Source of Seasonal Variations in Solar Radiation at Mauna Loa

B. A. BODHAINE[1] AND R. F. PUESCHEL

Atmospheric Physics and Chemistry Lab., NOAA, Boulder, Colo. 80302

9 April 1973 and 29 October 1973

ABSTRACT

Solar radiation transmission data taken at Mauna Loa exhibit a seasonal variation with the minimum in summer. On the basis of Barrett's model for the depletion of solar radiation by aerosols, it is suggested that these variations are due to the seasonal generation of organic aerosols by the biosphere. It is suggested that the naturally produced atmospheric background aerosol of organic origin causes the typical seasonal turbidity variations. Furthermore, changes in the amplitude or phase of transmission data could be used to indicate whether aerosols from anthropogenic sources would influence the earth's albedo.

Precipitable water calculations suggest that humidity data above Mauna Loa are not accurate enough to make a quantitative estimate of the effect of atmospheric water vapor on Mauna Loa radiation data. However, water vapor apparently cannot account for these variations on the basis of phase angle considerations.

1. Introduction

The effect of the atmospheric aerosol load on the earth's climate has been of great concern during the past decade. McCormick and Ludwig (1967), Bryson (1968) and Mitchell (1970) suggested that an increase of particulate loading would lead to a decrease in incoming solar radiation that would, in turn, lead to a general cooling of the earth's temperature as observed during the past 30 years. Subsequently, other investigators (Charlson and Pilat, 1969; Mitchell, 1971) have suggested that the inclusion of the absorption effects of tropospheric aerosols could very well lead to a warming at the earth's surface. It is generally agreed that stratospheric aerosols would lead to surface cooling, whereas uncertainty prevails about the consequences of an increase in tropospheric particulate loading.

The effects of atmospheric water vapor on incoming solar radiation are understood, and the dominant intense absorption spectrum in the near infrared is well known. The classical work of Fowle (1915) gave basic data for determining absorption of solar radiation by atmospheric water vapor. Other workers (e.g., MacDonald, 1960; Möller, 1963; Gates, 1960; Eldridge, 1967) have treated the subject further, but all refer to the basic data of Fowle.

Solar radiation has been monitored at Mauna Loa Observatory, Hawaii (3.4 km MSL, 20N, 155W) since 1957. Since then there has been no significant change at Mauna Loa attributable to anthropogenic sources (Ellis and Pueschel, 1971). In addition, the data from Mauna Loa exhibit three important effects: 1) an abrupt increase in turbidity in 1963, attributable to volcanic aerosols ejected into the stratosphere by the eruption of Mount Agung, Bali; 2) a seasonal variation in the amount of normal incident solar radiation; and 3) a phase angle that gives a summer maximum in attenuation (Pueschel *et al.*, 1972).

Seasonal variations in atmospheric transmission have been observed elsewhere as early as 1908 (Roosen, 1972), but until now there has been no serious attempt to explain these variations. In all cases, including the Southern Hemisphere, atmospheric transmission shows a summer minimum (Flowers *et al.*, 1969). Although other investigators agree that seasonal variations exist, controversy persists about whether these changes are caused by tropospheric or stratospheric constituents (Dyer and Hicks, 1968; Elsaesser *et al.*, 1972), and which constituents play the major role. An answer to this question is important because of possible climatic implications of an increased atmospheric aerosol load. Furthermore, if the seasonal turbidity variations are typical for the atmospheric background aerosol, the parameters (amplitude and phase) of this periodic function could be used as criteria that are sensitive to changes of aerosols from anthropogenic sources.

Implications are that the seasonal turbidity variations at Mauna Loa most likely originate in the upper troposphere, since it is well known that the residence times of stratospheric, upper tropospheric and lower tropospheric constituents are of the order of years, months and days, respectively. The long residence time of stratospheric aerosols is well illustrated by the slow recovery of the Mauna Loa radiation data after the Agung eruption in 1963.

[1] Present affiliation: Mauna Loa Observatory, Hilo, Hawaii 96720.

