References and Notes

1. A. Cox, R. Doell, B. Dalrymple, *Science* **144**, 1537 (1964); I. McDougall and D. G. Tarling, *Nature* **202**, 171 (1964).
2. W. M. Elsasser, *Phys. Rev.* **69**, 106 (1946); E. N. Parker, *Astrophys. J.* **122**, 293 (1955); W. V. R. Malkus, *Science* **169**, 259 (1968).
3. E. C. Bullard and H. Gellman, *Phil. Trans. Roy. Soc. London Ser. A* **247**, 213 (1954); F. E. M. Lilley, *Proc. Roy. Soc. Ser. A* **316**, 153 (1970).
4. J. R. Heirtzler, G. O. Dickson, E. M. Herron, W. C. Pitman III, X. Le Pichon, *J. Geophys. Res.* **73**, 2119 (1968).
5. N. D. Opdyke, B. Glass, J. D. Hays, J. Foster, *Science* **154**, 349 (1966).
6. J. D. Hays and N. D. Opdyke, *ibid.* **158**, 1001 (1967); R. J. Uffen, *Nature* **198**, 143 (1963).
7. A. Cox and B. Dalrymple, *J. Geophys. Res.* **72**, 2603 (1967).
8. K. Momose, *J. Geomagn. Geoelec.* **10**, 12 (1958); T. Sigurgeirsson, *Advan. Phys.* **6**, 240 (1957); M. A. Goldstein, D. W. Strangway, E. E. Larson, *Earth Planet. Sci. Lett.* **7**, 231 (1969).
9. N. D. Watkins, *Geophys. J. Roy. Astron. Soc.* **17**, 121 (1969); E. E. Larson, personal communication.
10. J. S. V. Van Zijl, K. W. T. Graham, A. L. Hales, *Geophys. J. Roy. Astron. Soc.* **7**, 23 (1962); *ibid.*, p. 169.
11. C. G. A. Harrison and L. K. Somayajulu, *Nature* **212**, 1193 (1966); D. Heye, *Earth Planet. Sci. Lett.* **9**, 82 (1970).
12. I. G. Kaporovich, Z. V. Makarova, G. N. Petrova, R. S. Rybak, *Izv. Acad. Sci. USSR Phys. Solid Earth Ser.* **1**, 92 (1966).
13. G. Pulliaih and R. K. Verma, *Phys. Earth Planet. Interiors* **2**, 158 (1970); V. Bucha, *J. Geomagn. Geoelec.* **22**, 253 (1970); A. Ya. Vlasov and G. V. Kovalenko, *Bull. Acad. Sci. USSR Geophys. Ser.*, No. 4, 522 (1963); G. Z. Gurariy, *Izv. Acad. Sci. USSR Phys. Solid Earth Ser.* **6**, 105 (1969).
14. H. Ito and M. Fuller, in *Palaeogeophysics*, S. K. Runcorn, Ed. (Academic Press, New York, 1970), p. 133.
15. M. Bikerman, personal communication.
16. R. S. Fiske, C. A. Hopson, A. C. Waters, "Geology of Mount Rainier National Park, Washington," *U.S. Geol. Surv. Prof. Pap. 444* (1963).
17. T. L. Wright, thesis, Johns Hopkins University (1960).
18. L. A. Bauer, *Amer. J. Sci.* **50**, 109 (1895); N. Kawai, K. Hirooka, S. Sasajima, *Proc. Jap. Acad.* **41**, 398 (1965).
19. A. Cox and R. R. Doell, *Bull. Seismol. Soc. Amer.* **54**, 2243 (1964).
20. The samples have been exposed to standard techniques such as alternating-field and thermal demagnetization, alternating-field demagnetization of partial thermoremanence, optical, and scanning electron microscopy. In order to determine the relative importance of single and multidomain contributions to the remanence, alternating-field stability characteristics were determined [M. Fuller and W. Lowrie, *Eos* **51**, 276 (1970); W. Lowrie and M. Fuller, *J. Geophys. Res.*, in press]. In addition combined optical microscopy and magnetic measurements of "thin" sections demonstrated that the stable fraction of remanence was unaffected by the removal of the large multidomain grains, which do, however, apparently carry significant soft NRM.
21. E. Thellier and O. Thellier, *Ann. Geophys.* **15**, 285 (1959).
22. L. R. Ingersoll and O. J. Zobel, *Mathematical Theory of Heat Conduction* (Ginn, Boston, 1913); H. S. Carslaw and J. C. Jaeger, *Conduction of Heat in Solids* (Oxford Univ. Press, London, 1959).
23. T. S. Lovering, *Geol. Soc. Amer. Bull.* **48**, 69 (1935).
24. T. Rikitake, *Electromagnetism and the Earth's Interior* (Elsevier, Amsterdam, 1966); D. W. Allan, *Proc. Cambridge Phil. Soc.* **58**, 671 (1962); F. J. Lowes and I. Wilkinson, *Nature* **219**, 717 (1968); A. Herzenberg, *Phil. Trans. Roy. Soc. London Ser. A* **250**, 543 (1958).
25. E. N. Parker, *Astrophys. J.* **158**, 815 (1969).
26. T. Nagata, *J. Geomagn. Geoelec.* **21**, 701 (1968).
27. S. I. Braginskii, *J. Exp. Theoret. Phys.* **47**, 1084 (1964); *Geomagn. Aeron. USSR* **7**, 401 (1967).
28. A. Cox, *Science* **163**, 237 (1969).

