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Atmospheric Electric Characteristics of Regions

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ABSTRACT

Measurements of both polar conductivities, the electric field, mobility, density of small ions, and other related atmospheric variables were made from an airplane between 30 m and 6 km on two different series of flights separated by six years. Twenty-two soundings made in 1955-56 show that the general electrical characteristics can be classified by geographical regions. The variation of conductivity with altitude in the Arctic is shown to agree well with theory, if the value of mobility obtained in a 1962 series is used. A comparison of the two series indicates that the conductivity above the exchange layer and the mechanism by which the atmospheric potential is maintained was nearly the same, on the average, during both series of measurements.

PROBLEM STATUS

This is an interim report; work is continuing on other phases of the problem.

AUTHORIZATION

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ATMOSPHERIC ELECTRIC CHARACTERISTICS OF REGIONS

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INTRODUCTION

The electrical characteristics of the fair-weather atmosphere are simply represented by a weakly conducting medium in which the conductivity increases almost exponentially with altitude, a vertical electric field which decreases almost exponentially with altitude from a value of about 100 v/m at the earth's surface, and the resulting current density which remains nearly constant with altitude. The flow of positive charge downward is maintained by worldwide thunderstorm activity.

To refine the understanding of the fair-weather troposphere and to study the variations in atmospheric electric parameters with time, geographical location, and altitude, a series of vertical soundings up to 6 km were made with an instrumented airplane in 1955-56. Some of these results have been presented previously by Clark (1,2) and Kraakevik (3,4). The total atmospheric potential, when corrected for diurnal variations caused by a corresponding diurnal variation in thunderstorm activity, was found to remain relatively constant from one day to the next and from one region to another, having a value of 290 kv ±10%. The conduction current density was found to be constant within 10% at all altitudes above the exchange layer and had an average value of 2.7×10^{-12} amp/m^2. The existence of a convection current which was frequently greater than the total current and in the opposite direction was observed within the exchange layer.

This series raised the question of the correct value of mobility of atmospheric ions. The observed ratio of polar conductivities (negative-to-positive) above the surface exchange layer was found to be 1.1 and could be interpreted in one of two ways. One interpretation is that the presence of water vapor and pollution reduces the mobility of both positive and negative ions, so that the mobility ratio is less than the commonly accepted laboratory value of 1.4. The other possibility is that the laboratory values of mobility are correct but that the presence of atmospheric particles reduces the number of small ions present and the conductivity is less than might otherwise be expected. Here

$$\lambda_{\pm} = n_{\pm} e k_{\pm} , \tag{1}$$

where $\lambda_{\pm}$, $n_{\pm}$, and $k_{\pm}$ are the polar conductivities, ion densities, and mobilities, respectively, and e is the electronic charge. To explain the observed conductivity ratio of 1.1 above the surface exchange layer, if the mobility ratio is 1.4, an unbalance in ion densities would be required, possibly due to the preferential diffusion of the more mobile negative ions to atmospheric particles.

Neither explanation was very satisfactory; so an investigation was initiated in 1962 to measure λ, n, and k separately at several altitudes above the exchange layer. In addition, vertical soundings of electric field, conductivity, and other atmospheric electric and meteorological variables were made to obtain the electrical characteristics of the atmosphere in the region where the ion mobility and density data were taken. The results of the mobility measurements have shown that the average mobility of positive and

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negative ions reduced to STP is 1.2×10^{-4} m^2/v-sec and that the negative-to-positive ratio is 1.1, substantially in agreement with previous conductivity data. These results are discussed in detail by Hoppel and Kraakevik (5). The results of the soundings are given in the present report.

The purpose of this report is to present: (a) the general atmospheric electric characteristics of several regions including areas over the Atlantic Ocean, the Pacific Ocean, the Arctic, and the Eastern United States, (b) a comparison of theoretical and experimental values of conductivity in the Arctic, and (c) a comparison between the results of 1955-56 and the results of 1962 over the Atlantic.

