The Atmospheric Electric Climate at Mauna Loa Observatory, Hawaii

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ABSTRACT

The final analysis is presented of a one-year measurement of the atmospheric electric elements at an isolated mountain site in Hawaii, where the environmental electrical properties are generally representative of the mid-Pacific troposphere at 3.4 km. The importance of the atmospheric electric climate as an indication of the global suspended fine-particle pollution is discussed. Data are presented showing the influence of local meteorological parameters on the electric elements in both fair and disturbed weather at Mauna Loa.

1. Introduction

Several years ago, Mauna Loa Observatory in Hawaii was chosen as the site to initiate a benchmark measurement of the atmospheric electric climate. A one-year record of all the fair-weather data was published in 1962 (Cobb and Phillips), together with details of the instrumentation, measuring procedures, etc.

Presented in this report are the results of a further analysis of that data and a discussion of the significance of the monitored atmospheric electric climate at Mauna Loa. Departures from normal of the electric elements are compared to concurrent meteorological parameters in both fair and disturbed weather.

The global concept of atmospheric electricity is that which views the earth and the ionosphere as highly conducting layers separated by an imperfectly insulating atmosphere. The basic electrical current flow within this atmospheric condenser, often called the "Wilson Circuit" (Wilson, 1920), is generally considered to be controlled and maintained by the worldwide thunderstorm activity; as many as 2300 thunderstorms (Krumm, 1962) are continuously required to maintain the fair-weather air-earth current. Although the behavior of the electric parameters in fair weather is considered as a separate aspect of atmospheric electricity, its direct relationship to the total thunderstorm activity and the action of the earth-ionosphere electric circuit, shown in Fig. 1, should be remembered.

In contrast to the short-lived wild fluctuations of the electrical parameters in or near thunderstorms, the response of these elements in fair-weather areas produces periodical variations that, ideally, are the same at all fair-weather areas of the atmosphere. Such periodicities, discussed by Israel (1965), are small in magnitude and generally emerge only when based on a long term data record gathered from locations where a representative global atmospheric sample can be obtained.

2. The fair-weather atmospheric electric climate

In the same manner that meteorological elements are used for climatic description, such parameters as potential gradient, air-earth current and conductivity, measured over a long period, can be used to describe the electrical state of the atmosphere.

The measurement of the atmospheric electric climate can serve several functions. It can lead to the standardization of the atmospheric electric station with regard to instrumentation, location of sensors, and proper air-sampling techniques. It can also lead to an evaluation of local meteorological-electrical effects where such parameters as atmospheric turbulence, local pollution, radioactive soil substances, etc., can create electrical convection currents and space charges which will affect the earth-ionosphere Ohm's law relationship. If these local effects are small, then the electrical properties of the sampled air will be responsive to worldwide fluctuations of the atmospheric electric climate.

Perhaps the most important function of an electric station such as Mauna Loa is the establishment of an atmospheric "benchmark," where the monitored electrical elements will yield data interpretable as an index of the amount of particulate matter suspended in the atmosphere. The 1960–61 benchmark measurement was made for this purpose.

3. Atmospheric electricity and suspended fine particle pollution

The correlation between the atmospheric electric climate and the suspended fine particle pollution is generally understood and has been described by Cobb and Phillips (1962). Sources of atmospheric pollution have increased greatly. The amount of suspended pollution, represented by the balance between that material continually being injected into the atmosphere, from whatever source, and that continually settling to the

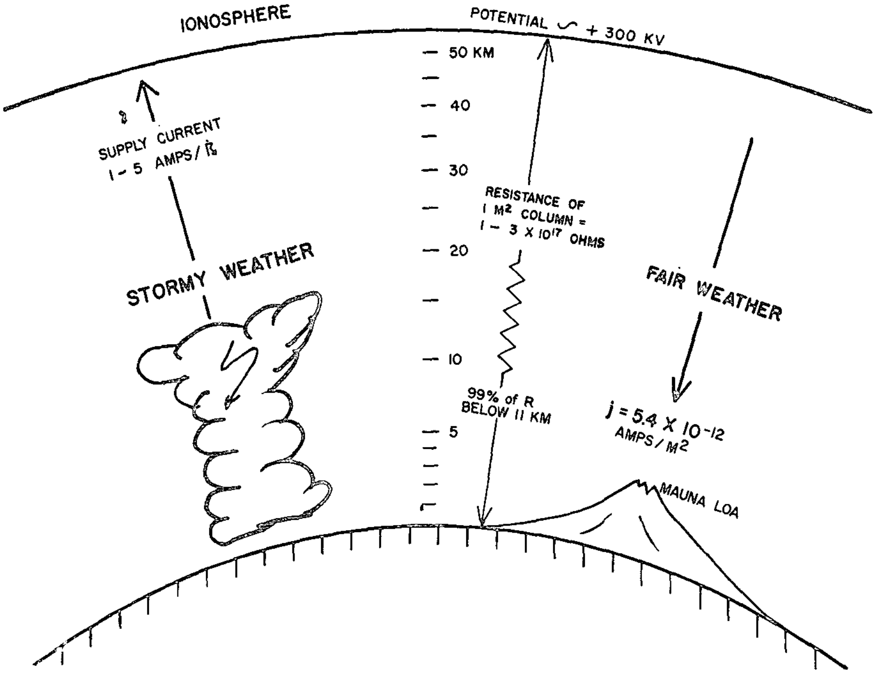

Fig. 1. The earth-ionosphere electric circuit under stormy and fair weather conditions. The circuit requires about 2000 thunderstorms to maintain the fair-weather air-earth current. The fair-weather current at Mauna Loa averaged 5.4×10^{-12} A m^{-2} and varied about 40% diurnally as shown in Fig. 4.

earth, may be increasing also. The ability of the atmosphere to cleanse itself through natural processes of aerosol removal is apparently inadequate in the face of ever-increasing sources of pollution.