This paper presents a quantitative explanation of the Mauna Loa data in terms of atmospheric water vapor and aerosol particles.

2. Precipitable water above Mauna Loa

To estimate the water vapor content of the atmosphere over Mauna Loa, 13 years of Hilo, Hawaii, radiosonde data were analyzed and precipitable water was calculated according to the method of Solot (1939). Harrison (1970) gives an exhaustive discussion of the theory of precipitable water calculations, but we feel that radiosonde humidity values above Mauna Loa do not merit such an exact treatment. The years 1958 through 1970 were used because these are the years of radiation data presented by Ellis and Pueschel (1971). All precipitable water calculations began at the 700-mb level, since this is the approximate level of Mauna Loa Observatory and because this is a standard level given in the *National Climatological Summary* (Environmental Data Service). Two sets of data were used: 1) monthly data from the *Climatological Summary* were used to determine the general seasonal moisture climatology over Mauna Loa; and 2) individual daily ascent data were used for all control days as defined by Ellis and Pueschel (1971) for 1958 to 1970 in order to determine moisture trends directly related to control day solar radiation measurements.

It is not possible to deduce precipitable water from surface humidity data, as shown by Reber and Swope (1972) for three locations in California. It appears even less likely at Mauna Loa, being an isolated peak above a marine environment.

To facilitate computations with a desk-top programmable calculator, values of saturation vapor pressure from 10 to −50C taken from List (1966) were approximated by a second-degree logarithmic least-squares fit:

$$\ln e_s = 1.81638 + 0.071676T - 0.00038948T^2, \quad (1)$$

where e_s is the saturation vapor pressure (mb), and T the temperature (°C). The standard deviation was $\sigma = 0.000959$ and the fit provided better than 1% accuracy all along the curve.

The mixing ratio at any given level was then calculated from

$$w = \frac{6.22 e_s R}{P - 0.378 e_s}, \quad (2)$$

where w is the mixing ratio (gm kg^{-1}), R the relative humidity (percent), and P the pressure (mb).

Finally, values of precipitable water were calculated upward from 700 mb by the standard formula:

$$W = \frac{1}{980} \sum w \Delta P, \quad (3)$$

where W is the precipitable water (cm) and ΔP the layer thickness (mb) between significant levels.

Data were read from a microfilm reader and entered directly into the calculator, level by level, with a running total of precipitable water being kept automatically by the machine.

Several points must be kept in mind when calculating precipitable water from radiosonde humidity data. For a lithium chloride sensor, the data are reliable until the signal at the receiver begins to "motorboat," indicating that the sensor has reached its lower limit, usually at relative humidities near 15%. In these instances, a statistical value of relative humidity is assigned; however, when a carbon element is used, statistical values are not assigned. To be assured that only reliable humidity data were used, we considered only non-motorboating data. The changeover from lithium chloride sensors to carbon sensors took place in the early 1960's but, unfortunately, was made gradually so that no single date can be given for all stations (Whiting, 1971). Finally, diurnal variations in humidity data due to solar heating of the carbon elements were discussed by Morrissey and Brousaides (1970), Salemela and Sissenwine (1970) and Whiting (1971). The problem was defined and solved (Teweles, 1970; Friedman, 1972) by a new design for the radiosonde case.

A glance at the Hilo, Hawaii, radiosonde data reveals that the change to the carbon element must have been accomplished in January 1965, since relative humidity values are given at consistently high altitudes after that time. Therefore, Hilo radiosonde data on individual control days were analyzed for monthly averages for 1958–64 and 1965–70. These calculations were performed using the 0130 HST ascents and repeated using an average of the 0130 and 1330 HST ascents. This was done because all radiation data used for control day values were taken during the early morning. However, we feel that the nighttime values alone are more representative of water vapor above Mauna Loa because the 1330 HST ascent is well after the thermally induced upslope windflow is established. In addition, we feel that precipitable water calculations above Mauna Loa are more reliable for 1965 and after.