THEORETICAL CONSIDERATIONS

Let the xy plane be horizontal and the z axis vertical. The fair-weather atmospheric electric field $\bar{E}$ and the conduction current density $\bar{j}$ then lie along the z axis. The electric field is

$$E = -|\Delta V| = -\frac{\partial V}{\partial z}, \tag{2}$$

where V is the atmospheric potential. The normal fair-weather field is negative, or directed downward, but the direction of $\bar{E}$ is without ambiguity, since only fair-weather data are discussed in this report. The conduction current density at any point is

$$j = (\lambda_+ + \lambda_-)E = \lambda E, \tag{3}$$

and the space charge density is

$$\rho = \epsilon \frac{\partial E}{\partial z}, \tag{4}$$

where ϵ is the permittivity of the atmosphere. At equilibrium the total current, which is the sum of the conduction and convection currents, remains constant with altitude. Since the convection current results from mechanical transport of space charge, its contribution to the total is negligible at higher altitudes because both the net charge and vertical transport diminish above the exchange layer. The conduction current j can also be obtained from

$$j = V_t / R_t, \tag{5}$$

where V_t is the total atmospheric potential and R_t is the columnar resistance defined by

$$V_t = -\int_0^H E\,dz \tag{6}$$

and

$$R_t = \int_0^H \frac{dz}{\lambda}, \tag{7}$$

where H is the altitude of the equalizing layer above which negligible current flows. Therefore, j, V_t, and R_t are more representative of the region as a whole, whereas E, λ, and ρ are strongly dependent upon local conditions.

In the absence of pollution ion equilibrium is determined by the rate of production q and the rate of recombination,

$$q = \alpha n^2 , \tag{8}$$

where α is the recombination coefficient and n is the density of positive or negative ions, which are assumed equal. The pollution particles can be ignored only when their density is much smaller than the small ion density. This occurs well above the exchange layer generally but almost down to the surface in clean air such as exists in the Arctic. Thomson's (6) theory of volume recombination may be used to find α as a function of temperature and pressure, and since $n = \sqrt{q/\alpha}$, Eq. (1) may be used to calculate the conductivity. According to the Thomson theory (7),

$$\alpha = 1.73 \times 10^{-11} \sqrt{\left(\frac{273}{T}\right)^3 \left(\frac{1}{M_m}\right)} f(x) , \tag{9}$$

in units of m^3/sec, where T is the Kelvin temperature, M_m is the mass of the ion relative to hydrogen, and $f(x)$ is a probability function defined by

$$f(x) = 1 - \frac{4}{x^4}\left[1 - e^{-x}(x+1)\right]^2$$

in which

$$x = \frac{2d_0}{L} ,$$

where L is the mean free path and d_0 is the trapping distance. If Thomson's expression is used for the trapping distance, then

$$x = 8.1 \times 10^{-8} \left(\frac{273}{T}\right)^2 \left(\frac{P}{760}\right) \frac{1}{L_0} ,$$

L_0 being the mean free path of the ion in meters at STP and P the pressure in mm Hg. The effective ionic mean free path can be related to the mass and mobility of the ion by the solid-elastic mobility equation of Langevin,

$$k = 0.815 \times 10^{-4} \frac{e}{M} \frac{L}{C} \sqrt{1 + \frac{M}{m}} , \tag{10}$$

where k is the mobility, M is the mass of the molecule, C is the rms thermal velocity of the molecules, and m is the ionic mass. If 28.8 is taken as the average mass of molecules in air, then

$$28.8 \frac{1}{M_m} = \frac{M}{m} ,$$

and the unknown ionic mass ratio M_m and mean free path L can be determined from Eqs. (9) and (10) by using the known values of α and k at STP denoted by α_0 and k_0. For atmospheric applications it is felt that the best known value of α_0 is that given by Nolan (8) as 1.4×10^{-12} m^3/sec, where the ionization rate was maintained constant with time. The value of ionic mobility at STP, k_0, is 1.20×10^{-4} m/sec per v/m, which was the average value between 3 and 6 km determined from the mobility distribution measurements of the 1962 series (5). By using these values for α_0 and k_0, Eqs. (9) and (10) can be solved simultaneously to obtain

$$x = 4.13 \left(\frac{273}{T}\right)^2 \left(\frac{P}{760}\right) \tag{11}$$

and

$$\alpha = 1.42 \times 10^{-12} \sqrt{\left(\frac{273}{T}\right)^3} f(x). \tag{12}$$

As a by-product of this analysis the values $M_m = 148$ and $L_0 = 1.96 \times 10^{-8}$ m can be obtained; however, these values of M_m and L_0 can be grossly misleading since they depend upon the expression for the trapping distance. The mass calculated from Natanson's (9) correction to Thomson's trapping distance yields a mass about equal to the mass of the average "air molecule," and the trapping distance from the more rigorous theory of Brueckner (10) gives an unrealistically small mass.

