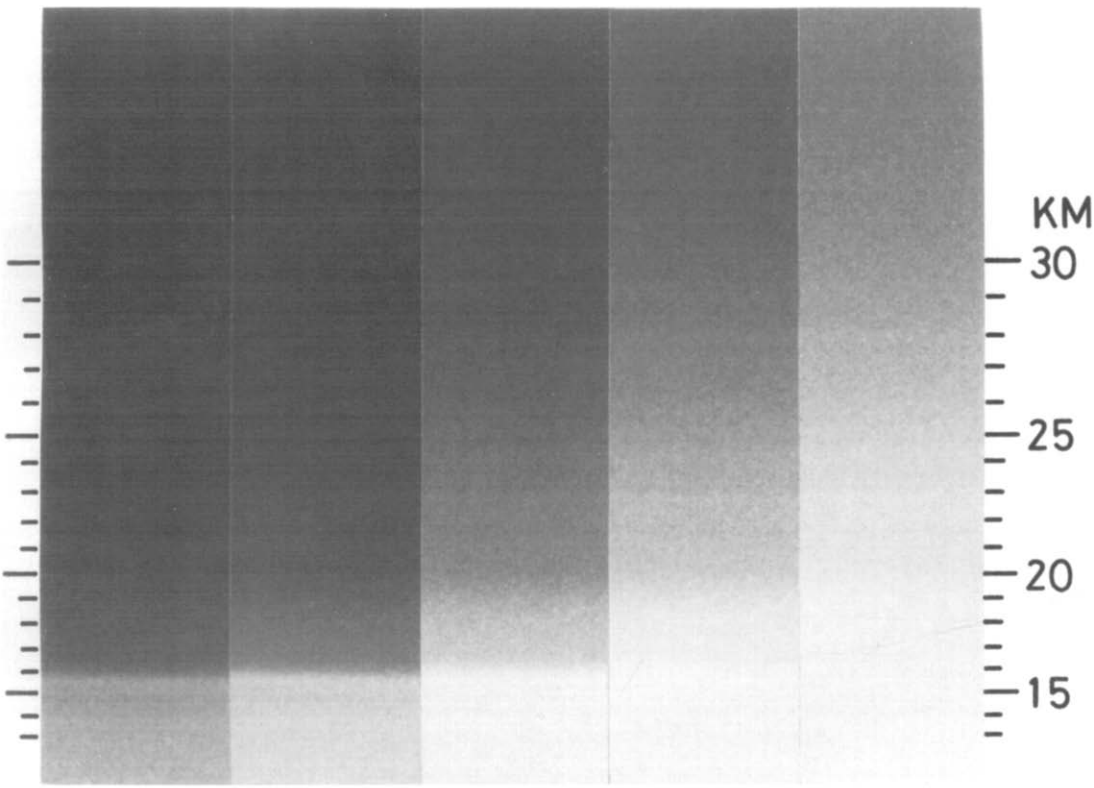

FIG. 2. PRINTS MADE AT DIFFERENT EXPOSURES OF THE SAME PORTION OF FILM (0.65 μm) AT A SOLAR AZIMUTH ANGLE OF 31°.

Several exposures are presented in order to cover on paper the film dynamic range used. The tangent altitudes are indicated in km. The vertical length of each strip corresponds to about 4 mm on the film.

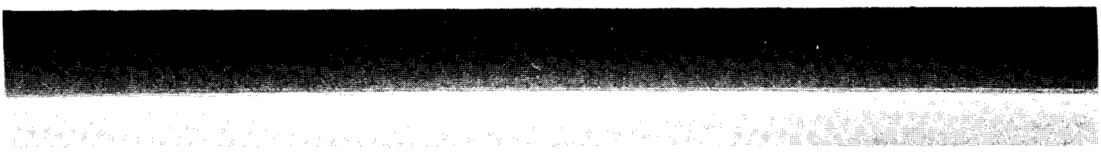

FIG. 5. OBSERVATION OF A THIN LAYER (ABOUT 150 m THICKNESS) BEING SLIGHTLY DETACHED FROM THE TOP OF THE MAIN BODY OF THE MOUNT ST HELENS VOLCANIC CLOUD AS IT WAS OBSERVED (ACKERMAN *et al.*, 1980) WHEN IT ARRIVED OVER EUROPE 17 DAYS AFTER THE 18 MAY 1980 ERUPTION.