29. Supported by NSF grants GA-835 and GA-13135. We thank members of the rock magnetism group at the University of Pittsburgh for their help. We thank R. Day, W. Drew, and Yee-Ming Wu for assistance with the fieldwork; J. DeJournett for much of the measurement of NRM and data reduction and for his care in performing this work; and N. Bishop, park naturalist at Mount Rainier, for help during our fieldwork. In addition, we thank H. Dole and his colleagues at the Oregon Geological Survey for their help, and, in particular, we thank A. Corcoran for his help in the initial fieldwork. Finally, we acknowledge the benefits of many convivial discussions with T. Nagata, who has consistently encouraged us to pursue this research.

18 January 1971; revised 11 March 1971

Solar Radiation: Absence of Air Pollution Trends at Mauna Loa

Abstract. *Measurements of solar radiation made at Mauna Loa, Hawaii, over a period of 13 years give no evidence that human activities affect atmospheric turbidity on a global scale. Short-term fluctuations in insolation appear to be associated with naturally produced tropospheric aerosols. The intrusion of volcanic dust into the stratosphere results in prolonged increases in atmospheric opacity due to the extended residence times of aerosols in the stratosphere.*

Concern over the earth's energy balance has been expressed in discussions about the diminution of solar radiation and the associated variations in world climate, consequent on the continuing and increased emission into the atmosphere of particulate matter by industrial processes. Observations of an increase in atmospheric turbidity, which is a measure of the extinction of solar radiation in excess of that to be expected from a clean atmosphere, in Washington, D.C., and Davos, Switzerland, led McCormick and Ludwig (*1*) to hypothesize the long-term effects of pollutant aerosols. Flowers *et al.* (*2*) have examined the data from a network of stations designed to measure turbidity and have established a pattern for the continental United States which clearly shows a correlation between high turbidity concentrations and geographic locations with heavy industrialization.

The occurrence of air pollution, however, to which these turbidity increases can be attributed, is a property of the lower troposphere and thus subject to temporal and spatial variations within short intervals. In each of the documented episodes of acute pollution in the past (for example, the Meuse Valley, 1930; Donora, Pennsylvania, 1948; London, 1952 and 1962; and the U.S. East Coast, 1970) a prolonged period (several weeks) of unusual weather conditions accompanied the air pollution incidence, which resulted in a failure of the usual natural processes to dilute and dissipate air pollutants.