Evidence of an increase in global pollution based on measurements of the electrical conductivity of the atmosphere has been rather meager. Surely, the alarming trend indicated by Wait (1946) has not been realized. More recently, Gunn (1964) reports, ". . . that there has been a measureable, but not dramatic, increase in the air pollution over the mid-Atlantic during the last 33 years." His deduction is based on measurements made in the North Atlantic during May and June of 1962 and compared with earlier and well-known measurements of the research ship *Carnegie*.

Unfortunately, several months before Gunn's measurements were made, the atmosphere was contaminated by the release of unknown amounts of radioactive debris following the resumption of atmospheric nuclear detonations. The extent to which the electrical properties of the lower atmosphere over the North Altantic were altered by the following spring is not known. Libby and Palmer (1960) have shown that radioactive debris can accumulate at high levels near the poles during the winter and descend toward the troposphere the following spring. The presence of any such debris in the sampled air would result in a temporarily increased conductivity, in which case the secular increase in atmospheric pollution indicated by Gunn for the previous 33 years would appear less than actual.

The sporadic influx of man-made radioactive debris since 1945 has made the detection of secular changes in the atmospheric electric climate much more difficult. Schilling (1964) has compiled a table of the conductivity of oceanic air, as measured by various investigators during the decade of 1952-1962, showing mean values differing by as much as 250%. Such a large variation in the conductivity of oceanic air does not appear realistic. The influence of atmospheric radioactive debris is undoubtedly a factor. Also to be considered are seasonal and latitudinal effects. In addition, much of this variation is probably due to different instrumental and atmospheric sampling techniques used by the investigators. Gunn (1964), for example, has shown that the *Carnegie* Cruise VII conductivity data (Torreson *et al.* 1946) need to be corrected upward because more than one-third of the light ions were removed from the incoming air by the air-intake system.

4. Mauna Loa Observatory as an atmospheric benchmark site

In view of the wide variability in the atmospheric electric values reported by various investigators from ocean vessels, as well as low-level land stations, it was decided that there would be considerable merit in establishing a permanent land-based station above the austausch region. Preliminary measurements were made at several sites in the continental United States, but even above 3 km in the northwest Rocky Mountains, the environment was often locally affected, particularly during the dry "forest fire" season.

For the purpose of making a "benchmark" measurement of the atmospheric electric elements, there are several advantages to a mountain top location. Primarily is the fact that the electrical properties of the atmospheric sample will be more representative of the global troposphere and less representative of the local environment below the exchange layer. On the ocean's surface, for example, visibility is generally restricted by the presence of salt particles, or what is often referred to as sea salt haze. This type of fine-particle pollution is created whenever wave and wind action is sufficient to produce sea-water droplets which evaporate leaving salt particles to be transported aloft by turbulent and thermal mixing processes. Local regions of space charge produced by the above process (Blanchard, 1966) make more difficult the detection of the universally controlled component of the atmospheric electric elements. Over the vast oceanic tradewind regions of the earth there is a persistent temperature inversion, which, for the most part, keeps the fine-particle pollution below about 2 km and provides an added advantage to a mountain station located in Hawaii. Also, with respect to the universal electric circuit, there is a great difference between the total columnar resistance from sea level to the ionosphere and from a high mountain station to the ionosphere. Cole and Pierce (1965) have calculated that 90% of the columnar resistance lies below 2.4 km. The relative ease with which current flows from mountain top to ionosphere, and vice versa, probably explains why the air-earth conduction current measured at Mauna Loa is responsive to global changes in the earth-ionosphere electric circuit.

Mauna Loa Observatory is located at an elevation of 3.4 km on the large and sparsely populated island of Hawaii. A good description of the Observatory and its suitability as an atmospheric sampling site has been published by Price and Pales (1963). Few such sites possess its qualifications: remoteness from sources of atmospheric pollution, elevation above the tradewind inversion level, year-round accessibility, and little expected change in the future. Illustrating the extreme clarity of the atmosphere above Mauna Loa is the fact that the intensity of the normal incident solar radiation sometimes exceeds 85% of the solar constant (Price and Pales, 1963).

5. Origin and diurnal variation of the atmospheric sample at Mauna Loa

Mauna Loa is a large mount-shaped mountain, and, although geographically located in the northeast tradewind zone, it generates its own local climate and circulation. The mountain is several thousand feet higher than the trade inversion, above which vegetation and rainfall decline rapidly. The local wind regime, which determines the origin of the air sample at the observatory, is largely controlled by the diurnal heating and cooling of the mountain slopes. The typical nocturnal circulation can be thought of as a large gravity-induced pump. The air near the mountain surfaces cools rapidly after sunset and drains katabatically along the slopes to the surrounding ocean. New air is drawn in from above the mountain and from upstream in the prevailing easterlies

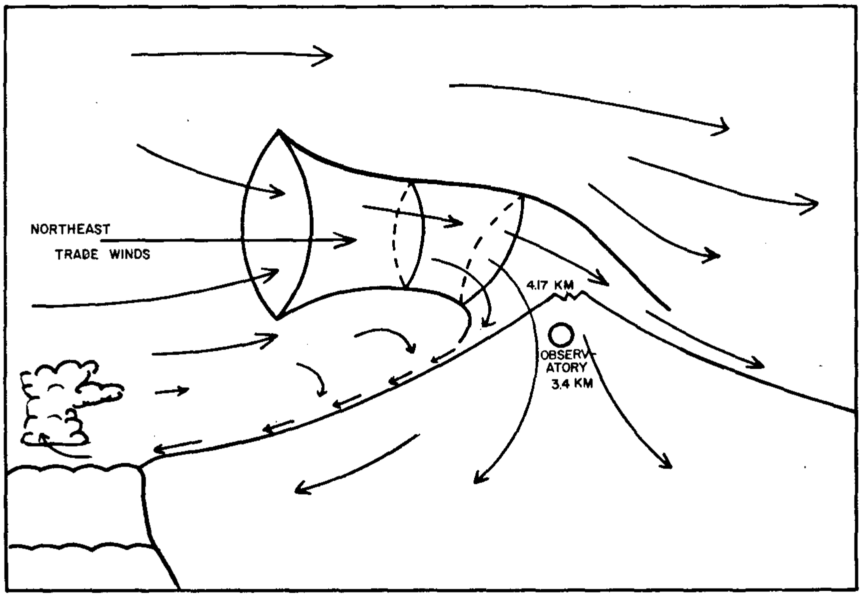

FIG. 2. The nocturnal air circulation on Mauna Loa. This circulation determines the origin of the air sample, which at night is extremely clean and dry. The electrical properties of the observatory environment at night are probably quite representative of the global troposphere above the austausch region.