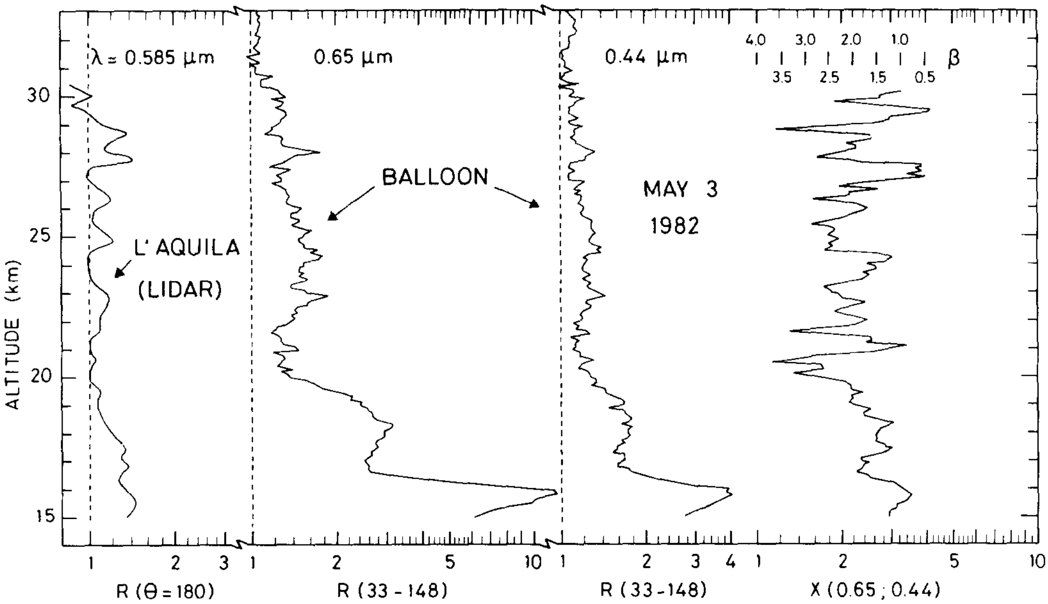

FIG. 3. LIDAR BACK SCATTERING RATIO, $R(\theta = 180°)$, OBSERVED AT L'AQUILA (D'ALTORIA AND VISCONTI, 1983) AND AEROSOL SCATTERING RATIO, $R(33–148)$, AS DESCRIBED IN THE TEXT, OBSERVED FROM THE BALLOON GONDOLA IN RED (0.65 μm) AND IN BLUE (0.44 μm) LIGHT VS ALTITUDE IN KILOMETERS.
The ratio, $X(0.65; 0.44)$ of forward scattering in both colors, is also shown with the corresponding β values as expressed in equations (4) and (7). For $X(0.65; 0.44)$, the running average over 3 points (300 m) has been plotted.

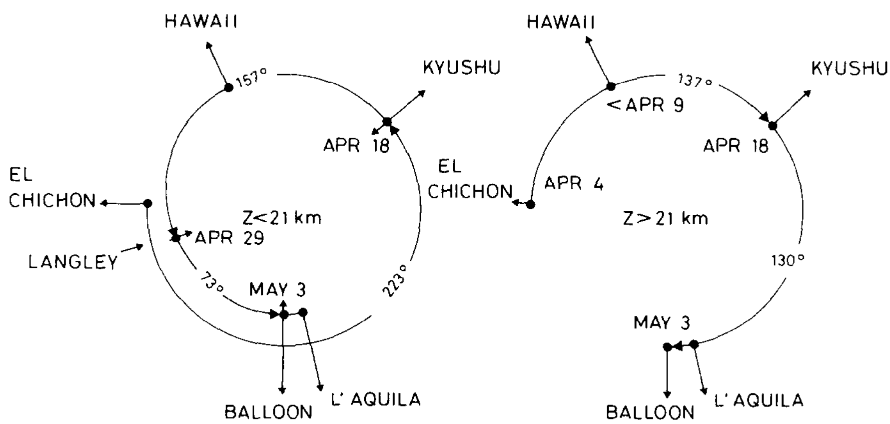

FIGURE 4. FROM THE VARIOUS OBSERVATIONS PERFORMED AT DIFFERENT LOCATIONS ON SUCCESSIVE DATES IT APPEARS THAT THE MERIDIANS CROSSINGS OCCURRED AT THE RATE OF ABOUT 16 DEGREES PER DAY AND 9 DEGREES PER DAY FOR THE EL CHICHON CLOUD BEING TRANSPORTED AROUND THE EARTH BELOW AND ABOVE 21 km ALTITUDE RESPECTIVELY; EASTWARD IN THE FIRST CASE AND WESTWARD IN THE SECOND ONE.
This corresponds, as already expressed by Hirono and Shibata (1983) to mean respective speeds equal to 18 and 10 m s^{-1}.

