Tellus (1979), *31*, 217–229

Pyrheliometric and circumsolar sky radiation measurements by the Smithsonian Astrophysical Observatory from 1923 to 1954

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(Manuscript received October 13; in final form December 19, 1978)

ABSTRACT

The pyrheliometric and circumsolar sky radiation measurements of the Smithsonian Astrophysical Observatory (APO) are examined from 1923 to 1954. The measurements at Mt Montezuma, Chile, in the Southern Hemisphere and Table Mountain, California, in the Northern Hemisphere are examined in most detail. It is found that Paluweh (8°19′S, 121°42′W), which erupted in 1928, had a dust veil index of 100 using Lamb's (1970) definition of the dust veil index. Quizapu (35°39′S, 70°46′W), which erupted in 1932, has a dust veil index of 35. Both of these volcanoes are climatologically significant. Between April 1932 and 1950 there are no detectable volcanic eruptions in either hemisphere. Local pollution at both stations after 1950 degrades the observations at these sites. There was a change of 0.6–0.7% in the radiation scale at Mt Montezuma about 1940. No evidence for an 11- or 22-year cycle is found in the pyrheliometer data and any variation in the solar constant on this time scale seems to be a fraction of a tenth of a percent. The pyrheliometer and pyranometer serve complementary purposes and confirm the reality of changes in the atmospheric dust loading.

1. Introduction

The Astrophysical Observatory of the Smithsonian Institution (APO) for many years made solar radiation measurements at a variety of locations all over the world. These measurements were part of a larger program to determine the value of the solar constant and its possible variations (e.g., Hoyt, 1979a). Pyrheliometric measurements of the total irradiance of the sun were made using silver disk and Ångström pyrheliometers (Abbot and Aldrich, 1942). The total irradiance of a region of circumsolar sky was measured using the "pyranometer" of Abbot and Aldrich (1916a, 1916b).

The pyrheliometer and pyranometer measurements of Abbot and Aldrich (1942) and Aldrich and Hoover (1954) are examined in this paper. After 1952 data from the Smithsonian Archives are used. Earlier APO measurements are available but are scattered both in time and in space. Solar radiation was measured at Mt Montezuma, Chile (22°40′S, 68°56′W), over the entire 1923–1954 period and at Table Mountain, California (34°22′N, 117°41′W), from 1926 to 1954. Tyrone, New Mexico (32°35′N, 108°26′W), and Mt St Katherine, Egypt (28°31′N, 33°56′E), have shorter records and are briefly considered. Various aspects of the APO program including information on the solar constant, atmospheric transmission, and atmospheric composition have been considered by Roosen et al. (1973), Hoyt (1978a, 1979a, 1979b), and Roosen and Angione (1977).

The silver disk pyrheliometer (Abbot, 1911) is a calorimeter or energy meter (e.g., West and Churney, 1970; Hoyt, 1973). Basically, this instrument operates by the exposure of a quantity of material of known specific heat to radiation for a measured period of time (usually 2 minutes). The temperature rise is measured by a mercury thermometer and corrected for heat losses by conduction, convection, and radiation so that the total heat energy coming into the instrument in a known period of time can be calculated. Once the inner aperture area is known, the total irradiance is

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simply calculated as the energy per unit time per unit area. In practice, the silver disk pyrheliometer was not used as an absolute radiometer but rather as a secondary pyrheliometer whose calibration is traceable to the electrically, self-calibrating water flow pyrheliometer (Abbot and Fowle, 1908; Hoover and Froiland, 1953).

The Ångström pyrheliometer operates by balancing the radiant input to one blackened strip of metal and the electrical input to a nearly identical shaded blackened strip of metal such that both are heated to the same steady-state temperature. Each strip is alternatively exposed to radiant energy to avoid errors caused by slight differences in their construction. A measure of the electrical heat needed to balance the radiant heat gives a measure of the total irradiance after some small corrections for the non-equivalence of the two heat sources and sinks are made. In practice this instrument was not used as an absolute instrument but was calibrated in the APO program by a comparison to the silver disk pyrheliometer.

The silver disk pyrheliometers are of two types known as the short vestibule and long vestibule types. The short vestibule pyrheliometer has a 20 cm length aperture tube and a 10.6° field-of-view. The long vestibule pyrheliometer has a 40 cm length aperture tube and a 3.22° field-of-view (Abbot et al., 1932). At Mt Montezuma the short-tube silver disk pyrheliometers were used in daily observations until November 4, 1932 when they were replaced by long-tube pyrheliometers (Fouts, 1977). The long-tube pyrheliometers were used until November 25, 1936 when the Ångström pyrheliometers were introduced. At Table Mountain the Ångström pyrheliometers were introduced for daily observations on May 15, 1937. All the pyrheliometer measurements were corrected for the aureole so that the published values have a zero sky brightness and thus measure the sun's intensity only (Abbot and Aldrich, 1942).

Each observer who used a silver disk pyrheliometer got slightly different readings from that of all other observers. To correct for differences between observers, Abbot introduced the so-called personal equation. The personal equation is a constant percentage correction, different for each observer, that was used to correct the silver disk pyrheliometer readings of an observer to that which would have been attained by A. F. Moore. These corrections were of the order of a few tenths of a percent.

The "pyranometer" measured the brightness of the sky in a doughnut-shaped ring about the sun. Today it would more appropriately be called an aureole brightness meter. The region of the sky from 3.5° to 14.5° from the center of the sun was viewed in the pyranometers built after 1921 (Abbot et al., 1932). A thermopile detector was used to measure the intensity of the radiation over all wavelengths. In June, 1932 at Mt Montezuma and in May, 1933 at Table Mountain, a shade was added to the pyranometer 1 m from the outer aperture and of sufficient size to shade the entire outer aperture. The geometry was modified in such a way that the overall intensity of the radiation viewed was less. The viewing angles of the new geometry were from 8.5° to 18.5° from the center of the sun. It is difficult to invert the pyranometer measurements alone to find out details of the aerosol properties. The integration over all wavelengths and over a region of the sky plus the complications introduced by a possible non-uniform detector (Bossy and Pastiels, 1948) further complicate this inversion problem. In view of this, the pyranometer measurements can only be considered as a relative measure of circumsolar sky radiation and hence of atmospheric turbidity. Ångström (1974a, 1974b) has used these data with the other APO instrumental data to derive turbidity values.

2. Pyrheliometer data

The pyrheliometric measurements were made at many sea level air mass values the most common being 1.5, 2.0 and 2.5. The corresponding solar zenith angles are 48.3°, 60.0°, and 66.6°. Monthly means are calculated using the daily observations which were almost always made in the morning. Plots of the monthly mean values for air mass 2.0 are plotted in Figs. 1 and 2 for Mt Montezuma and Table Mountain.