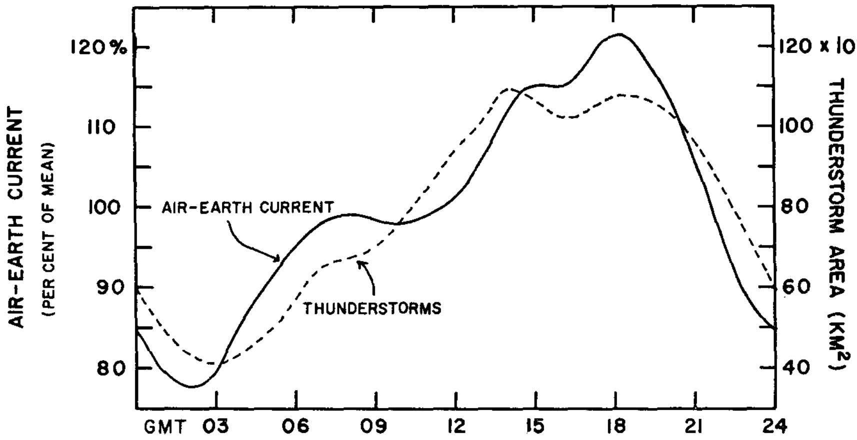

FIG. 3. Diurnal variation of the global thunderstorm area (Whipple and Scrase, 1936) and the fair-weather air-earth conduction current at Mauna Loa Observatory.

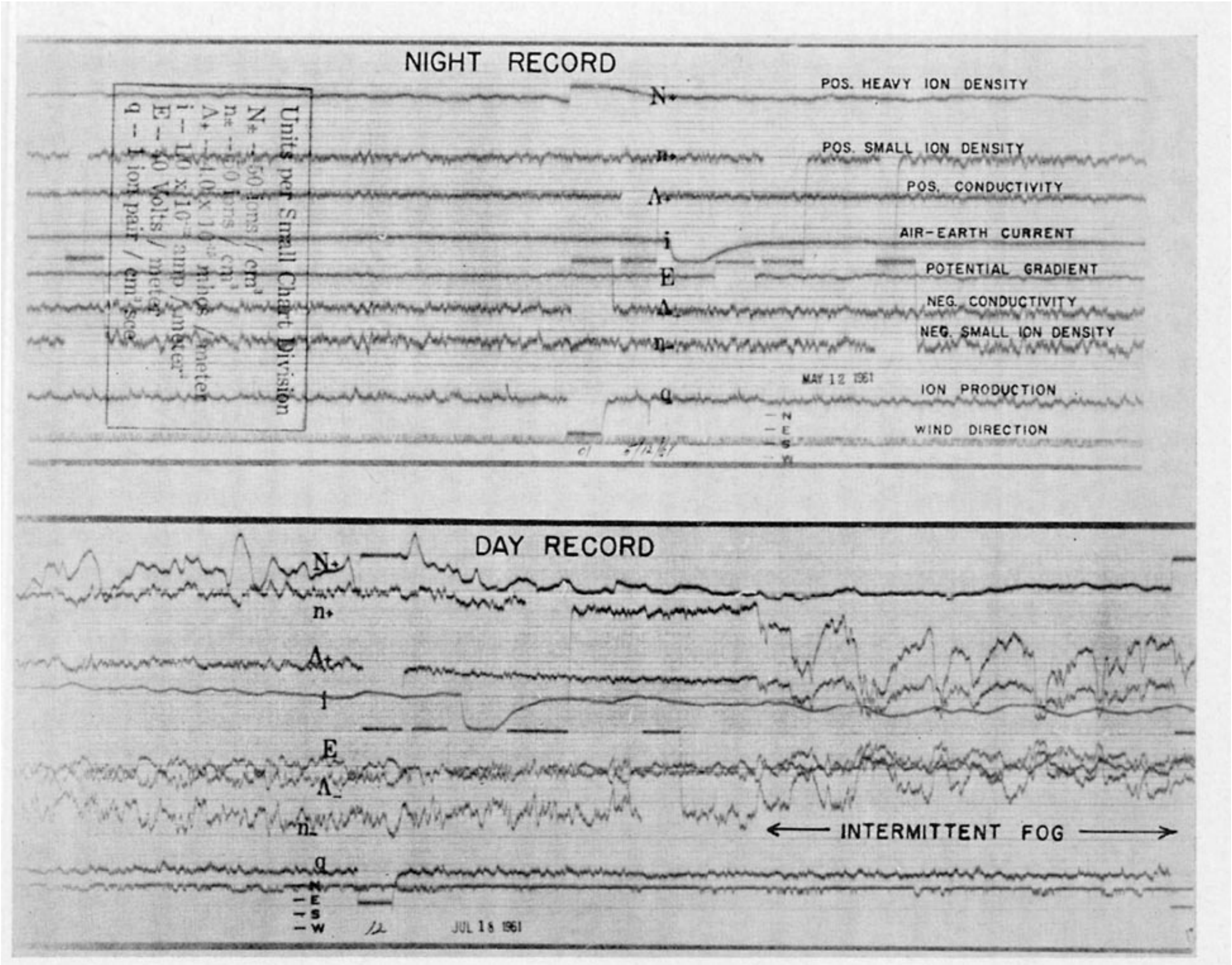

FIG. 4. Typical night and day examples of the recorded fair weather electric elements. Daytime measurements are typical of the "atmospheric electric agitation" described by Israel (1959).

as shown in the sketch (Fig. 2). This regime begins soon after sunset and continues until mid-morning, after which the wind direction at the observatory generally shifts 180° and upslope flow begins.