Although it is impossible with present recombination theories to calculate the mass and mean free path of the atmospheric ion, all three theories yield Eq. (12), when M_m and L_0 are eliminated using α_0 and k_0.

The conductivity is then given by

$$\lambda = 2nek = 2ek_0 \sqrt{\left(\frac{\rho_0}{\rho}\right)\left(\frac{q_0}{\alpha}\right)},$$

where k_0 and q_0 are the values of mobility and ionization rate reduced to STP.

Using Eqs. (1), (8), and (12), the conductivity is

$$\lambda = 2.83 \times 10^{-14} \left(\frac{760}{P}\right)^{1/2} \left(\frac{T}{273}\right)^{5/4} \left(\frac{q_0}{f(x)}\right)^{1/2} \text{ ohm}^{-1}\,\text{m}^{-1} \tag{13}$$

where q_0 is determined from cosmic-ray data.

METHOD OF MEASUREMENT

In the 1955-56 series a P4Y naval aircraft was instrumented to measure and record both polar conductivities, electric field, aircraft charge, temperature, pressure, and relative humidity. The conductivity was measured with a Gerdien condenser and the electric field with induction-type field meters located on the lower fuselage and at the wing tips. The individual instruments as well as the aircraft system as a whole are described by Kraakevik and Clark (11). In this series 22 soundings were made between 15 m and 6 km over the Atlantic Ocean near Bermuda, 100 miles east of the Virginia Coast, the Gulf of Mexico, the Pacific Ocean off the California coast, and over the land areas of Greenland, Newfoundland, Maryland, and Kansas.

In the 1962 series an EC-121 aircraft was instrumented to measure the small ion-mobility spectrum, ion densities, condensation nucleus density, and dew point, in addition to the quantities measured in the previous series. In a few soundings, measurements of particle density were made with a photoelectric nucleus counter, and the meteorological variables were measured and recorded with an aerograph and automatic thermoelectric dew-point hygrometer.

Figure 1 shows a view of the EC-121 airplane. The ducts protruding from the upper radome collected the air for the conductivity, ion-density, and mobility measurements. A description of the measurement technique for these variables is given in a paper by Hoppel and Kraakevik (5).

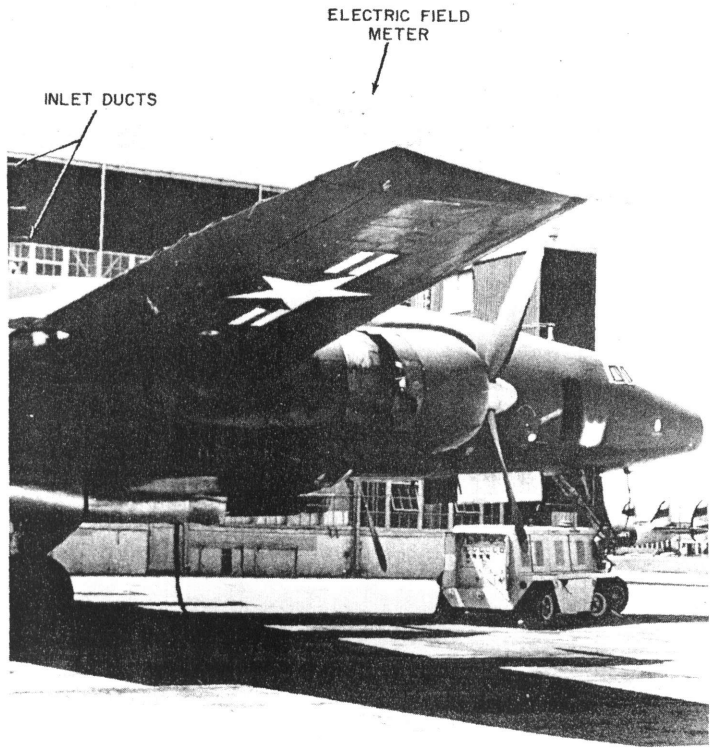

Fig. 1 - EC-121 aircraft

Electric-field meters (EFM's) were located in the top center of the radome and symmetrically at each wing tip. The field meters were calibrated with a known potential applied to a calibration plate. The outputs of the port, starboard, and top EFM's may be expressed as:

$$V_p = (p_y E_y + p_q Q)\, G_p \,, \tag{14}$$

$$V_s = (-p_y E_y + p_q Q)\, G_s \,, \tag{15}$$

and

$$V_t = (t_z E_z + t_q Q)\, G_t \,, \tag{16}$$

where E_y and E_z are the components of the undistorted external field along the port wing and the vertical axis of the aircraft, respectively; p_y and t_z are the corresponding geometric augmentation factors for the external field components; Q is the self-charge of the aircraft; p_q and t_q are the geometric augmentation factors due to self charge and include $1/(4\pi\epsilon a^2)$, a being the radius of a sphere having the same capacitance as the aircraft; and G_p, G_s, and G_t are the gains of the EFM amplifiers.

Using the same technique as Clark (1), the sum and difference of Eqs. (14) and (15) give

$$\frac{V_p + V_s}{2} = p_q Q G_p = V_Q \tag{17}$$

and

$$V_p - V_s = 2p_y E_y G_p = V_Y , \tag{18}$$

where $G_p = G_s$. By subtracting Eq. (17) from Eq. (16),

$$V_t - V_Q = G_t t_z E_z + Q(t_q G_t - p_q G_p) ,$$

which is independent of aircraft charge E_q only if

$$\frac{G_t}{G_p} = \frac{p_q}{t_q} .$$

The gains G_s and G_t were adjusted in flight so that V_Y and $V_t - V_Q$ were independent of Q. From the ratio of the gains, p_q/t_q was found to be 7.09. Thus,

$$V_t - V_Q = \left(\frac{p_q}{t_q}\right) t_z E_z G_p = V_Z . \tag{19}$$

Equations (17), (18) and (19) relate the EFM outputs to the two external field components E_y and E_z and to the aircraft charge Q. The three voltages V_Y, V_Z, and V_Q are obtained directly from the output of an analog computer and recorded in flight.

The ratio p_y/t_z was obtained from precision rolls of the aircraft through 45 degrees using Eqs. (18) and (19) and was found to be 16.8. The top augmentation factor t_z was obtained by repeated low-altitude passes over a recording ground station in southern Maryland and was evaluated as 1.93. Based upon the dispersion of the available data, the probability is 0.85 that this value of t_z is within 10% of the correct one. Thus, the geometric augmentation factors for the EC-121 aircraft were found to be: t_z = 1.93, p_y = 32.4, and p_q/t_q = 7.09.

Theoretically, the airplane may be represented approximately by a conducting prolate spheroid, where the major axis 2a is along the wings and the minor axis 2b from lower to upper radomes. Clark (1) has shown that the ratio of the corresponding self-charge augmentation factor is $p_q/t_q = a/b$. From the measured value of 7.09 for p_q/t_q the external-field augmentation factors may be calculated. This analysis gives the following values: t_z = 2.0 and p_y = 29.0. It is considered that the agreement is satisfactory in view of the rough approximation of the airplane to a spheroid.

Since t_z is much smaller than p_y, the electric field E is obtained from Eq. (19) only at the lower altitudes where the field E is large compared to residual fields of the EFM's and their changes. At higher altitudes the plane is banked a known amount (usually 30 degrees), and E is calculated from Eq. (18).

EXPERIMENTAL RESULTS

Geographical Studies

The 22 soundings made in the 1955-56 series provide data by which the general electrical characteristics of the five regions may be assessed. These results are presented in Table 1. Since soundings were made at different times, it was necessary to standardize all flights with respect to universal diurnal variations. This standardization was done by using the Carnegie surface potential results (12). The normalization with respect to the diurnal mean values is denoted in Table 1 by J_d and V_{td}. Reading down the table from the Arctic to the Eastern United States, the regions are seen to be increasingly contaminated. This contamination is indicated by an increase in the total columnar

resistance and a corresponding decrease in current density. The slight variation in conductivity at 6 km (λ_6) with geomagnetic latitude may result from the variation in ionization rate with latitude, caused by the cosmic-ray latitude effect. The regional variation in total potential V_{td} is thought to be random. The average value of V_{td} for all the flights is 290 kv ± 10%.