Japan it is then very reasonable to accept that mid-latitude was reached over Europe. The detachment of thin layers from the main body of the volcanic cloud injected in the stratosphere may occur. Figure 5 shows an example of this observed in the case of the Mount St Helens eruption when the volcanic dust was photographically observed over Europe (Ackerman *et al.*, 1980). The transport of thin air layers from the Central American region to Europe has been observed and studied in detail in the case of ozone (Piaget, 1971).

The 16 km layer was observed towards the South as well as towards the North indicating that it was already well spread over Europe on 3 May. It may even have had such a Northeastward orientation that it was not observed over L'Aquila as shown on Fig. 3. The upper layers particularly at 28 km were observed at this station and were not observed towards the North from the balloon gondola.

Aerosol properties

The forward scattering observed in two colors for identical volume elements can be used to deduce indications of the properties of the aerosol. The ratio X, the last term of equation (3) at 0.65 and 0.44 μm has been computed and its running mean over 300 m has also been plotted in Fig. 3;

$$X(0.65;0.44) = (n_A\sigma_A/n_M\sigma_M)_{0.65\,\mu m}/(n_A\sigma_A/n_M\sigma_M)_{0.44\,\mu m} \quad (4)$$

can be used to derive the wavelength dependence, β, of the scattering cross section by taking into account the wavelength dependence, α, of the air scattering cross section,

$$(\sigma_M)_{\lambda_1} = (\sigma_M)_{\lambda_2}\left(\frac{\lambda_1}{\lambda_2}\right)^{-\alpha} \quad (5)$$

where $\lambda_1 > \lambda_2$. By putting

$$(\sigma_A)_{\lambda_1} = (\sigma_A)_{\lambda_2}(\lambda_1/\lambda_2)^{-\beta}, \quad (6)$$

$$\beta = \alpha - [\log X(\lambda_1;\lambda_2)]/\log(\lambda_1/\lambda_2). \quad (7)$$

The values of β corresponding to X are given on Fig. 3 for α taken equal to 4.

By definition, X is essentially related to the forward scattering differential cross section of which the wavelength dependence is related to the variation of the total scattering cross section and, to a smaller degree, to the variation of the scattering phase function with the wavelength. The total scattering cross section is usually considered to vary almost linearly with wavelength. Its β value is considered to be 0.7 in the *Handbook of Geophysics* while Elterman (1966) suggests $\beta = 1$. The size distribution of the aerosol particles and their complex index of refraction, particularly its imaginary part, can alter β. The value of β reaching 0.7 at the maximum of the 16 km layer is most probably the indication of large particles being present at that altitude. In the Junge layer a minimum value of $\beta = 1.2$ is reached at the scattering maximum located at 18.3 km. β increases below and above that altitude to reach a value of 3 ± 0.5 slightly above 20 km. This behavior is in agreement with previous findings (Ackerman *et al.*, 1981; Turco *et al.*, 1982) according to which the number of small particles is relatively larger in the Junge layer vertically away from the peak, lower and higher.

Above 21 km altitude, β oscillates around 2 with peaks as high as 3.5 and as low as 0.5 indicating large variations of the optical properties of the aerosol particles. There is a striking correlation between the lidar back scattering maxima at 30.0, 28.8, 27.8, 26.3, 25.0, 23.8 and 21.6 km and the maxima of β observed at the same levels. It suggests that, at least on this particular occasion, the lidar back scattering vertical profile represented more the size distribution or the refractive index or the combination of both than the particles abundance.

As far as the correlation between the sulfur enhancement observed by means of ion mass spectrometry and the El Chichon eruption is concerned, it is observed here that aerosols were present up to at least 33 km altitude but there is no indication of sharply defined thin layers above 28 km which would then correspond to newly injected material. Since the ion measurements took place later, the assumption of a volcanic effect can, however, not be ruled out up to the upper levels on the basis of the data presented here. The enhancement indicated by Arnold and Bührke at 25 km is very likely to correspond to a volcanic effect since the main body of the El Chichon cloud appears at 25 km altitude on 24 May over Japan, in July over Italy and United States (Labitzke *et al.*, 1983) and since some of it had already leaked at 42° North as we observe it near 25 km altitude, particularly at 24.6 and 25.2 km, on 3 May.

CONCLUSION

Our observations, combined with those performed in United States, Japan and Italy shortly after the El Chichon 1982 eruption show that some amount of material had leaked from the main volcanic cloud to reach all levels up to 28 km in the stratosphere over Europe on the first days of May 1982. The observations which also fit the lidar observations made at Langley (37°N, 76.3°W) by Labitzke *et al.* (1983) confirm the splitting of the zonal circulation at 21 km altitude as mentioned by Hirono and Shibata (1983). They also indicate a fast meridional isentropic transport of thin air layers, a mechanism which, as such, has not been taken into account in atmospheric models.

The observations reported indicate also that radiation models should include variable optical properties of aerosols with altitude.

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