As might be expected, the air sampled during the downslope wind cycle is extremely clean and dry and probably quite representative of the free atmosphere over the mid-Pacific at 3–5 km. Aitken nuclei counts taken in the early morning had an average value of 200 nuclei cm^{-3} and often fell to less than 100, illustrating the very low aerosol concentration during downslope conditions.

6. Fair-weather data

Continuous measurements were made over a 1-yr period of the air-earth conduction current density, the potential gradient, and the polar conductivities, the three elements often called the Ohm's law parameters. Additionally, continuous measurements were made of the large and small polar ion densities and the small-ion production rate, thus completely describing the ionic composition of the environment.

The average fair-weather values of the electrical parameters for the year ending 1 September 1961 are shown below:

Air-earth current density	5.4×10^{-12} A m^{-2}
Potential gradient	120 V m^{-1}
Conductivity, positive	3.9×10^{-14} Ω^{-1} m^{-1}
Conductivity, negative	2.9×10^{-14} Ω^{-1} m^{-1}
Small-ion density, positive	932 ions cm^{-3}
Small-ion density, negative	676 ions cm^{-3}
Large-ion density, total	250 ions cm^{-3}
Small-ion production rate	4.9 ion pairs cm^{-3} sec^{-1}

The predominate feature of all the recorded atmospheric electric elements is a persistently repeated diurnal variation due in part to a changing daily pattern of the meteorological environment and in part to global influences.

For some parameters, ion density for example, the local influence is predominate; for others, particularly the air-earth current, the earth-ionosphere electric circuit driven by the global thunderstorm activity is the controlling influence (Fig. 3). Departures of the hourly integrated values of the electric elements during fair weather from the mean annual data are generally small, less than 20%. This is indicative of an atmospheric sample from above the exchange layer and less associated with the higher aerosol concentration and convective mixing processes occurring within the austausch region.

A typical example of the recorded electric elements is shown in Fig. 4. Notice that during the night the electric elements are very stable, appearing almost as ruled line traces. The different appearance of the daytime record is an example of "electric agitation" (Israel, 1959). This change in the character of the recorded elements, which quite obviously coincided with the onset of heating of the mountain's lava surface, does not affect the hourly integrated values of the electric elements.

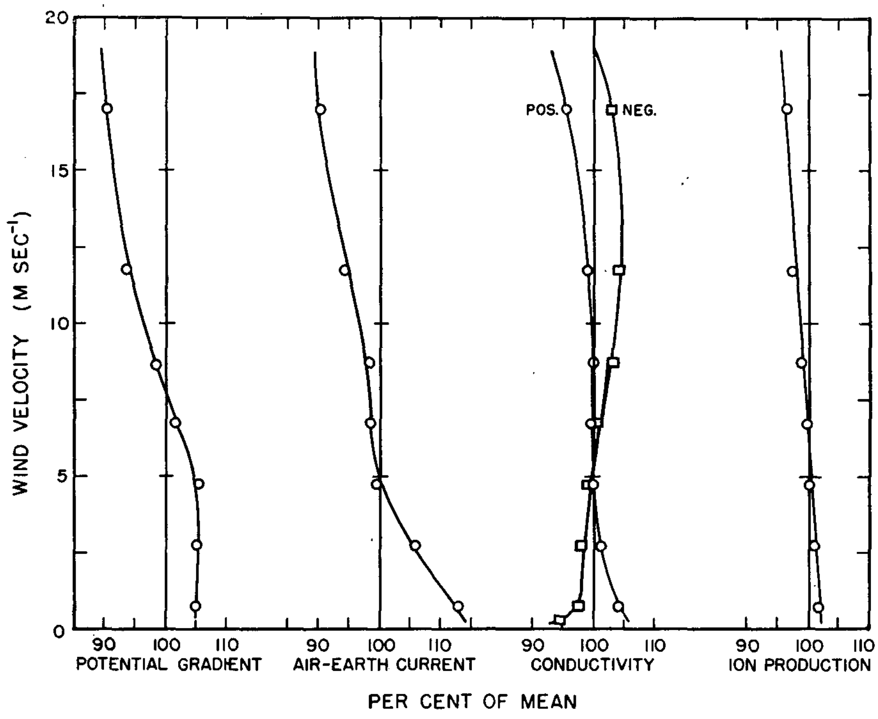

FIG. 5. Influence of the surface wind velocity at Mauna Loa on the basic atmospheric electric elements in fair weather.