Monthly averages of the radiation data have been considered for the same periods: 1958–64 and 1965–70. Fortunately, 1958–64 also spans the pre-Agung period of radiation data acquisition at Mauna Loa.

Fig. 1 shows monthly average precipitable water and radiation data for 1958–64 and 1965–70. These data were subjected to a 12-point harmonic analysis to show annual and semi-annual trends, and the results are shown in Table 1 and Fig 1. Note that during 1958–64, radiation data show a seasonal variation with a minimum in June amounting to a peak-to-peak variation of approximately 0.9% about the mean of 0.932. The water vapor data show fairly erratic behavior with a possible peak-to-peak variation of as much as 0.1 cm,

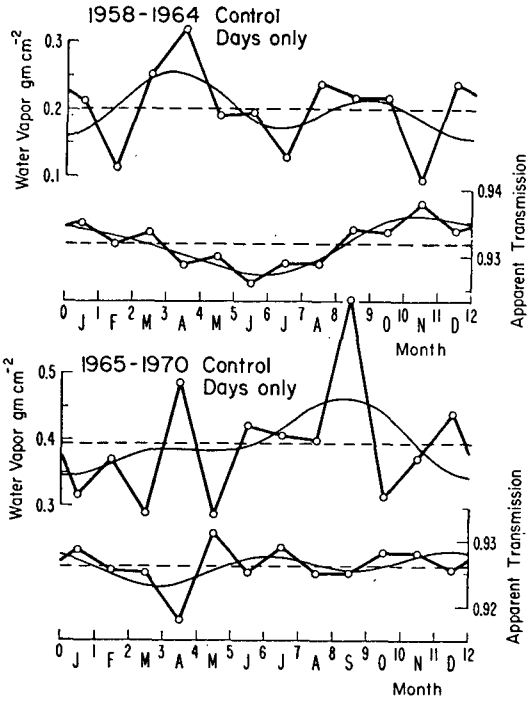

FIG. 1. Precipitable water above 700 mb calculated from Hilo, Hawaii, radiosonde data for control day monthly averages. Only the nighttime ascents were used. Upper curves give water vapor and apparent transmission for 1958–64, lower curves for 1956–70. Smooth curves show harmonic fits, dashed lines averages.

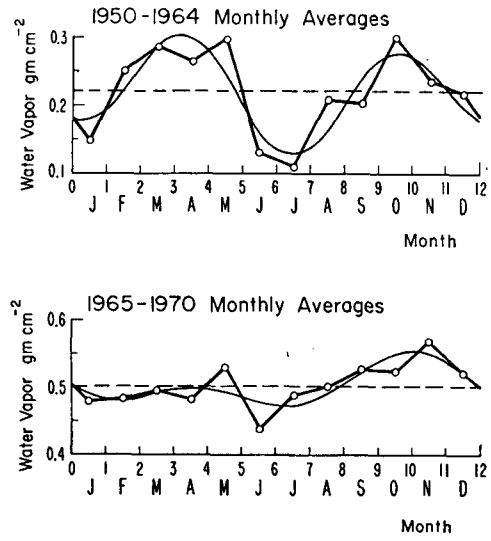

FIG. 2. Precipitable water above 700 mb calculated from *National Climatological Summary* monthly averages for Hilo, Hawaii. Upper curve is for 1950–1964, lower curve for 1965–70. Smooth curves show harmonic fits, dashed lines averages.

but this is apparently not in phase with the radiation data. A correlation coefficient of −0.23 for transmission and water vapor data showed a predominantly semi-annual trend. This suggests either that precipitable water calculations may not be reliable above the level of Mauna Loa or that changes in transmission are caused by variations in atmospheric constituents other than water vapor. Of the two time periods considered, 1965–70 shows the most erratic behavior of radiation data, most certainly because of the Agung eruption and the increase of the stratospheric dust which would mask the background variations of the pre-Agung period. The average transmission is significantly lower during the post-Agung period, although the full impact of the eruption is masked by the long-term average. Water vapor data are again erratic but appear to be more in phase with transmission and show a correlation coefficient of −0.64.