The most evident feature in these time series is the annual cycle. A maximum appears each winter and a minimum each summer (Fig. 3 and Tables 1 and 2). This annual variation is caused mainly by variations in total precipitable water. The maximum of water vapor in summer causes a minimum in atmospheric transmission (Hoyt, 1979b). Other more subtle features are also evident in Figs. 1 and 2, such as the decrease in direct radiation caused by smoke emissions from the Chuquicamata

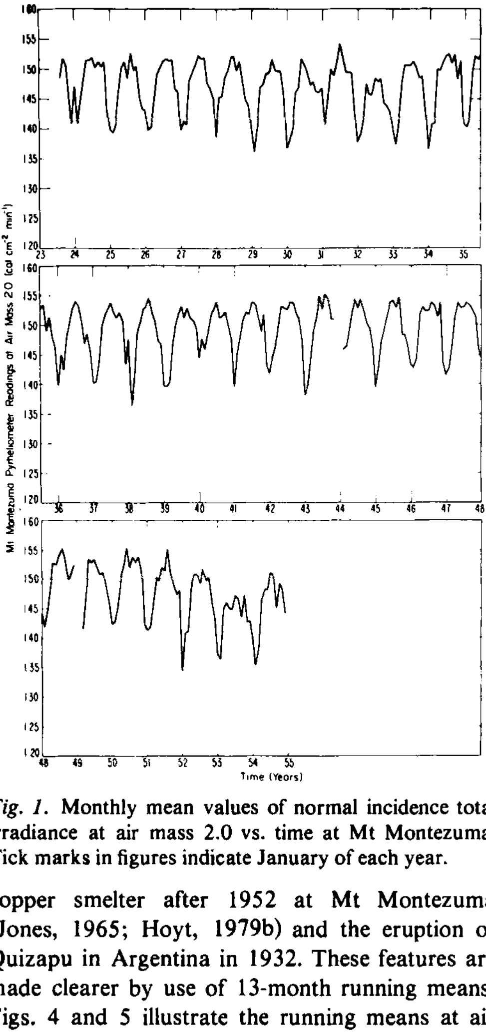

Fig. 1. Monthly mean values of normal incidence total irradiance at air mass 2.0 vs. time at Mt Montezuma. Tick marks in figures indicate January of each year.

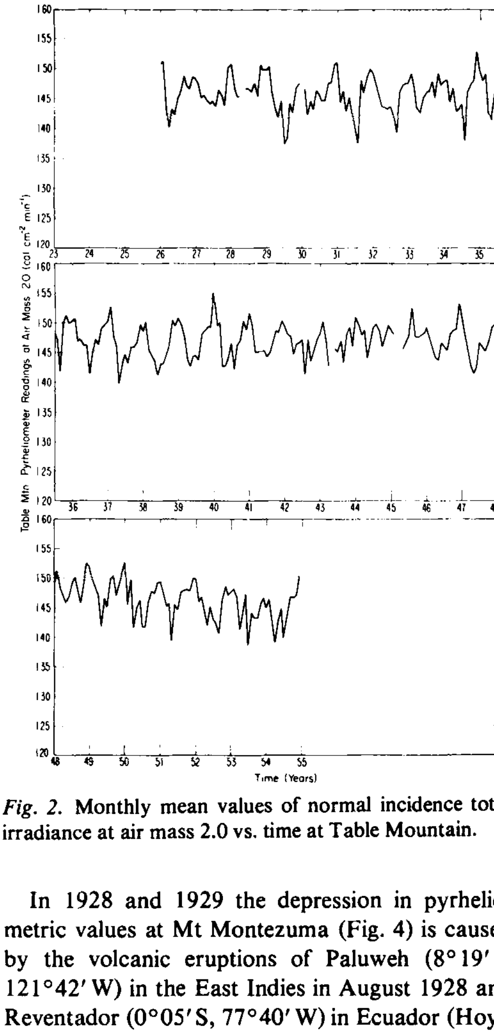

Fig. 2. Monthly mean values of normal incidence total irradiance at air mass 2.0 vs. time at Table Mountain.

copper smelter after 1952 at Mt Montezuma (Jones, 1965; Hoyt, 1979b) and the eruption of Quizapu in Argentina in 1932. These features are made clearer by use of 13-month running means. Figs. 4 and 5 illustrate the running means at air mass 2.0 for Mt Montezuma and Table Mountain.

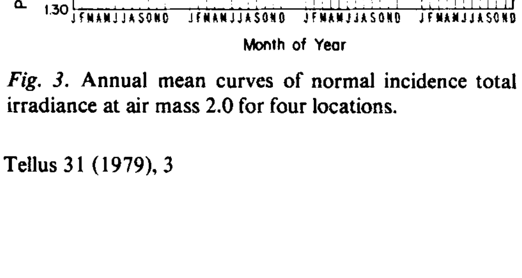

Fig. 3. Annual mean curves of normal incidence total irradiance at air mass 2.0 for four locations.

In 1928 and 1929 the depression in pyrheliometric values at Mt Montezuma (Fig. 4) is caused by the volcanic eruptions of Paluweh (8°19′S, 121°42′W) in the East Indies in August 1928 and Reventador (0°05′S, 77°40′W) in Ecuador (Hoyt, 1978a) in 1929. The eruption of Quizapu (35°39′S, 70°46′W) in Argentina about 1450 kilometers south of the Mt Montezuma station in April 1932 is also very evident. These volcanic eruptions injected aerosols into the stratosphere which caused the decreases in the pyrheliometric values. The effects of the eruption of Reventador about 2500 kilometers north of Mt Montezuma in 1926 are not clearly evident in these plots. These volcanic eruptions will be discussed in more detail in a section below.