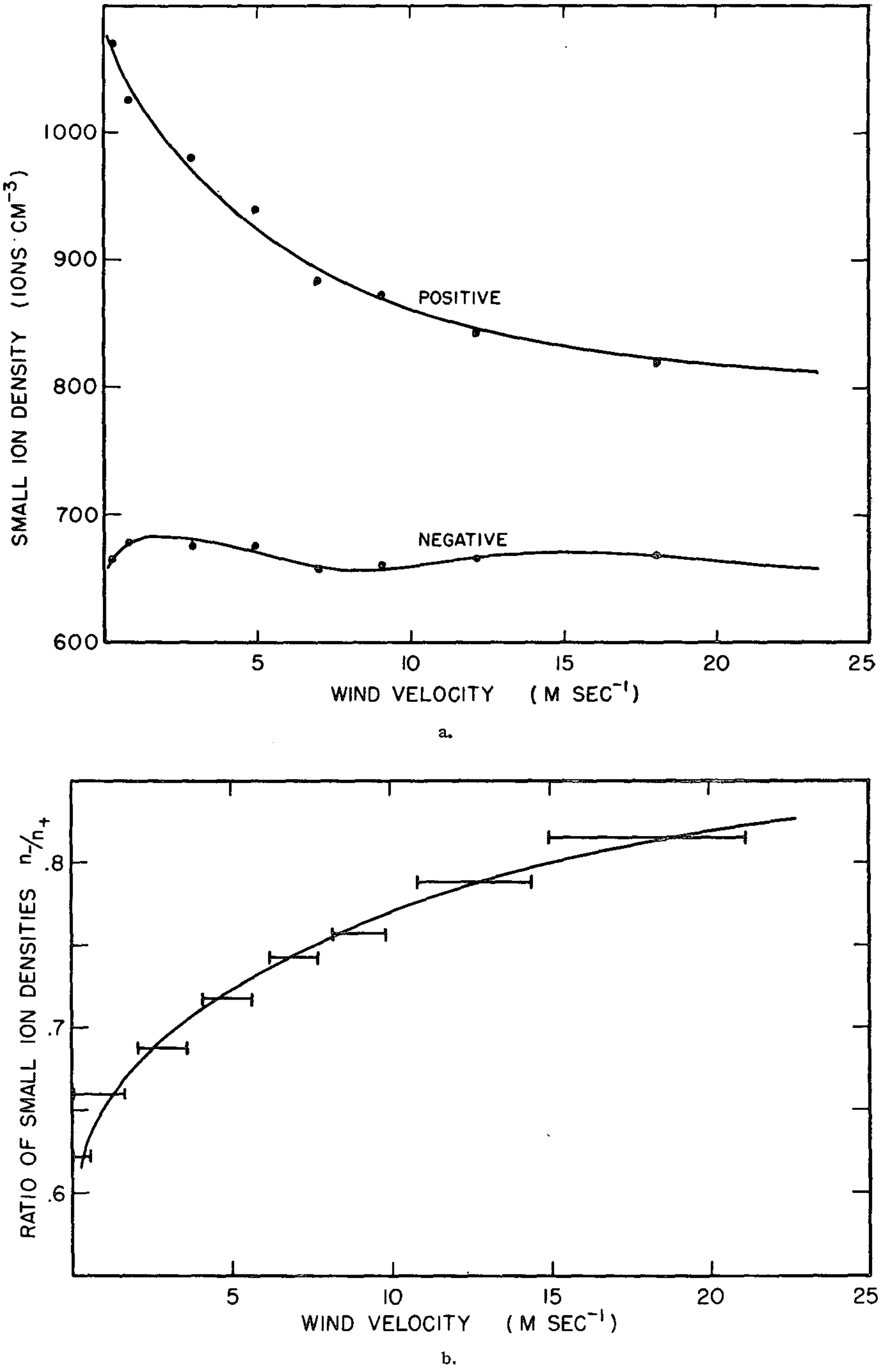

Fig. 6. Influence of the wind on the positive and negative small-ion densities, a., and on the negative to positive small-ion density ratio, b., in fair weather.

7. Correlation between meteorological and electrical parameters in fair weather

A complete meteorological record was maintained at Mauna Loa, and hourly values of wind, temperature humidity, and sky conditions were recorded along with atmospheric electric elements. It seemed most likely that wind velocity and humidity might affect the electrical parameters, and several hundred hours of fair-weather data were analyzed comparing these meteorological elements with the electrical measurements. The results are shown in Figs. 5–8.

Electrical measurements and surface wind. Fig. 5 shows the influence of the surface wind on the basic Ohm's law parameters and on the ionic production rate.

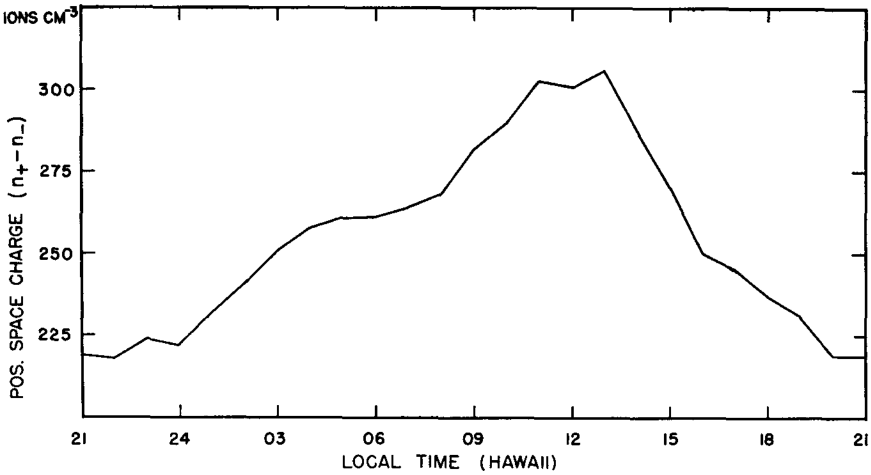

FIG. 7. Mean diurnal variation of the positive space charge ($n_+ - n_-$) at Mauna Loa. Approximately 14% of the negative ions were removed from the sampled air during the maximum intensity of the electrode effect.

In general, the electric elements behave similarly, decreasing in value with an increasing wind; the polar negative conductivity, however, is apparently affected by the depletion of negative ions in the electrode layer, especially at low wind velocities.

Ion-production rate and surface wind. The production of small ions in the atmosphere is mostly attributed to cosmic radiation. A portion of the total ion production, however, is due to local sources of radioactivity and varies with the location of the measuring site. The local component is near zero over the oceans and polar regions and may amount to 50% of the total on land areas where the earth contains significant amounts of radioactive material.