It is interesting at this point to consider precipitable water above Mauna Loa calculated from the monthly data in the *National Climatological Summary*. Fig. 2 shows monthly averages of precipitable water for 1950–64 and 1965–70. The semi-annual trend is very evident in 1950–64 but to a lesser extent in 1965–70. The data of 1950–64 have a much lower average value because of the use of the lithium chloride element through 1964. The results of a harmonic analysis are shown in Table 2.

The effects of variations of water vapor on solar radiation may be studied by referring to the works of Fowle (1915), MacDonald (1960) and Kondratyev (1969). All three agree that with about 0.5 gm cm^{-2} of water vapor in the ray path, radiation depletion would amount to about 10% per gm cm^{-2}. Note that typical fluctuations in water vapor have peak-to-peak variations of about 0.1 gm cm^{-2}, which corresponds to a 1%

TABLE 1. Twelve-point harmonic analysis of water vapor and radiation data for monthly averages of 1958–64 and 1965–70: W, precipitable water (gm cm^{-2}); T, atmospheric transmission as defined by Ellis and Pueschel (1971); m, month with $m=0$ at 0000 HST 1 January. Water vapor data are for the nighttime ascents on control days only.

Years	Precipitable Water	Atmospheric Transmission
1958 – 1964	$W = 0.2021 + 0.0213 \cos\frac{\pi}{6}(m - 3.7)$ $+ 0.0340 \cos\frac{\pi}{3}(m - 0.1)$	$T = 0.9319 + 0.0040 \cos\frac{\pi}{6}(m - 11.3)$ $+ 0.0010 \cos\frac{\pi}{3}(m - 0.9)$
1965 – 1970	$W = 0.3965 + 0.0445 \cos\frac{\pi}{6}(m - 7.7)$ $+ 0.0266 \cos\frac{\pi}{3}(m - 5.2)$	$T = 0.9262 + 0.0013 \cos\frac{\pi}{6}(m - 9.3)$ $+ 0.0018 \cos\frac{\pi}{3}(m - 5.4)$

TABLE 2. Twelve-point harmonic analysis of precipitable water calculated from the *National Climatological Summary* for 1950–64 and 1965–70.

Years	Precipitable Water
1950 – 1964	$W = 0.2217 + 0.0288 \cos\frac{\pi}{6}(m - 1.2)$ $+ 0.0704 \cos\frac{\pi}{3}(m - 0.7)$
1965 – 1970	$W = 0.5048 + 0.0281 \cos\frac{\pi}{6}(m - 10.1)$ $+ 0.0227 \cos\frac{\pi}{3}(m - 1.6)$

variation in solar radiation. Unfortunately, the phase angle of the water variations does not occur such that maximum water vapor coincides with minimum solar radiation. It appears, therefore, that on the basis of precipitable water calculations from radiosonde ascents, we must look to other causes for seasonal variations in solar radiation at Mauna Loa.

3. Aerosols above Mauna Loa

In general, the atmosphere above Mauna Loa is extremely clean and fairly representative of a background tropospheric aerosol of continental origin (Simpson, 1972). Typical values for the total background aerosol mass at Mauna Loa Observatory are about 1 μg m^{-3}. This is complicated further by a diurnal mountain wind system (Mendonca, 1969) that induces an upslope component during daytime and a downslope component at night. Consequently, a well-developed upslope windflow may penetrate the tradewind inversion (Mendonca and Iwaoka, 1969) bringing maritime and island aerosol components to Mauna Loa (Pueschel and Mendonca, 1972; Bodhaine and Pueschel, 1972). The cleanest time of the day, therefore, is in the early morning before upslope flow develops.