The major unexpected feature in the Mt Montezuma pyrheliometric time series is the apparent increase in pyrheliometer val$^{\text{ı}}$ues in late 1939. Both Allen (1958) and Hoyt (1979a) suggest these two data sets are either different or were handled differ-

Table 1. *Long-term monthly and yearly mean values of the normal incidence radiation (I) in cal cm^{-2} min^{-1} at Mt Montezuma for three air mass values m. Mean and standard deviation for the year are found using the unweighted monthly means from 1923 to 1954*

	$m = 1.5$		$m = 2.0$		$m = 2.5$	
Month	N	I p	N	I p	N	I p
1	226	1.4911 ± 0.0767	222	1.4065 ± 0.0903	64	1.3395 ± 0.0663
2	195	1.4894 ± 0.0749	219	1.4098 ± 0.0861	49	1.3355 ± 0.0506
3	374	1.5144 ± 0.0960	389	1.4335 ± 0.0977	143	1.3638 ± 0.0886
4	415	1.5624 ± 0.0519	486	1.4861 ± 0.0638	188	1.4208 ± 0.0551
5	340	1.5793 ± 0.0527	501	1.5051 ± 0.0743	190	1.4334 ± 0.0542
6	255	1.5922 ± 0.0581	468	1.5157 ± 0.0834	202	1.4445 ± 0.0685
7	253	1.5979 ± 0.0540	467	1.5201 ± 0.0684	193	1.4615 ± 0.0581
8	335	1.5960 ± 0.0636	466	1.5211 ± 0.0788	170	1.4614 ± 0.0735
9	405	1.5848 ± 0.0859	458	1.5089 ± 0.0915	135	1.4405 ± 0.0742
10	446	1.5738 ± 0.0654	468	1.5000 ± 0.0749	160	1.4312 ± 0.0363
11	431	1.5623 ± 0.0718	399	1.4847 ± 0.0842	137	1.4160 ± 0.0715
12	322	1.5307 ± 0.0680	306	1.4534 ± 0.0748	96	1.3762 ± 0.0510
Year	364	1.5565 ± 0.0441	373	1.4796 ± 0.0466	335	1.4143 ± 0.0517

N = sample size. I = mean normal incidence radiation. p = standard deviation.

ently by the APO staff. Aldrich and Hoover (1954) indicate that starting in October, 1939, the pyrheliometry was reduced at Mt Montezuma by 0.92% to place it on the Smithsonian Scale of 1913. However, since the post-1939 values are still higher than the pre-1939 values, it is apparent that they did not entirely achieve their goal. It also suggests that over the period from the 1920's to 1949 when calibrations of the Mt Montezuma instruments were done, there was an upward drift in the basic radiation standards of the APO of the order of 0.6–0.7%, or there was an error in the original calibrations of the Mt Montezuma silver disk pyrheliometers during the 1920's. The latter seems

Table 2. *Long-term monthly and yearly mean values of the normal incidence radiation (I) in cal cm^{-2} min^{-1} at Table Mountain for three air mass values m. Mean and standard deviation for the year are found using the unweighted monthly means from 1926 to 1954*

	$m = 1.5$		$m = 2.0$		$m = 2.5$	
Month	N	I p	N	I p	N	I p
1	0		242	1.4980 ± 0.0463	192	1.4264 ± 0.0488
2	50	1.5507 ± 0.0384	192	1.4853 ± 0.0491	134	1.4163 ± 0.0476
3	118	1.5378 ± 0.0346	170	1.4637 ± 0.0463	105	1.4003 ± 0.0462
4	115	1.5165 ± 0.0393	125	1.4364 ± 0.0499	67	1.3639 ± 0.0525
5	128	1.5092 ± 0.0410	163	1.4339 ± 0.0398	86	1.3662 ± 0.0399
6	291	1.5186 ± 0.0541	338	1.4505 ± 0.0560	211	1.3792 ± 0.0544
7	193	1.5194 ± 0.0706	318	1.4457 ± 0.0849	188	1.3877 ± 0.0717
8	171	1.5141 ± 0.0740	281	1.4463 ± 0.0940	185	1.3726 ± 0.0890
9	208	1.5291 ± 0.0567	351	1.4611 ± 0.0810	233	1.3982 ± 0.0816
10	177	1.5347 ± 0.0488	364	1.4659 ± 0.0589	268	1.4000 ± 0.0609
11	3	1.5343 ± 0.0430	350	1.4836 ± 0.0497	264	1.4174 ± 0.0463
12	0		231	1.4941 ± 0.0452	202	1.4326 ± 0.0426
Year	239	1.5243 ± 0.0288	343	1.4639 ± 0.0312	325	1.3978 ± 0.0352

N = sample size. I = mean normal incidence radiation. p = standard deviation.

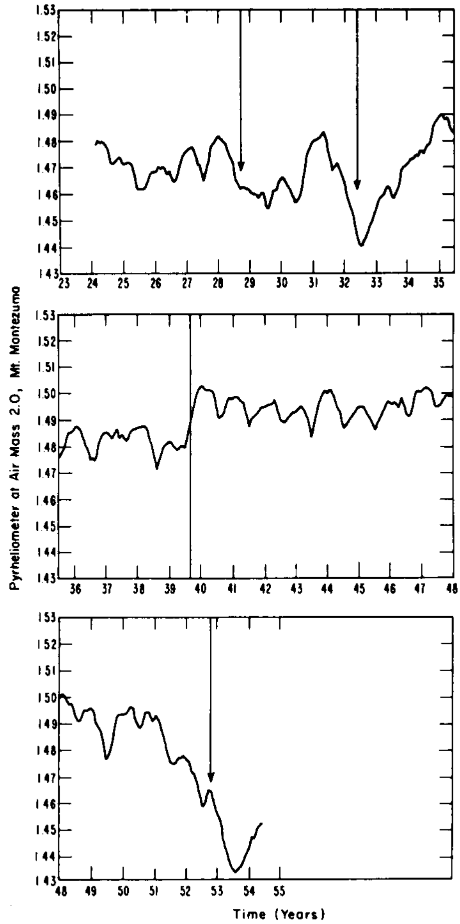

Fig. 4. 13-Month running mean of normal incidence total irradiance at air mass 2.0 vs. time at Mt Montezuma. The annual cycle is not entirely removed by the smoothing. The eruptions of Paluweh (1928) and Quizapu (1932) and the start of the Chuquicamata copper smelter (1952) are indicated by the arrows. The pyrheliometric values decrease prior to the arrows because a running mean is used. The vertical line in 1939 represents the division of the data between volumes 6 and 7 of the *Annals of the Astrophysical Observatory of the Smithsonian Institution* and is the time of a change in the radiation scale.