In order to detect secular trends in turbidity on a global scale, it is necessary to subdue by experimental design the short-term existence of airborne particulate matter in the lowest portions of the atmosphere in the proximity of pollution sources. Fischer (*3*) carried out measurements of atmospheric turbidity in Antarctica in 1966–1967. A comparison of these data with earlier data on Antarctica led him to conclude that no pronounced change in Antarctic turbidity had occurred in the 16-year period prior to 1966. Mauna Loa Geophysical Observatory (19°32′N, 155°35′W) at an altitude of 3400 m qualifies as a bench-mark station for probing the trace constituents of the atmosphere in virtue of its great distance from continents, the absence of potential pollution sources on the island of Hawaii, and the protection of the measurement site from local emissions, including water vapor, afforded frequently by a persistent trade wind inversion. The monitoring of solar radiation at Mauna Loa is part of a bench-mark program initiated at the beginning of the International Geophysical Year (*4*). Eight pyrheliometers have been used in a continuing program to monitor the normal component of the solar beam. Peterson and Bryson (*5*) concluded, from the evaluation of radiation data taken at Mauna Loa Observatory, that a steady increase in turbidity has taken place between 1958 and 1963.

We have carefully evaluated the data presented in this report (collected over a 13-year period) in order to eliminate as much as possible all contributions to turbidity from random variations of the optical density of the atmosphere, including those caused by locally produced tropospheric aerosols such as sea spray and volcanic effluents. Control days, distinguished from the

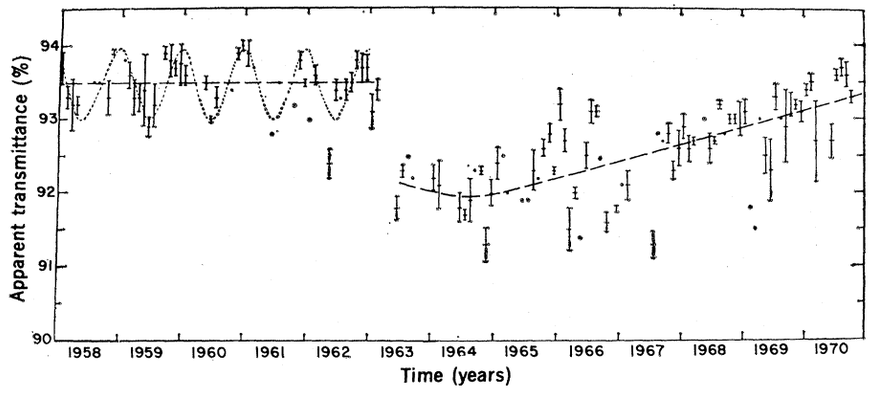

Fig. 1. Temporal variations of the monthly means of transmission factors of solar radiation, which transverses through air masses that differ by units of the secant of the zenith angle.

other days by atmospheric uniformity in addition to clearness, were determined by inspection of the strip-chart traces of the pyrheliometer output and the weather records. Only 410 out of 4473 days, or approximately 9 percent of the total, qualified as control days, an indication that local tropospheric disturbances remain quite frequent at Mauna Loa despite its favorable topographic and climatological features. Evaluation of data for these control days revealed that, for zenith angles (in units of the secant of the zenith angle z) between 2 and 5, the atmosphere exhibited the minimum amount of fluctuation in the optical density. In this discussion, in order to eliminate local influences as much as possible, we therefore present only data taken on control days for sun elevations corresponding to these zenith angles. Transmission factors, q, as identified by Bouguer's law,

$$I_n = I_0 q^n$$

(where I_0 is the solar constant), were computed from measurements of the wavelength-integrated intensity I_n by adaptation of the formula:

$$q = \frac{I_n}{I_{n-1}}$$

where the exponent of q is unity (n is the secant of the zenith angle corrected for refraction). For the broad spectrum, the transmission factor is influenced by the zenith angle; however, by averaging q for a representative interval ($2 \leq n \leq 5$) in the forenoon of each day, a relative representation of the optical transmittance of the atmosphere was obtained. This method of evaluating data recorded at the Mauna Loa Observatory on control days eliminates errors due to uncertainties in the calibration of the sensors, compensates for seasonal changes in the sun-earth distance, and excludes short-term fluctuations in turbidity due to aerosol clouds in the lower atmosphere.