At Mauna Loa the measured ion production rate was a nearly constant 5 ion pairs cm^{-3} sec^{-1}. As shown in Fig. 5, however, there is a slight but consistent decrease in ion production with increasing wind velocity. This 7% decrease can be attributed to the dispersal of local radioactive material through a thicker atmospheric

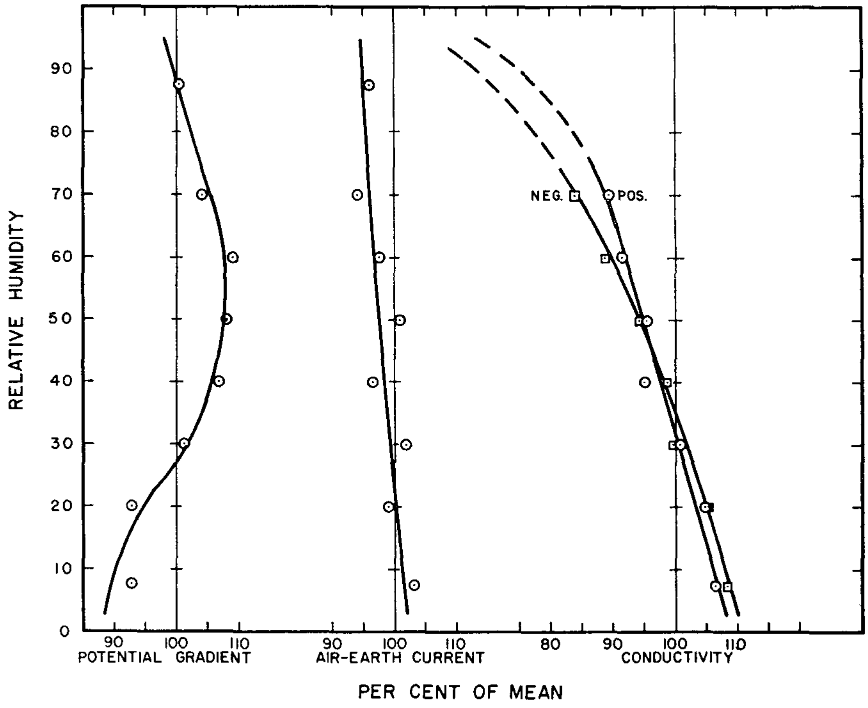

FIG. 8. Influence of the relative humidity at Mauna Loa on the Ohm's law electric variables. The air-earth conduction current is least affected.

layer by turbulent mixing processes. Thus, of the total ionization of the ambient air sampled at Mauna Loa, about 93% can be attributed to a relatively constant cosmic ray source. The remaining "local" component may vary as shown in Fig. 5. Small variations can be significant, however, since any change in the production of ions will directly affect the ion densities and the conductivity.

Surface wind velocity and the small ion densities. Figs. 6a and 6b, showing the variation of ion density with wind velocity, are based on much more data than has previously been available. Even so, it is difficult to explain the complex interactions that occur in the region of variable turbulence, eddy diffusion, and "electrode layer" effects near the earth's surface.

The oppositely charged ions are affected quite differently by the wind. As shown in Fig. 6a, there is a gradual decrease in the concentration of positive ions with increasing wind velocity. This decrease in the number of positive small ions can be attributed to an analogous increase in particulate matter airborne by the stronger winds. Any increase in particulate pollutants will provide increased surfaces for the diffusional loss of ions of both sign.

The negative ion density varies quite differently with the wind, reacting to two opposing forces. On the one hand, an increasing wind and subsequent airborne pollution will decrease the negative ion density the same as for positive ions; on the other hand, an increasing wind will, through vertical mixing, tend to destroy the electrode layer and increase the negative ion density.

As seen in Fig. 6a, the intensification of the electrode layer at near-calm conditions results directly in a more rapid decrease in negative ion density. There is a corresponding increase in the number of positive ions, since recombination losses are reduced. In other words, less negative ions are available to recombine with positive ions and the average life expectancy of the positive ions is increased. The same relationship is shown in Fig. 6b, except that the ion densities are shown as a ratio.

The electrode effect. It is surprising that the relative increase in negative ion density with wind speed (Fig. 6b) persisted even for the highest winds recorded at the observatory. Ruhnke (1962) found a similar increase in the negative conductivity with increasing wind on the Greenland ice cap. Reiter (1964), however, found nearly the opposite relationship at the Farchant station in the Bavarian Alps. Crozier (1963) reported that the electrode layer above the semi-desert of New Mexico was less than 50 cm deep at times and could be largely eliminated by winds in excess of 1 m sec^{-1}. At Mauna Loa the air sample was obtained at about 5 m above the surface, and even the strongest winds did not entirely destroy the positive space charge.

The continued increase in the ratio of negative to positive ions with increasing winds (Fig. 6b) is difficult to explain. The electrode layer space charge seemingly would be soon destroyed by winds above 5 m sec^{-1}, but perhaps the depth of the electrode space charge layer, which builds upward during low turbulence periods, becomes so deep and persistent that some influence remains even at sustained winds above 13 m sec^{-1}.

The usual nocturnal recording of the electric elements displayed a nearly constant positive conductivity and positive ion density, accompanied by a steadily decreasing negative conductivity and negative ion density. The nocturnal wind velocity at Mauna Loa is not greatly different from that in the afternoon and averages about 6 m sec^{-1}. It is the belief of this writer that the decrease in negative ions and negative conductivity at night is due to an intensification of the electrode layer. The nocturnal downslope wind at Mauna Loa is apparently not accompanied by the vertical exchange necessary to destroy the electrode layer space charge. In the afternoon, on the other hand, heating of the mountain's barren lava surface produces the thermal convection and atmospheric mixing to effectively destroy the electrode layer.

The electrode effect remains an ill-understood phenomenon, of which the intensity and even the existence are often argued. The influence of the electrode layer on the surface atmospheric electric measurements usually applies only to a specific site. Kasemir (private communication) points out that the existence of an electrode layer depends largely on the nature of the surface (porosity), radioactive content, etc., explaining, perhaps, why Chalmers (1957) finds "no simple" electrode effect, or why Mühleisen (1961) finds a strong electrode layer above the Sea of Constance.