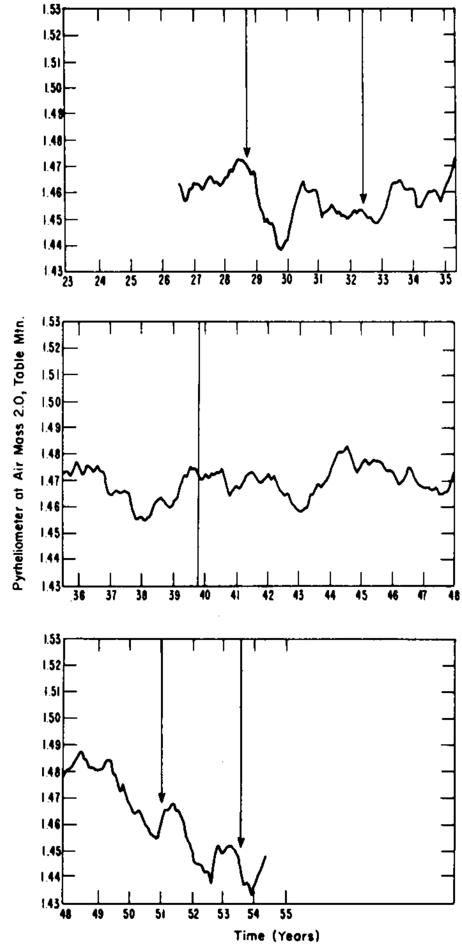

Fig. 5. 13-Month running mean of normal incidence total irradiance at air mass 2.0 vs. time at Table Mountain. The eruptions of Paluweh (1928), Quizapu (1932), Mt Lamington (1951), and Mt Spurr (1953) are represented by the arrows. Because Paluweh is in the Southern Hemisphere its effect on the pyrheliometric values is delayed until 1929. The Quizapus eruption is only barely evident. The vertical line again represents the division of the data between volumes 6 and 7 of the *Annals of the Astrophysical Observatory of the Smithsonian Institution.*

more likely since a similar 0.67% downward correction at Table Mountain seems to have been properly done.

As mentioned previously, the atmospheric transmission and hence pyrheliometric measurements decreased starting about 1950 because of the nearby Chuquicamata copper smelter. Aldrich (1955) on this topic states: "due to the poorer quality of the currently available ore, the electrolytic method has been replaced by the smelting process, which sends great quantities of gases and dust into the air continuously". The first smelter unit began operation on October 15, 1952 and in Fig. 4, the pyrheliometric measurements drop sharply. The drop in pyrheliometric values prior to the operation of the smelters, however, is not explained, but is probably from another source of local pollution.

Most of the features in the Table Mountain 13-month running mean curve (Fig. 5) can also be explained. The eruptions of Paluweh and Reventador in 1928–1929 are more evident at Table Mountain than at Mt Montezuma. These volcanoes are located in the tropics and injected dust into the stratosphere of both hemispheres. Quizapu, which erupted in 1932, is located at 35° S and this is barely evident in the Table Mountain records.

The depressions in normal incidence radiation at Table Mountain (Fig. 5) about 1937–1938 and 1942 are probably caused either by poor sampling in these periods or by increased water vapor amounts at those times. Lamb (1970) lists the eruption of Sopka Tolbachik (55° N, 100.5° E) in 1937 as a possible source of stratospheric aerosol and this may have caused the depression in pyrheliometric values at this time. The eruption, however, is not evident in the circumsolar sky measurements, as will be discussed below, and for this reason the eruption of Sopka Tolbachik appears to have had a very small effect on atmospheric transmission compared to the other eruptions in the APO record. Oliver (1976) also shows that the Northern Hemisphere surface temperatures were at a maximum during this period so this volcanic eruption apparently had a minimal effect on climate. Lamb lists no volcanic eruption in 1942, Oliver has no temperature depression after 1942 which could be attributed to a volcanic eruption, and aureole measurements are constant at this time so the depression in pyrheliometric values in 1942 at Table Mountain is caused mostly by sampling errors.

After about 1950 the pyrheliometric values decrease apparently because of atmospheric pollutants from the growth of nearby Los Angeles. On this topic Jones (1965) states: "At Table Mountain ... observations suffered ... from smog and haze created by industrial expansion and refineries in southern California." Part of the decrease in normal incidence radiation after 1950, however, may be caused by the eruptions of Mt Lamington (9° S, 148° E) in New Guinea in January, 1951 and Mt Spurr (61° N, 153° W) in Alaska in July, 1953. Since these volcanic eruptions are not evident in the Lincoln, Nebraska and Albuquerque, New Mexico, records (Dyer, 1974), local pollution would appear to be the most likely cause of the variations in the two APO stations. The eruption of Hekla (64° N, 19.5° W) in Iceland in March, 1947 is not evident in the Table Mountain pyrheliometric records.

3. Pyranometer data

Monthly means of the pyranometer values at air mass 2.0 are plotted in Figs. 6 and 7 at Mt Montezuma and Table Mountain. The vertical lines indicate the times the geometry of the pyranometers were reported to have changed with viewing angles such that less radiation was measured thereafter. Because of the high pyranometer values at Table Mountain after the reported change, it is possible the change was actually made a few months later. Unfortunately, the pyranometer changes were made in 1932 and 1933 while the

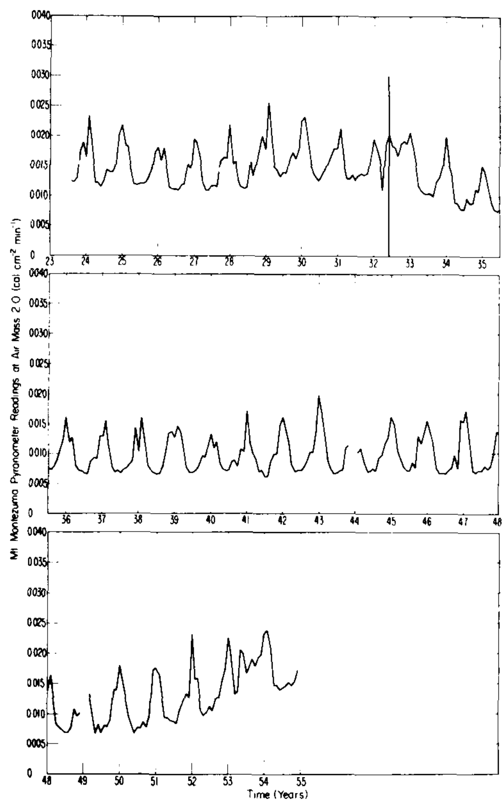

Fig. 6. Monthly mean values of circumsolar sky radiation at air mass 2.0 vs. time at Mt Montezuma. The vertical line indicates an instrument change in June, 1932.

effects of the eruption of Quizapu in April, 1932 were being observed. In Fig. 6 one can see the sharp rise in aureole brightness just prior to the instrument change but its full rise is not shown. If the winter-time turbidity in the period 1926–1929 is about the same as the winter-time turbidity in the period 1936–1939, the actual rise in aureole brightness is about 0.012 cal cm^{-2} min^{-1} rather than 0.008 cal cm^{-2} min^{-1} illustrated in the figure. After the eruption the decay in aureole brightness can be seen particularly by comparison of successive winter values to each other. By the winter of 1935, the circumsolar sky brightness has returned to normal. Thus the residence time of the stratospheric aerosols is no more than 3 years which agrees well with previous estimates (e.g., Kimball, 1918).