Table 1
Atmospheric Electric Characteristics of Regions

Region	No. of Flights	Season	Geo-magnetic Latitude (deg)	λ_6 (10^{-14} ohm-m)	R_6 (10^{-16} ohm-m^2)	R_t (10^{-16} ohm-m^2)	J_d (10^{-12} amp/m^2)	V_{td} (kv)
Arctic	6	Su	76	27.1	6.11	8.11	3.85	304
Pacific	4	Wi	41	25.5	8.93	11.13	2.55	281
Gulf of Mexico	3	Sp	36	24.6	8.90	11.10	2.41	260
Atlantic	5	Sp	45	26.0	14.03	16.03	1.63	272
Eastern U.S.	4	Sp–Su	50	26.6	20.21	22.41	1.32	302

The variation of conductivity with altitude seems to provide distributions which characterize each geographical area. These conductivities are presented in Figs. 2 through 5, where the experimental points from all flights in a given region lie in the shaded area. Figure 2 shows the conductivity distribution for six soundings over Søndre Stromfjord, Greenland and two over Newfoundland. Plotted on semilogarithmic scale, the distribution is seen to be nearly exponential, and is typical of those taken in clean air. Little variation occurs in the conductivity with time at a given altitude; indeed, the total columnar resistance on these flights varied less than 3% about the mean value of 8.11×10^{12} ohm-m^2.

Figure 3 shows the conductivity distribution off the California coast. It is characterized by unusually low values of conductivity near the earth's surface, rapidly increasing with altitude to become exponential above 1 or 2 km. The ratio of maximum (6 km) to minimum (surface) conductivity off the California coast is 34, whereas the Greenland ratio is only 6. The low value of λ near the surface is due to a rather shallow and stable exchange layer in which pollution is trapped and gives rise to the frequent smog over some coastal areas. Two soundings were made near San Diego and two near San Francisco.

Figure 4 is the composite conductivity distribution typical over the Eastern United States. The exchange layer is thick and the average conductivity within it is low. The top is seen at about 2 km.

The Atlantic distribution is similar to those distributions taken over the east coast, except the effect of the inversion is much less pronounced. The results of the five flights off the Atlantic coast in 1955-56 are shown in Fig. 5. In both Figs. 4 and 5 the increase in conductivity above the exchange layer is almost exponential as would be expected.

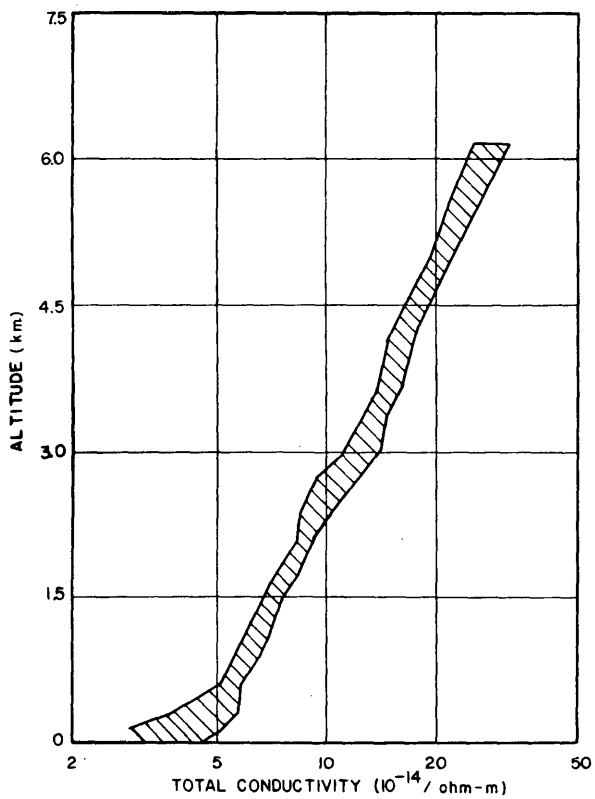

Fig. 2 - Conductivity profile above Greenland (six flights, Aug.-Sept. 1955) and Newfoundland (two flights, Oct. 1954 and May 1955)