Fair-weather measurements of small ion densities at the earth's surface generally show an excess positive ion population. At Mauna Loa there were on the average from 200–300 more positive ions cm^{-3} than negative ions. This difference represents a positive space charge and Fig. 7 shows how this space charge varied diurnally. The gradual increase in positive space charge during the night and forenoon can be associated with an intensification of the electrode effect and a corresponding decrease in atmospheric turbulence. Quite the opposite occurs during the afternoon, and the positive space charge declined rapidly during the period of maximum turbulence and vertical mixing.

The ion density at the observatory was measured at 5 m above the surface, and at this height it can be reasonably assumed that the electrode layer was largely destroyed during the afternoon. From Fig. 7, then, it can be said that during its maximum strength, the electrode effect was responsible for diminishing the negative ion density by approximately 90 ions cm^{-3}. This represents about 14% of the normal negative ion population. The electrode effect thus becomes a significant influence upon the ionic composition of the air sample at Mauna Loa.

Relative humidity and the fair-weather electric elements. Fig. 8 shows the effect of changes in the humidity on the basic electric variables. Periods of higher humidity at the observatory nearly always occur in the afternoon during upslope wind conditions when the environment contains greater numbers of cloud nuclei, large ions and aerosol particles.

The resulting decrease in the conductivity can be seen in Fig. 8 and illustrates the sensitivity of the atmospheric conductivity to the origin and nature of the air sample. The air-earth conduction current, on the other hand, is least influenced by the humidity and is probably the best indicator of the global atmospheric electric state.

Even in the afternoon, however, the environmental air sample at Mauna Loa was never greatly contaminated. The large-ion density, which is a good indicator of the local aerosol level, seldom exceeded 1000 large ions cm^{-3}. By contrast, large-ion counts in urban areas may often exceed 30,000 large ions cm^{-3}.

Fig. 9 shows the variation of the basic electrical parameters with the unipolar large-ion density. Once again, it is apparent that the air-earth current is least affected by the local environment.

8. Non fair-weather electrical measurements

The observatory was commonly engulfed in cloud during the afternoon as cumulus and stratocumulus clouds rose above the trade inversion. These periods were analyzed to establish a value of the atmospheric conductivity in fog. Data reduction was limited to periods when visibility was reduced to 0.5 mi or less by non-precipitating clouds and when the electric field remained reasonably close to fair-weather values. These restrictions insured a true conductivity measurement not affected by tribo-electrification from raindrops or from corona currents in high electric fields.

The change from fair weather to "in fog" conditions was investigated for 30 events and the mean transitional conductivity pattern is shown in Fig. 10. Beginning about 3 hr before the "in fog" conditions at the observatory, there was a very gradual decline in the conductivity of about 10% in the first 2 hr. In the third hour, the conductivity (both positive and negative) generally fluctuated greatly from nearly fair-weather to in-cloud values until there was a stable foggy environment with visibility less than 0.5 mi. The conductivity then became quite steady and, in the most dense fog, was reduced to 10% of its fair-weather value. The conductivity in the post-fog period generally rose sharply, and from 1 to 3 hrs after the fog, the conductivity exceeded its normal fair-weather value by 5–10%.

The 30 "fog cases" investigated admittedly comprise the rather particular example of mountain slope fog which generally rose from below the station. The transitional conductivity pattern, however, is quite similar to that reported by Serbu and Trent (1958) and Anderson and Trent (1966) in studies of fog forecasting from conductivity changes. The initial decrease in conductivity, perhaps the first 5%, generally occurred before an increase was noted in the relative humidity but coincidentally with an increase in the large ion

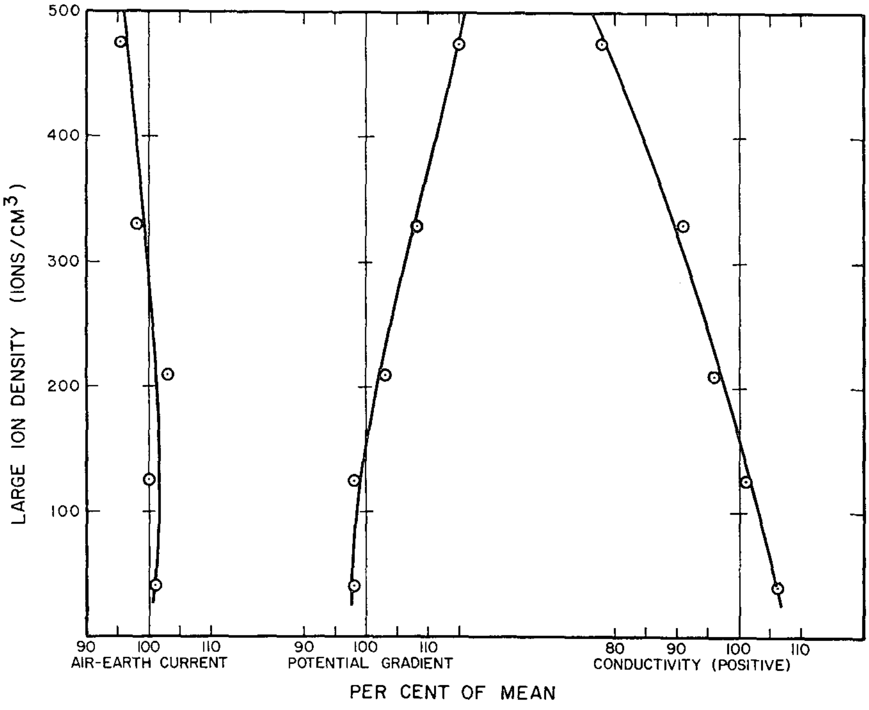

FIG. 9. Influence of the large-ion density on the electric elements. The large-ion density is a good indicator of the aerosol content of the environment. Again the air-earth current is least affected.