The 13-month running means at both stations are illustrated in Figs. 8 and 9. The dotted values

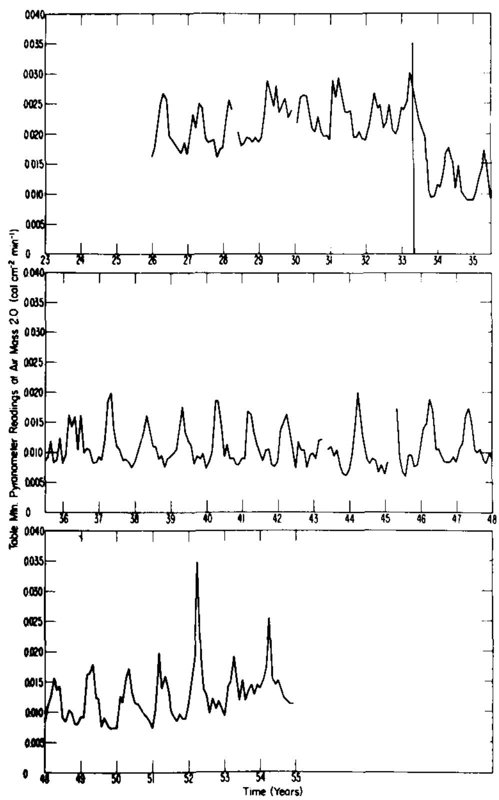

Fig. 7. Monthly mean values of circumsolar sky radiation at air mass 2.0 vs. time at Table Mountain. The vertical line indicates the reported time of an instrument change in May, 1933.

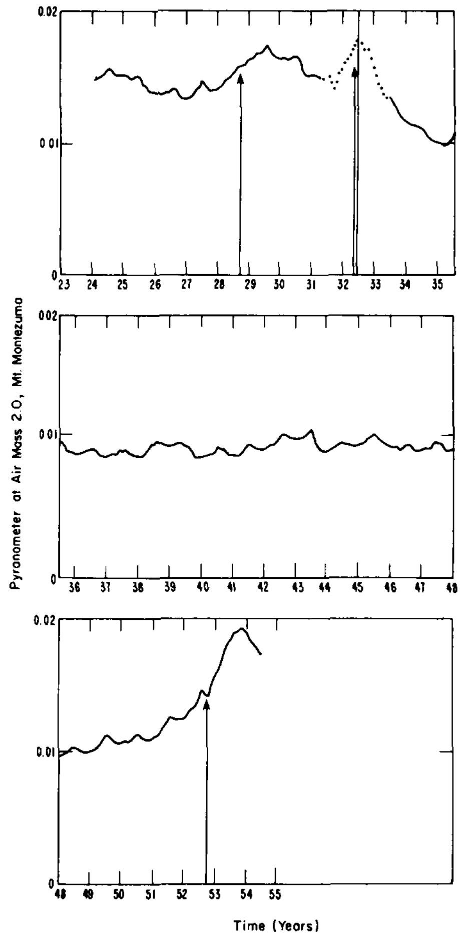

Fig. 8. 13-Month running means of circumsolar sky radiation at air mass 2.0 vs time at Mt Montezuma. The dotted line is a period about the time of the instrument change (vertical line) when the running mean is not valid. The arrows represent the eruptions of Paluweh (1928) and Quizapu (1932) and the start of operation of the Chuquicamata copper smelter (1952).

are not valid data because of the pyranometer instrument changes. At Mt Montezuma, in the period 1933–1935, the aureole brightness is returning to normal after the Quizapu eruption. After 1950 the aureole brightness is increasing because of local pollution by the Chuquicamata copper smelter. About 1928–1929 there is a rise in aureole brightness caused by the eruptions of Paluweh in the East Indies and Reventador in Ecuador. These eruptions show up more clearly in the atmospheric transmission plots (Hoyt, 1978a, 1979b). The period 1935–1950 has very little change in aureole

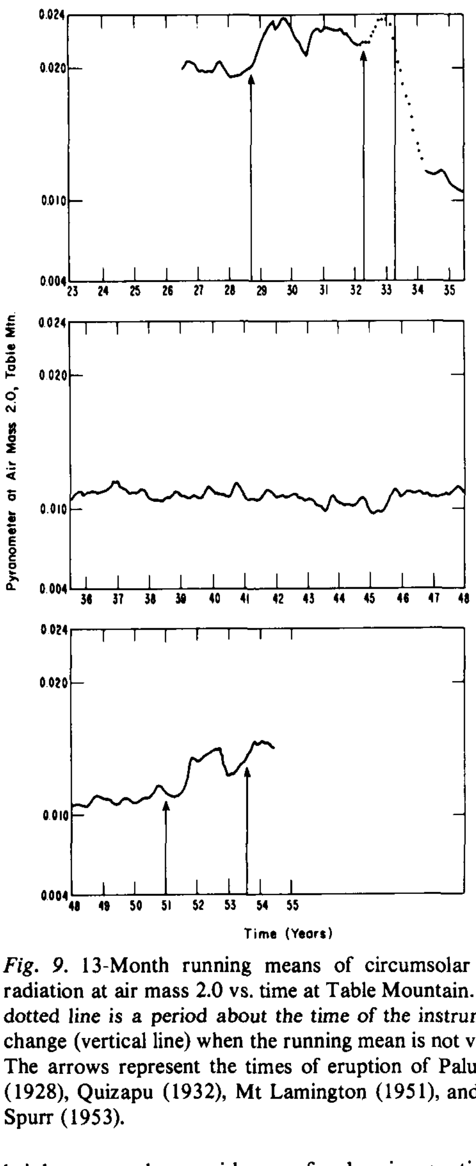

Fig. 9. 13-Month running means of circumsolar sky radiation at air mass 2.0 vs. time at Table Mountain. The dotted line is a period about the time of the instrument change (vertical line) when the running mean is not valid. The arrows represent the times of eruption of Paluweh (1928), Quizapu (1932), Mt Lamington (1951), and Mt Spurr (1953).

brightness and no evidence of volcanic eruptions. At Table Mountain, the Quizapu eruption is evident about 1934–1935 and possible local pollution effects can be seen after 1950 (Hoyt, 1979b). The period 1935–1950 has a steady circumsolar sky irradiance with no effects of major volcanic eruptions evident.