Figure 1 shows the monthly mean values of the apparent optical transmittance q of the atmosphere (in percent) as a function of time for the 13-year period. The root-mean-square deviations from the means are indicated by vertical bars for all cases for which a sufficient number of data are available. Within a margin of about ± 1 percent fluctuation in data there is not discernible any systematic trend in solar insolation for the period 1958–1963, contrary to the conclusion drawn by others (*5*). The decrease in insolation in the summer of 1963 coincides with the eruption of Mount Agung, Bali. We conclude from the data that only after 7 years does the transmission recover to the pre-1963 level. This long residence time of the volcanic aerosols in the stratosphere, if compared to the average stratospheric residence time of tracers such as ^{90}Sr and ozone (of the order of 1 year), indicates that the volcanic dust has probably been emitted up to heights exceeding 60 km (*6*). The long recovery period could also be caused by a delayed and continuing production of aerosols (for example, the formation of sulfuric acid by the oxidation of sulfur dioxide in volcanic gases) or by the input of additional particles by subsequent volcanic eruptions (for example, Mount Taal, Philippines, 1965; Saputan, Indonesia, 1966; Kutinoerabu, Japan, 1968), or both; these two mechanisms counteract the natural removal of the original volcanic particulate matter (*7*). A final answer on which of these processes plays the predominate role in determining the lifetime of stratospheric aerosols cannot be given on the basis of radiation measurements alone, but will require direct investigations of the physical and chemical properties of these particles and their variations in time.

On the basis of the data collected prior to 1963, it follows that solar radiation received by the earth apparently undergoes annual cycles such that atmospheric transmission is lower during the summer months, most likely the result of increased worldwide photochemical aerosol formation caused by the oxidation of volatile organic materials of plant origin in the atmosphere (*8*), or the result of the seasonal variations in general atmospheric circulation, or both. From the time scales of recovery it can be concluded that such an aerosol is confined, for the most part, to the troposphere, in contrast to the volcanic aerosol which must have penetrated the stratosphere to a large extent.

If an annual cycle in solar radiation is caused by variations in the production rate of aerosols, rather than by seasonally altered atmospheric residence times, such an annual cycle supports the interesting proposition that at geographic locations sufficiently remote from pollution sources the natural aerosol component predominates over the particulate air pollutants that affect solar radiation. Furthermore, a decrease in the amplitude of the annual variations would be indicative of an increased influence of anthropogenic contaminants on the earth's radiation budget.

The data presented here for Mauna Loa, in conjunction with findings reported by Fischer (*3*) for the Antartic, support the hypothesis that on a global scale natural sources contribute more than man to the turbidity of the atmosphere.

HOWARD T. ELLIS
RUDOLF F. PUESCHEL
National Oceanic and Atmospheric Administration, Mauna Loa Observatory, Hilo, Hawaii 96720

References

1. R. A. McCormick and J. H. Ludwig, *Science* **156**, 1358 (1967).
2. E. C. Flowers, R. A. McCormick, K. R. Kurfis, *J. Appl. Meteorol.* **8**, 955 (1969).
3. W. H. Fischer, *ibid.* **6**, 958 (1967).
4. S. Price and J. C. Pales, *Mon. Weather Rev.* **91**, 665 (1963).
5. J. T. Peterson and R. A. Bryson, *Science* **162**, 120 (1968).
6. O. I. Leipunskii, J. E. Konstantinov, G. A. Federov, O. G. Scotnikova, *J. Geophys. Res.* **75**, 3569 (1970).
7. F. E. Volz, *ibid.*, p. 5185.
8. R. A. Rasmussen and F. W. Went, *Proc. Nat. Acad. Sci. U.S.* **53**, 215 (1965).

5 January 1971; revised 1 March 1971