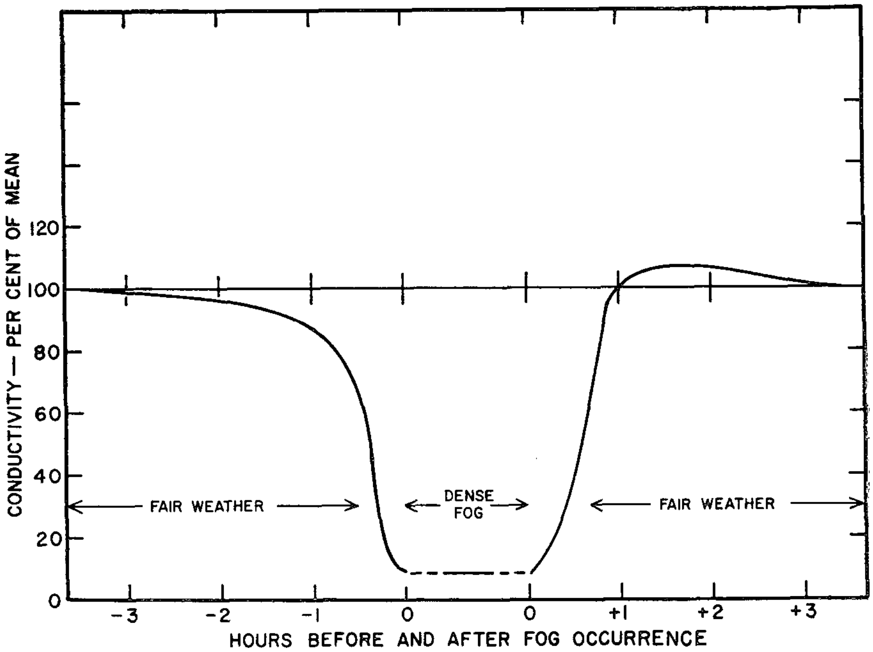

FIG. 10. Average departure from normal of the total conductivity from 3 hr before until 3 hr after the occurrence of dense fog at Mauna Loa Observatory.

concentration. Initially, then, the decreasing conductivity, before fog reached the observatory, apparently resulted from increasing aerosol pollution. In the last hour or less, the rapidly declining conductivity may be attributed to the growth of the aerosol particles once the humidity has reached 70% (Junge, 1963).

Even a slight growth is sufficient to provide an increased surface area for the diffusional loss of light ions and subsequent reduction in the conductivity. Also, the most mobile ions are more easily captured, reducing the overall mobility spectrum and further reducing the conductivity. All of the above occurs in the 3 hr or so preceding the fog (Fig. 10) even though the environment is still classified as fair weather with little or no reduction in the visibility. As soon as visible fog particles enter the air sampling system, however, the conductivity falls almost immediately. The atmospheric electric fog effect has been discussed in detail by Dolezalek (1963).

9. Summary and conclusions

The more significant results of the foregoing report are summarized by the following statements:

1) The environment at Mauna Loa Observatory is considered to be generally representative of the mid-Pacific troposphere at 3.4 km. The atmospheric sample from soon after sunset until mid-morning originates above the tradewind inversion level and in the afternoons there is generally a mixture of air from above and below the trade inversion.

2) The atmospheric electric elements are characterized by persistent diurnal variations which are repeated day after day. The chances are good that the recorded trace of any atmospheric electric element for one 24-hr period will closely follow the mean annual diurnal variation curve for that element.

3) The stability of the electric elements is illustrated by the fact that the potential gradient and the air-earth current reversed polarity for less than 16 hr during the entire year and these times occurred only during thunderstorms or convective type precipitation and never during fair weather.

4) The air-earth conduction current, detected by an automated "Wilson plate," was found to be the element most responsive to global atmospheric changes. The diurnal variation of the air-earth current exhibits a remarkably close correlation to the well known Whipple-Scrase (1936) global thunderstorm curve.

5) Most significant of the meteorological-electrical relationships is the influence of the wind velocity on the polar small-ion densities. It was found that the ratio of negative to positive ions continued to increase even for velocities in excess of 13 m sec^{-1}.

6) An electrode effect and resulting positive space charge became progressively stronger during the night and forenoon hours and at its maximum strength reduced the normal free-atmosphere negative ion density by 14%. The destruction of this electrode layer space charge during the afternoon occurred not so much as the result of an increasing wind, as from an increase in vertical exhange occurring near the mountain's heated lava surface.

7) Changes in the relative humidity and in the large-ion density were compared to the Ohm's law atmospheric electric variables in fair weather and it is significant that the air-earth current density varied no more than 5% from its mean over a wide change in relative humidity.

8) The atmospheric conductivity in dense cloud was found to be reduced by 90% from its fair-weather value.

A feature of the measurement not discussed heretofore, perhaps because it has not been explained, is the non-compliance of the measured parameters with the well known Ohm's law relationship, $i=E(\lambda_+ + \lambda_-)$, where i is the air-earth current density E the potential gradient and λ_+ and λ_- the polar conductivities. The current density was, in fact, found to be more nearly equal to the product $E\lambda_+$ with an average value 16% greater than $E\lambda_+$. This illustrates the importance of measuring all the Ohms law components or conversely the fallacy of measuring two and computing the third.

The reliability of Mauna Loa as an atmospheric benchmark site remains to be proved or disproved as future measurements are made. Presently, it appears to be a very good location for monitoring changes in the universal electric circuit and perhaps of greater importance, a site for establishing an index of the globally suspended fine-particle pollution.

This investigator and others now recognize the need to attempt standardization of the atmospheric electric measurement with regard to sensor location, sampling techniques, etc., and welcome the efforts of the Joint Committee on Atmospheric Electricity of the International Association of Meteorology and Atmospheric Physics (IAMAP) to develop an acceptable definition of what shall comprise "fair-weather" data.

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