In the period 1928–1929 there is a rise in aureole brightness at Table Mountain. Although this rise is probably caused by an increase in aerosol loading of the atmosphere after the eruptions of Paluweh and Reventador in 1928 and 1929, the data from this period need to be approached with caution. Abbot et al. (1932) state: "... it was found that the pyranometer values had suddenly increased by more than 10% about August 12" in 1927. The reason for the increase was not discovered until September, 1928 when it was found necessary to reblacken the inner vestibule of the pyranometer to eliminate a source of stray light. Even then it was felt that the pyranometer values were too high so they were reduced by a constant amount from September to December 1928. The erroneous pyranometer data from August 1927 to December 1928 were statistically corrected to agree with earlier measurements of the aureole brightness. These corrections, which always reduced the pyranometer values, would serve to obscure the onset of the aerosol effects from the Paluweh and Reventador volcanic eruptions. Since the pyranometer values rise in the late 1928 and early 1929 period, there is still evidence that stratospheric aerosols from these tropical volcanoes were present in the Northern Hemisphere.

Each station has an annual periodicity in the aureole brightness. The annual mean periodicities at four APO stations at air mass 2.0 are illustrated in Fig. 10 and tabulated for Mt Montezuma and Table Mountain in Tables 3 and 4 for the data after January 1, 1934. A maximum in aureole brightness is present in the spring or summer at all stations when the aerosol loading of the atmosphere is greatest. The minimum aureole brightness is in the winter. From the tabular values it is evident the aureole increases in brightness the closer the sun is to the horizon.

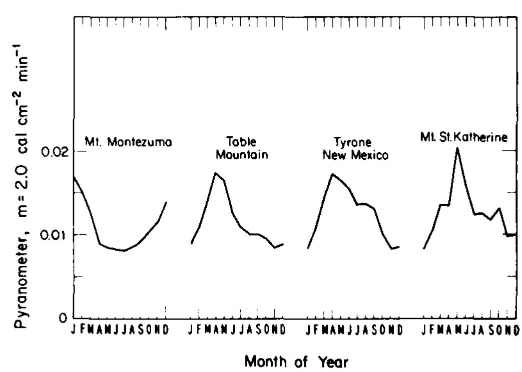

Fig. 10. Annual mean curves of circumsolar sky radiation at air mass 2.0 for four locations.

Table 3. *Long-term monthly and yearly mean values of the pyranometer measurements (P) in cal* cm^{-2} min^{-1} *at Mt Montezuma after 1934 for three air mass values m. Mean and standard deviation for the year are found using the unweighted monthly means from 1934 to 1954*

	$m = 1.5$		$m = 2.0$		$m = 2.5$	
Month	N	P p	N	P p	N	P p
1	157	0.0132 ± 0.0075	154	0.0168 ± 0.0104	46	0.0205 ± 0.0081
2	132	0.0124 ± 0.0059	146	0.0152 ± 0.0078	34	0.0187 ± 0.0047
3	255	0.0099 ± 0.0065	253	0.0126 ± 0.0084	102	0.0148 ± 0.0103
4	260	0.0074 ± 0.0060	323	0.0091 ± 0.0073	144	0.0106 ± 0.0063
5	206	0.0070 ± 0.0059	344	0.0085 ± 0.0106	145	0.0101 ± 0.0071
6	140	0.0069 ± 0.0044	324	0.0083 ± 0.0102	154	0.0099 ± 0.0062
7	137	0.0065 ± 0.0058	308	0.0081 ± 0.0094	148	0.0090 ± 0.0058
8	204	0.0069 ± 0.0087	312	0.0085 ± 0.0112	134	0.0100 ± 0.0102
9	246	0.0073 ± 0.0086	288	0.0093 ± 0.0114	103	0.0109 ± 0.0098
10	275	0.0084 ± 0.0070	296	0.0104 ± 0.0080	122	0.0127 ± 0.0067
11	281	0.0093 ± 0.0069	248	0.0115 ± 0.0088	97	0.0135 ± 0.0088
12	203	0.0111 ± 0.0048	198	0.0139 ± 0.0070	69	0.0169 ± 0.0060
Year	239	0.0088 ± 0.0032	248	0.0109 ± 0.0039	224	0.0127 ± 0.0049

N = sample size. P = mean pyranometer measurements. p = standard deviation.

Table 4. *Long-term monthly and yearly mean values of the pyranometer measurements (P) in cal* cm^{-2} min^{-1} *at Table Mountain after 1934 for three air mass values m. Mean and standard deviation for the year are found using the unweighted monthly means from 1934 to 1954*

	$m = 1.5$		$m = 2.0$		$m = 2.5$	
Month	N	P p	N	P p	N	P p
1	0		179	0.0089 ± 0.0047	141	0.0102 ± 0.0056
2	19	0.0101 ± 0.0030	138	0.0109 ± 0.0065	88	0.0127 ± 0.0065
3	67	0.0116 ± 0.0034	112	0.0140 ± 0.0055	62	0.0150 ± 0.0048
4	63	0.0135 ± 0.0048	71	0.0174 ± 0.0068	35	0.0198 ± 0.0062
5	77	0.0138 ± 0.0046	112	0.0164 ± 0.0045	58	0.0174 ± 0.0058
6	190	0.0111 ± 0.0056	242	0.0126 ± 0.0062	152	0.0146 ± 0.0065
7	113	0.0087 ± 0.0035	229	0.0108 ± 0.0059	130	0.0118 ± 0.0047
8	109	0.0089 ± 0.0038	201	0.0100 ± 0.0053	120	0.0114 ± 0.0052
9	135	0.0088 ± 0.0037	230	0.0100 ± 0.0047	128	0.0115 ± 0.0038
10	97	0.0081 ± 0.0032	239	0.0095 ± 0.0050	157	0.0108 ± 0.0048
11	0		233	0.0084 ± 0.0050	166	0.0097 ± 0.0054
12	0		136	0.0088 ± 0.0046	114	0.0099 ± 0.0048
Year	167	0.0105 ± 0.0030	249	0.0114 ± 0.0037	231	0.0127 ± 0.0040

N = sample size. P = mean pyranometer measurements. p = standard deviation.

4. Dust veil indices and volcanic aerosol optical depths

The APO pyrheliometric records provide a means to estimate both the dust veil indices and the increases in optical depth for two volcanic eruptions, Paluweh and Quizapu. Puyehue (40°35′S, 72°08′W), which erupted in December 1921, is also an important eruption evident in the earlier APO records.