To predict the depletion of solar irradiance due to aerosols above Mauna Loa, it is particularly convenient to use Barrett's (1971) model, although it neglects absorption and longwave effects. This model includes both direct and diffuse radiation over the entire hemisphere, whereas the Mauna Loa data are taken in a 7° arc centered on the solar beam. However, at least 80% of the solar energy at Mauna Loa is contained in the solar beam (Barrett, personal communication; Kondratyev, 1969) and, in addition, in the following discussion we are concerned primarily with relative changes rather than absolute values of radiation. From Barrett (1971), for low particulate loads (<1000 gm per hectare), the percent depletion is a linear function of aerosol mass and may be represented by $D=0.031M$ at latitude 20N, where D is the percent depletion and M the global aerosol load (gm ha^{-1}). In this linear region, any changes in aerosol will be reflected by $\Delta D=0.013\ \Delta M$.

If we first direct our attention to the major decrease in transmission occurring in 1963 after the Agung eruption, we find a decrease in average transmission of about 2% from the Mauna Loa data. According to Barrett's model, this corresponds to an addition of about 150 gm ha^{-1}, or a total averaged over the globe of about 8×10^6 metric tons. Mitchell (1970) estimates independently that the eruption ejected approximately 15×10^6 tons of aerosol into the stratosphere. The agreement is excellent and strongly suggests that the Barrett model is applicable to explain the additional features of the Mauna Loa data.

A rather obvious tropospheric summer aerosol source, which is receiving more attention (Rasmussen and Went, 1965; Fish, 1972; Rasmussen, 1972) is that of organic nature. Junge (1963) and Went (1966) estimate that the biosphere adds approximately (20–40) $\times10^6$ metric tons of aerosol of organic nature to the troposphere each summer. Atmospheric aerosol models (Valley, 1965) suggest that one-tenth of the tropospheric aerosol load may be located above the level of Mauna Loa, and it is reasonable to expect lateral transport of this continentally produced aerosol throughout the troposphere in a matter of weeks or months. This would amount to about 40 to 80 gm ha^{-1} over Mauna Loa and would correspond to a seasonal variation in solar radiation of about 1% according to Barrett's model. Hence we see that a summer aerosol source of organic nature accounts very well for the seasonal trend in radiation observed at Mauna Loa.

4. Other atmospheric constituents above Mauna Loa

Other atmospheric variables, notably carbon dioxide and ozone, exhibit seasonal effects that may contribute to seasonal variations in solar radiation. However, these contributions will now be shown to be small. Absorption of solar radiation by carbon dioxide is very weak (Kondratyev, 1969; Möller, 1963), so that the 2% variation of carbon dioxide concentration with season, as measured at Mauna Loa (Machta, 1972), gives a negligible effect on solar radiation. Ozone measurements at Mauna Loa (Komhyr *et al.*, 1971) show some scatter with deviations up to 5% but essentially no seasonal variation. Since total absorption of solar radiation by ozone amounts to only 2% (Kondratyev, 1969), any variations caused by ozone must be negligible. The choice of "control days" by Ellis and Pueschel (1971) was designed to eliminate any effects of clouds.

5. Discussion

Radiosonde humidity data taken at Hilo appear to be substantially more reliable after 1965, but are probably not reliable enough on the exceptionally clear days (defined as control days) to calculate sufficiently accurate values of precipitable water to rigorously explain variations in solar radiation. However, the data in Fig. 1 show that we may expect variations in water vapor of the order of 0.1 cm which would cause variations in solar radiation of about 1%. On the other hand, precipitable water calculated from the *National Climatological Summary* monthly average humidity data (Fig. 2) shows a very clear semi-annual cycle, which reflects storms and large-scale systems near Hawaii. Control-day data and the *Climatological Summary* data strongly resemble each other in amplitude and phase but not in overall average value. This suggests that the choice of "control days" has not eliminated the water vapor variable, as was intended by Ellis and Pueschel (1971), and that the water vapor content above Mauna Loa on a day-to-day basis could indeed be responsible for a

portion of the variations in solar radiation observed at Mauna Loa.