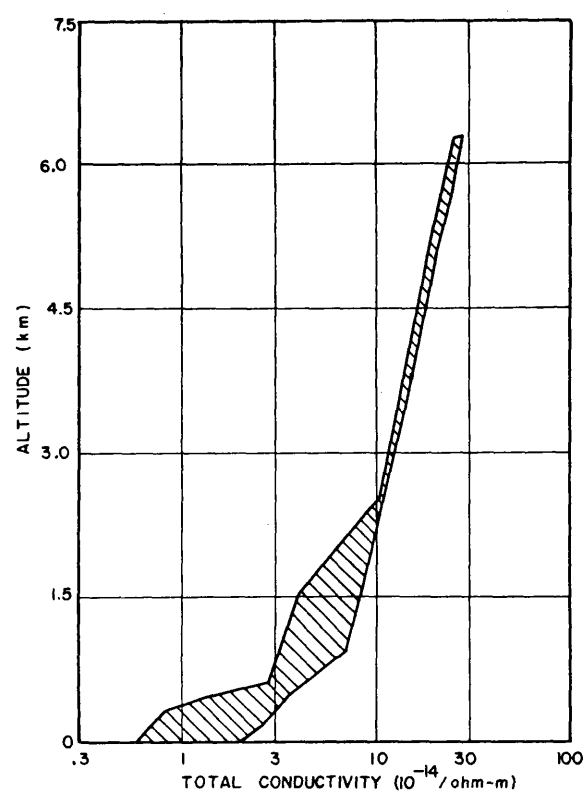

Fig. 3 - Conductivity off the California coast (four flights, Dec. 1955)

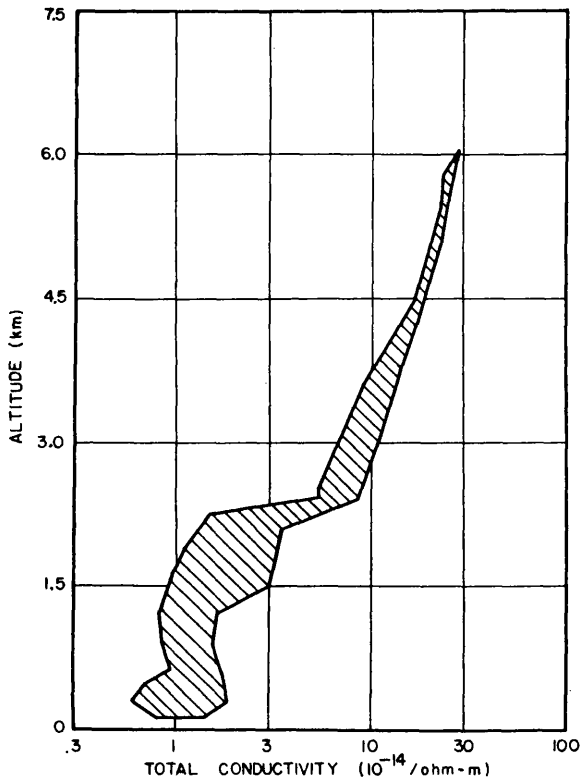

Fig. 4 - Conductivity over Eastern United States (Maryland, two flights, Aug. 1955 and May 1956; Virginia, two flights, Mar. 1955 and Mar. 1956)

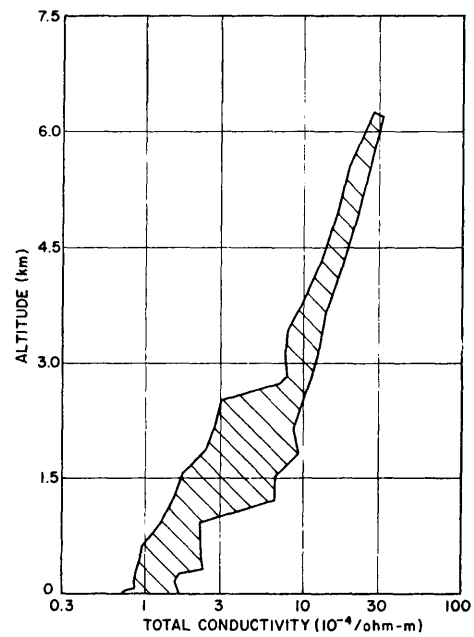

Fig. 5 - Conductivity off the Atlantic Coast (five flights, 1955-56)