The optical depth increases caused by the eruptions of Paluweh and Quizapu can be estimated by comparing the monthly mean pyrheliometric measurements to the long-term monthly mean

Table 5. *The monthly mean increases in optical depth normalized to unit air mass using data at a 60° solar zenith angle at Mt Montezuma and Table Mountain after the eruption of Paluweh in August and September, 1928 and Quizapu in April, 1932. The mean of all observations from August, 1923 to December, 1954 is used as the base period to calculate normal conditions*

		Mt Montezuma	Table Mtn.			Mt Montezuma	Table Mtn.
1928	Aug.	0.0119	−0.0065	1932	April	0.0040	0.0001
	Sept.	−0.0026	−0.0066		May	0.0222	−0.0009
	Oct.	0.0108	0.0056		June	0.0274	0.0084
	Nov.	0.0173	−0.0103		July	0.0165	0.0043
	Dec.	0.0072	−0.0058		Aug.	0.0199	0.0109
					Sept.	0.0115	0.0316
1929	Jan.	0.0062	−0.0002		Oct.	0.0269	0.0012
	Feb.	0.0249	−0.0084		Nov.	0.0219	0.0048
	March	0.0138	0.0022		Dec.	0.0117	0.0083
	April	0.0070	0.0009				
	May	0.0144	0.0074	1933	Jan.	0.0058	0.0098
	June	0.0101	0.0016		Feb.	0.0180	−0.0029
	July	0.0119	0.0343		March	0.0098	−0.0016
	Aug.	0.0020	0.0284		April	0.0052	0.0009
	Sept.	0.0057	0.0081		May	−0.0006	0.0033
	Oct.	0.0019	0.0180				
	Nov.	−0.0051	0.0065				
	Dec.	−0.0020	0.0076				

values and attributing the net deficit to the volcanic aerosols. Table 5 summarizes the month-by-month incremental increases in total optical depth. After the Paluweh and Reventador eruptions in 1928 and 1929, the optical depth increase averages 0.0134 for the first six months after the eruption at Mt Montezuma, but is −0.0028 at Table Mountain. It is not until March and April of 1929 that the increases in optical depth begin to be noticed at Table Mountain. From March to August 1929 the average increase is 0.0125. The stratospheric dust appears to be transported into the Northern Hemisphere during April, which is autumn in the Southern Hemisphere. A similar effect occurred after the eruption of Agung (8.5° S, 115.5° E) in 1963) (Lamb, 1970; Dyer and Hicks, 1968) when the optical depths in the Norther Hemisphere increased each successive April for several years after the eruption. The northward transport of stratospheric aerosols occurred similarly after both the Paluweh and Agung eruptions in the East Indies.

The eruption of Quizapu in April, 1932 was observed nearly simultaneously at both Mt Montezuma and Table Mountain. In the period May to October, 1932, the increase in optical depth averaged 0.0207 at Mt Montezuma and 0.0093 at Table Mountain. The smaller increase at Table Mountain occurs both because it is further from the eruption site and in the other hemisphere. The rapid world-wide distribution of aerosols after this eruption was facilitated by the northward transport of stratospheric aerosols during the Southern Hemisphere's autumn as it was for the eruptions of Agung and Paluweh.

Lamb (1970) introduced a dust veil index to give measure of the relative effects of volcanic eruptions on the solar radiation received at the earth's surface. It also provides a relative measure of the climatic effects of volcanic eruptions. Lamb defines the dust veil index differently based upon the data available. Each definition is supposed to give the same numerical value for the dust veil index. Using Lamb's first definition for the dust veil index and the maximum optical depths in Table 5, an air mass at the APO stations of about 1.5 which corresponds to a solar elevation angle where the mean normal incidence irradiance is achieved, and a 24-month residence time for the dust (Hoyt, 1979b), the eruption of Paluweh has a dust veil index of about 100. Similarly, the dust veil index computed for Quizapu is about 35 (Lamb estimates it as 35) and has a smaller value than Paluweh because it is further south and outside the tropics. Quizapu's effect on climate in the Northern Hemisphere appears to be as great as Paluweh's effect, perhaps because of the rapid transport of dust into the Northern Hemisphere in April. The dust veil index alone does not explain the relative climatic effects of these volcanic eruptions but the season when they occur must also be considered.

Using Lamb's second definition for the dust veil index and a Northern Hemisphere drop in surface temperatures of 0.26 °C for Paluweh and 0.33 °C for Quizapu (Budyko, 1969), the dust veil index for Paluweh is about 170 and for Quizapu is about 100 if the temperatures are affected for only 12 months. These estimates of the dust veil index differ from those above. This suggests there is enough uncertainty in the available climatic data so that the dust veil index cannot be reliably estimated using Lamb's second definition.

From the APO records, the eruption of Puyehue in 1921 had about twice the effect on radiation at Mt Montezuma than Paluweh did but is located 40° S, so a tentative estimate of its dust veil index is about 100. Lamb estimates it equals 100. Since it is so far south and since it erupted in early summer, its effect on the Northern Hemisphere surface temperature was very small.

5. Solar variations

The reported solar constant values of the APO program give no indication of solar variability greater than a few tenths of a percent as reported by Hoyt (1979a). The pyrheliometric measurements alone may be used to derive some information on solar variability if the atmospheric conditions are relatively constant from year to year.

The power spectra of each of the time series illustrated in Figs. 1 and 2 were calculated using the maximum entropy spectra analysis (MESA) technique (Strand et al., 1977) and are given in Figs. 11 and 12. Each power spectra has a strong peak at one year and its higher harmonics because the annual oscillations are non-sinusoidal. In addition, both power spectra appear to have very long period oscillations which, however, are caused by trends in the data. At both stations there is a net overall increase of the pyrheliometric values at air mass 2.0 from 1923 to 1954, which is very small. The long period changes in atmospheric transmission after volcanic eruptions or in the presence of local air pollution which occur simultaneously at both stations will also give the appearance of being long

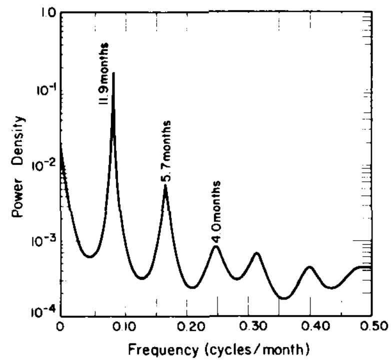

Fig. 11. Maximum entropy power spectrum of the normal incidence radiation at air mass 2.0 at Mt Montezuma.