This was suggested by Pueschel *et al.* (1974) on the basis of correlations between solar radiation, infrared hygrometer precipitable water, radiosonde precipitable water, and solar aureole measurements taken on control days over the period from August 1971 to May 1972. Correlation between infrared hygrometer data and radiation data was considerably higher than that between radiosonde precipitable water and radiation data. The not unexpected conclusion is that radiosonde precipitable water calculations above Mauna Loa, although sufficient to give a rough estimate, are not accurate enough to apply as a direct correction, on a day-to-day basis, to Mauna Loa radiation data. The radiosonde humidity element is simply not sensitive enough to give reliable readings at the low values of temperature and humidity encountered above Mauna Loa. Although it is difficult to estimate the amplitude of variations in radiation due to water vapor, the phase relationship between water vapor and radiation is such that there must be an additional, stronger contribution from some other source.

Atmospheric aerosols have been suggested as sources contributing to the variations in solar radiation, and a springtime tropospheric source of natural aerosols of only $(20\text{–}40)\times10^6$ metric tons of organic nature is likely to induce the observed variations and would provide the correct phase angle relationship. The presence of 50 gm ha^{-1} over Mauna Loa amounts to only about 0.5 $\mu g\ m^{-3}$, less than that measured at Mauna Loa Observatory.

Although the above speculations await more precise measurements of water vapor and aerosols above Mauna Loa, seasonal variations in turbidity observed at Mauna Loa probably reflect variations in the naturally produced tropospheric background aerosol. Any changes in the amplitude or phase of this periodic function may indicate an increased anthropogenic aerosol load.

Acknowledgments. We thank Ed Flowers and Don Pack for their helpful comments, Howard Ellis for providing control day radiation data, and Fred Rangel and Mary Jane Foley, University of Colorado students, for performing many of the calculations. Dr. Bodhaine has been supported under a National Research Council Resident Research Associateship.

REFERENCES

Barrett, E. W., 1971: Depletion of short-wave irradiance at the ground by particles suspended in the atmosphere. *Solar Energy*, **13**, 323–337.

Bodhaine, B. A., and R. F. Pueschel, 1972: Flame photometric analysis of the transport of sea salt particles. *J. Geophys. Res.*, **77**, 5106–5115.

Bryson, R. A., 1968: "All other factors being constant . . .". *Weatherwise*, **21**, 56–61.

Charlson, R. J., and M. J. Pilat, 1969: Climate: The influence of aerosols. *J. Appl. Meteor.*, **8**, 1001–1002.

Dyer, A. J., and B. B. Hicks, 1968: Global spread of volcanic dust from the Bali eruption of 1963. *Quart. J. Roy. Meteor. Soc.*, **94**, 545–554.

Eldridge, R. G., 1967: Water vapor absorption of visible and near infrared radiation. *Appl. Opt.*, **6**, 709–713.

Ellis, H. T., and R. F. Pueschel, 1971: Solar Radiation: Absence of air pollution trends at Mauna Loa. *Science*, **172**, 845–846.

Elsaesser, H. W., R. F. Pueschel and H. T. Ellis, 1972: Turbidity of the atmosphere: Source of its background variation with season. *Science*, **176**, 814–815.

Fish, B. R., 1972: Electrical generation of natural aerosols from vegetation. *Science*, **175**, 1239–1240.

Flowers, E. C., R. A. McCormick and K. R. Kurfis, 1969: Atmospheric turbidity over the United States, 1961–1966. *J. Appl. Meteor.*, **8**, 955–962.

Fowle, F. E., 1915: The transparency of aqueous vapor. *Astrophys. J.*, **42**, 394–411.

Friedman, M., 1972: A new radiosonde case: The problem and the solution. *Bull. Amer. Meteor. Soc.*, **53**, 884–887.

Gates, D. M., 1960: Near infrared atmospheric transmission to solar radiation. *J. Opt. Soc. Amer.*, **50**, 1299–1305.

Harrison, L. P., 1970: Calculation of precipitable water. ESSA Tech. Memo. WBTM TDL 33.

Junge, C. E., 1963: *Air Chemistry and Radioactivity*. New York, Academic Press, 382 pp.

Komhyr, W. D., E. W. Barrett, G. Slocum and H. K. Weickmann, 1971: Atmospheric total ozone increase during the 1960's. *Nature*, **232**, 390–391.