Analysis of the Greenland Data

Because of its remoteness from sources of pollution, the arctic atmosphere contains a negligibly small particle density. The equilibrium ion density is therefore determined only by the rate of ion production q and the small ion-recombination coefficient α. Equation (1) is valid, and the conductivity can be calculated and compared to the value found experimentally. It is assumed that the ion production up to 6 km does not change significantly with time or position north of 50 degrees GML. The validity of this assumption is supported by the agreement of results of various investigators whose measurements were made at different latitudes above 50 degrees. The values of q used to evaluate Eq. (13) were obtained from such results.

A comparison of calculated and experimental values of conductivity is shown in Fig. 6, where the points indicate the experimental values and the solid lines the theory for the two most widely accepted values of α. The dashed curve is obtained if the previously accepted mobility of 1.6×10^{-4} m/sec per v/m and recombination coefficient of 1.6×10^{-12} m^3/sec is used. As is evident from the figure, the average mobility of 1.2 gives much better agreement between the calculated and the measured λ than the previously accepted value.

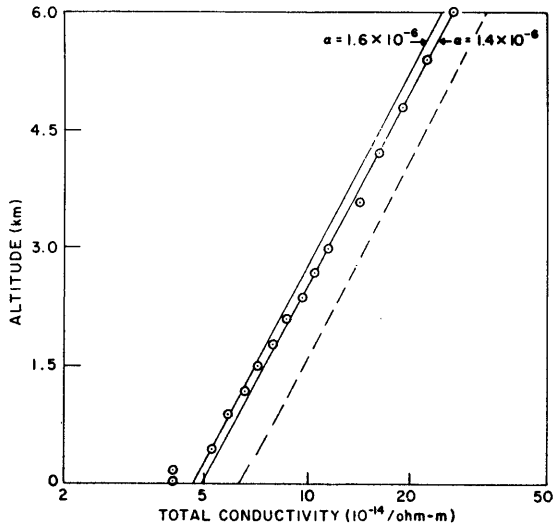

Fig. 6 - Comparison of the calculated and observed conductivity over the Arctic (Aug. and Sept. 1955). The dashed curve is obtained if the previously accepted mobility of 1.6×10^{-4} m/sec per v/m and recombination coefficient of 1.6×10^{-12} m^3/sec is used.

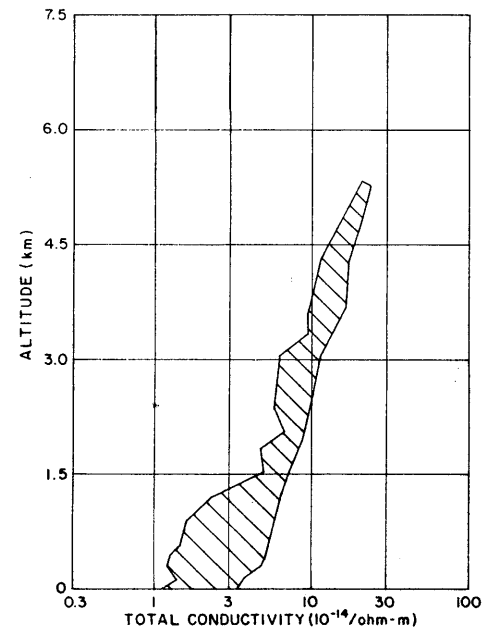

Fig. 7 - 1962 Atlantic Coast conductivity profile (four flights, Aug. 1962)

Comparison of 1955-56 and 1962 Results

Figure 7 shows the composite of the 1962 flights over the Atlantic. It is similar to those taken in 1955-56 (shown in Fig. 5) except that the exchange layer is more shallow. This can be explained in terms of seasonal variations. The 1955-56 flights were executed in the spring of 1955 and 1956, whereas the 1962 flights were made in August. Stable conditions existed during the August flights with low wind velocities up to 500 mb and a temperature inversion almost at the surface. The spring flights were characterized by higher wind velocities, more turbulent mixing, and a temperature inversion at higher altitudes.