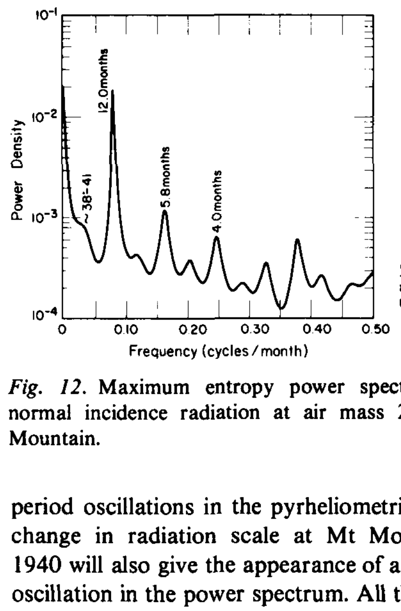

Fig. 12. Maximum entropy power spectrum of the normal incidence radiation at air mass 2.0 at Table Mountain.

period oscillations in the pyrheliometric data. The change in radiation scale at Mt Montezuma in 1940 will also give the appearance of a long period oscillation in the power spectrum. All these extraneous influences on the radiation measurements tend to obscure any information about possible solar variations which might be contained in the pyrheliometric records.

The extraneous influences can be removed, or a period of time with no known extraneous influences can be examined, to discover if the sun shows variations in its intensity. The latter approach is adopted here. Six-month means were calculated for the period 1940 to 1950 inclusive at the two APO sites and a Fourier analysis performed. The annual cycle was evident but no long frequency power appeared. At eleven years the power was about 5 × 10^{-5} the power of the annual cycle. The eleven-year cycle in the solar constant, if it exists, then apears to have an amplitude of about 0.02% or less of the solar constant. Without further massaging of the pyrheliometric data to remove atmospheric and radiation scale changes, no information on a 22-year cycle is provided by the APO data. In short, there is no apparent evidence for a solar signal in this data set.

6. Concluding remarks

Both the pyrheliometer and pyranometer reveal the same qualitative information about when volcanic or anthropogenic aerosols were present. In the APO program they each serve to confirm the validity of measurements by the other instrument. The two instruments allow sampling and instrumental errors to be distinguished from real atmospheric variations.

Each measurement is valuable in its own way. The circumsolar sky radiation measurement is a very sensitive indicator of aerosols. For a 15–20% change in pyrheliometer values at air mass 2.0, the pyranometer readings change by a factor of 4 to 5. In effect, its sensitivity to aerosols is about 25 times that of the pyrheliometer measurements. The pyrheliometer measurements are valuable because they allow the dust veil index and stratospheric aerosol optical depth to be calculated. The care with which the APO staff and observers measured solar radiation at constant air mass values over many years is indispensable for providing a homogenous data set.

Both measurements are responding to aerosol scattering but in opposite directions. At all stations and all air mass values the two quantities are significantly negatively correlated (Table 6) as expected. The lower the pyrheliometer values the greater the aureole brightness is, generally because of increased scattering by atmospheric aerosols.

From a climatological point of view, the identification of volcanic eruptions which inject aerosols into the stratosphere is the most important contribution of the APO pyrheliometer records.

Table 6. *Correlation of monthly mean normal incidence pyrheliometer and pyranometer measurements at various air mass values m for four stations*

Station	m	N	C	ρ	S
Mt Montezuma	1.5	239	−0.8310 ± 0.0224		0.0000
Mt Montezuma	2.0	248	−0.8713 ± 0.0171		0.0000
Mt Montezuma	2.5	224	−0.8762 ± 0.0176		0.0000
Table Mountain	1.5	167	−0.5773 ± 0.0556		0.0000
Table Mountain	2.0	249	−0.6818 ± 0.0371		0.0000
Table Mountain	2.5	231	−0.6351 ± 0.0428		0.0000
Tyrone, N. Mexico	1.5	36	−0.5064 ± 0.1495		0.0016
Tyrone, N. Mexico	2.0	61	−0.6802 ± 0.0833		0.0000
Tyrone, N. Mexico	2.5	56	−0.6765 ± 0.0885		0.0000
Mt St Katherine	1.5	42	−0.7040 ± 0.1036		0.0000
Mt St Katherine	2.0	47	−0.7941 ± 0.0702		0.0000
Mt St Katherine	2.5	43	−0.7760 ± 0.0794		0.0000

N = number of observations. C = simple correlation coefficient. ρ = one standard deviation uncertainty in correlation coefficient. S = significance level of correlation using the F-ratio test.

Between the eruptions of Mt Katmai in 1912 and Agung in 1963, the three most important volcanic eruptions on a world-wide basis appear to be Puyehue in 1921, Paluweh in 1928, and Quizapu in 1932. The dust veil indices for these three eruptions are about 100, 100, and 35, respectively, and the last two apparently caused world-wide temperature anomalies. Paluweh however is not included in major lists of volcanic eruptions (e.g., Lamb, 1970). Including it in future theoretical studies of climatic change will aid in the understanding of this topic. Many details of the temperature fluctuations in the period 1923 to 1954 cannot be explained using known volcanic eruptions but may represent internal noise in the climate system such as year-to-year random variations in total cloud cover (Hoyt, 1978b) or variations in ice and snow cover (Kukla and Kukla, 1974).

7. Acknowledgement

The author wishes to thank Clara Klemcke and Robert Roosen for supplying a magnetic tape with the Smithsonian Astrophysical Observatory data on it.

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ПИРГЕЛИОМЕТРИЧЕСКИЕ И ОРЕОЛЬНЫЕ ИЗМЕРЕНИЯ ИЗЛУЧЕНИЯ НЕБА СМИТСОНОВСКОЙ АСТРОФИЗИЧЕСКОЙ ОБСЕРВАТОРИИ С 1923 ПО 1954 ГОД

Анализируются данные пиргелиометрических и ореальных измерений излучения неба Смитсоновской астрофизической обсерватории (САО) с 1923 по 1954 год. Наиболее детально анализируются данные, полученные на горе Монтезума в Чили в Южном полушарии и на Столовой горе в Калифорнии в Северном полушарии. Найдено, что вулкан Пулавех (8°19′ ю.ш., 121°42′ з.д.), извергавшийся в 1928 г., дал индекс пылевой пелены, равный 100, если использовать его определение по Лэмбу (1970). Квизапу (35°39′ ю.ш., 70°46′ з.д.), извергавшийся в 1932 г., дал индекс пылевой пелены 35. Оба этих вулкана климатологически значимы. Между апрелем 1932 г. и 1950 г. ни в одном полушарии не было заметных вулканических извержений. Местные загрязнения на обеих станциях после 1950 г. портят результаты наблюдений. Около 1940 г. на г. Монтезума произошло изменение в 0,6÷0,7% в радиационном стандарте, которое прошло незамеченным сотрудниками САО. Не найдено каких-либо изменений с периодом 11 или 22 года в пиргелиометрических данных и любые вариации в величине солнечной постоянной кажутся не более доли десятой части процента. Пиргелиометр и пиранометр обслуживают дополнительные потребности и подтверждают реальность изменений в пылевой нагрузке атмосферы.