Kondratyev, K. Y., 1969: *Radiation in the Atmosphere*. New York, Academic Press, 912 pp.

List, R. J., 1966: *Smithsonian Meteorological Tables*. Smithsonian Institution Press, Washington, D. C.

Machta, L., 1972: Mauna Loa and global trends in air quality. *Bull. Amer. Meteor. Soc.*, **53**, 402–420.

McCormick, R. A., and J. H. Ludwig, 1967: Climate modification by atmospheric aerosols. *Science*, **156**, 1358–1359.

MacDonald, J. E., 1960: Direct absorption of solar radiation by atmospheric water vapor. *J. Meteor.*, **17**, 319–328.

Mendonca, B. G., 1969: Local wind circulation on the slopes of Mauna Loa. *J. Appl. Meteor.*, **8**, 533–541.

——, and W. T. Iwaoka, 1969: The trade wind inversion at the slopes of Mauna Loa, Hawaii. *J. Appl. Meteor.*, **8**, 213–219.

Mitchell, J. M., Jr., 1970: A preliminary evaluation of atmospheric pollution as a cause of the global temperature fluctuation of the past century. *Global Effects of Environmental Pollution*, S. F. Singer, Ed., New York, Springer-Verlag, 218 pp.

——, 1971: The effect of atmospheric aerosols on climate with special reference to temperature near the earth's surface. *J. Appl. Meteor.*, **10**, 703–714.

Möller, F., 1963: On the influence of changes in the CO_2 concentration in air on the radiation balance of the earth's surface and on the climate. *J. Geophys. Res.*, **68**, 3877–3886.

Morrissey, J. F., and F. J. Brousaides, 1970: Temperature induced errors in the ML-476 humidity data. *J. Appl. Meteor.*, **9**, 805–808.

Pueschel, R. F., and B. G. Mendonca, 1972: Sources of atmospheric particulate matter on Hawaii. *Tellus*, **24**, 139–149.

——, H. T. Ellis, G. F. Cotton, E. C. Flowers and J. T. Peterson, 1972: Normal incidence solar radiation trends on Mauna Loa, Hawaii. *Nature* **240**, 545–547.

——, C. J. Garcia and R. T. Hansen, 1974: Solar radiation: Effects of atmospheric water vapor and volcanic aerosols. *J. Appl. Meteor.*, **13** (in press).

Rasmussen, R. A., 1972: What do the hydrocarbons from trees contribute to air pollution? *J. Air Pollut. Control Assoc.*, **22**, 537–543.

——, and F. W. Went, 1965: Volatile organic material of plane origin in the atmosphere. *Proc. Nat. Acad. Sci.*, **53**, 215–220.

Reber, E. E., and J. R. Swope, 1972: On the correlation of the total precipitable water in a vertical column and absolute humidity at the surface. Rept. TR-0172 (2230 20)-13, The Aerospace Corporation, Los Angeles..

Roosen, R. G., 1972: Unpublished data presented at ASTRA Symposium, University of Washington, April 1972.

Salmela, H. A., and N. Sissenwine, 1970: A note on errors in upper air humidity climatology. *J. Appl. Meteor.*, **9**, 954–955.

Simpson, H. J., 1972: Aerosol cations at Mauna Loa Observatory. *J. Geophys. Res.*, **77**, 5266–5277.

Solot, S. B., 1939: Computation for depth of precipitable water in a column of air. *Mon. Wea. Rev.*, **67**, 100–103.

Teweles, S., 1970: A spurious diurnal variation in radiosonde humidity records. *Bull. Amer. Meteor. Soc.*, **51**, 836–840.

Valley, S. L., 1965: *Handbook of Geophysics and Space Environments*. Air Force Cambridge Research Laboratories.

Went, F. W., 1966: On the nature of Aitken condensation nuclei. *Tellus*, **18**, 549–556.

Whiting, D. M., 1971: Errors in upper air humidity climatology. *J. Appl. Meteor.*, **10**, 833–834.