Figure 8 shows the profile of the variables measured on August 13, 1962; N, n, and T are the condensation nucleus density, average of positive and negative ion densities, and temperature. A temperature inversion occurred at about 200 m, with a decrease of lapse rates at about 2 km. This decrease caused a large collection of condensation nuclei below the inversion and a smaller number trapped at 1.5 km. Small ions are lost by diffusion to the condensation nuclei; thus, n and λ are lower in regions of high nucleus concentration.

Table 2 gives a comparison of the averages from the two series over the Atlantic and the maximum variations encountered. The difference between the two average conductivities at 5 km, λ_5, of some 10% is well within the fluctuations in λ observed from flight to flight and is not considered significant. However, with the presence of more vertical mixing and a higher exchange layer in the spring (1955-56 series), it would be expected that more nuclei would be carried to a higher altitude; thus, the conductivity would be somewhat lower. The difference between the average columnar resistances is also explained by the deeper exchange layer in the earlier series. The current density varies inversely to R_ℓ, leaving the total potential essentially the same. Thus, there does

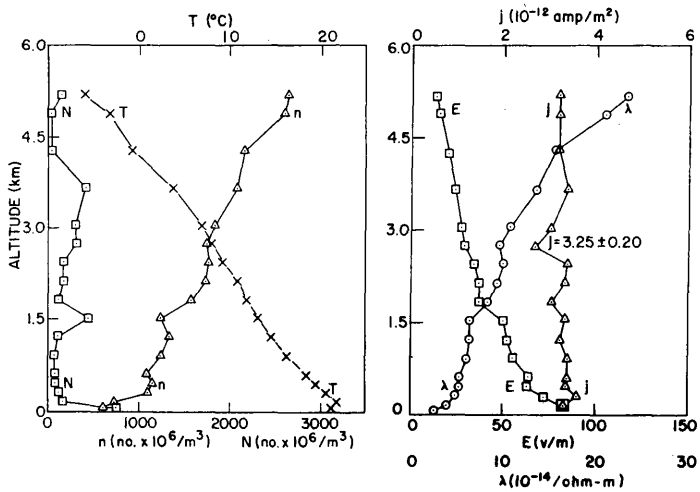

Fig. 8 - Profile of atmospheric electric variables over the Atlantic (Aug. 13, 1962)

Table 2
Comparison of 1955-56 and 1962 Results over the Atlantic Ocean

Series	No. of Flights	λ_5 (10^{-14} ohm-m)	R_t (10^{16} ohm-m^2)	J_d (10^{-12} amp/m^2)	V_t (kv)
1955-56	5	18.8 ± 2.6	16.0 ± 2.5	1.63 ± 0.47	272 ± 54
1962	4	21.0 ± 1.5	11.5 ± 3.1	2.27 ± 0.72	257 ± 59

not appear to be any significant modification in either the ion equilibrium above the exchange layer or the mechanism by which the atmospheric potential is maintained.

CONCLUSIONS

1. The conductivity profiles have a definite characteristic which depends upon the geographical location. This characteristic is modified by seasonal meteorological differences.

2. The measured conductivity in regions of clean air agrees well with theory, if the correct value of mobility is used.

3. The results of two series of flights separated by 6 years indicate that ionic equilibrium above the exchange layer and the mechanism by which the atmospheric potential is maintained was the same, on the average, during both series of measurements.

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13. ABSTRACT

Measurements of both polar conductivities, the electric field, mobility, density of small ions, and other related atmospheric variables were made from an airplane between 30 m and 6 km on two different series of flights separated by six years. Twenty-two soundings made in 1955-56 show that the general electrical characteristics can be classified by geographical regions. The variation of conductivity with altitude in the Arctic is shown to agree well with theory, if the value of mobility obtained in a 1962 series is used. A comparison of the two series indicates that the conductivity above the exchange layer and the mechanism by which the atmospheric potential is maintained was nearly the same, on the average, during both series of measurements.

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