Transactions, American Geophysical Union Volume 34, Number 4 August 1953

ON THE ELECTRICAL CONDUCTIVITY OF THE LOWER STRATOSPHERE

James E. McDonald

Abstract--The reality of the decrease of conductivity with height observed at the top of the Explorer II flight is supported by some measurements made earlier by Idrac. The cause of this decrease is discussed and an hypothesis of convective updraft of Aitken nuclei from troposphere to stratosphere is examined. The hypothesis appears incapable of accounting for a steady-state worldwide population of stratospheric nuclei sufficient to satisfy existing observations. It is urged that Idrac's measurements be repeated on a more extensive basis using more modern sounding techniques.

Introduction--One of the many results of the 1935 stratosphere balloon flight of the Explorer II was the observation of a surprising decrease of atmospheric electrical conductivity with height through the top few kilometers (19-22 km) of that flight. GISH and SHERMAN [1936] have discussed this feature of the sounding, and GISH [1939] has made some suggestions as to its possible origin; but no further attention seems to have been given this matter until HOLZER and SAXON [1952] recently examined, on theoretical grounds, the current distribution that may be expected to exist above and around an active thunderstorm. They approached this problem in an effort to check the significance of the important thunderstorm electrical measurements made by GISH and WAIT [1950].

Holzer and Saxon employed the assumption that atmospheric conductivity increases exponentially and hence monotonically with increasing height through the troposphere and stratosphere all of the way up to some conducting layer in the lower ionosphere. In making this assumption, these authors did not overlook the Gish-Sherman observations of a conductivity minimum, but they chose to omit this feature from their analysis on the basis that it is not known whether this represents a commonly occurring condition of the lower stratosphere or whether it was an anomaly peculiar to the Explorer II sounding. Holzer and Saxon point out that a shallow layer of low conductivity would not alter their principal conclusions concerning the ionospheric destination of the currents measured by GISH and WAIT [1950], but emphasize that such a layer could have a marked effect on certain other atmospheric electrical phenomena, notably the vertical-field fluctuations observable at the Earth's surface at distances of the order of many tens of kilometers from active thunderstorms.

Earlier evidence for a stratospheric conductivity decrease--The discussion by Holzer and Saxon has pointed up the uncertainty as to whether a stratum of low conductivity is a common, or indeed even a real, feature of the stratosphere and has prompted the present writer to call attention to an earlier study of the electrical state of the lower stratosphere in which there was found indirect evidence for a decrease of conductivity similar to that found in the Explorer II sounding. IDRAC [1926] made a number of balloon soundings of the vertical electric field intensity over Trappes, France, during a single day in June, 1926. Three of his releases led to soundings extending above 13 km and in these three Idrac found that the field intensity, after decreasing in the characteristic manner through the troposphere, started increasing above the tropopause. The average field strength at eight kilometers for all of his flights for that day was only 2.3 v/m, while in the region above 13 km it reached values as high as 40 v/m. Assuming a uniform vertical current density for all heights reached by Idrac's balloons, one finds that these intensity values imply a conductivity decrease by a factor of almost 20 in going from eight kilometers up to this level of maximum local field strength above 13 km. Fortunately, one of Idrac's flights extended to 20 km and revealed that the field intensity decreased again above 16 km, falling to 1.2 v/m at 19 km, thus showing that the conductivity did not remain low that day throughout the vertical extent of the stratosphere over France.

These observations by Idrac were not discussed by Gish and Sherman, with the result that there has probably been less significance attached to the Explorer II results in the 19-22 km region than might otherwise have been the case. Idrac's findings seem particularly valuable in that they refer to a region remote from that in which the Explorer II flight was made and to a time several years earlier, thus casting doubt on any supposition that the sort of low-conductivity stratum found by Gish and Sherman was an anomaly peculiar to that sounding. Furthermore, Idrac's measurements suggest that there may be only a rather thin layer of low conductivity in the stratosphere, while the Explorer II observations left this important point indeterminate. This latter contribution of Idrac's work strengthens the position taken by HOLZER and SAXON [1952] with respect to the slight importance of any regions of low conductivity in altering the upward flow of positive current from thunderstorm to ionosphere, while the former contribution (indication of worldwide extent of the low-conductivity layer) points to the need for further study of the suggestion made by Holzer and Saxon that such a layer may strongly influence surface field-strength fluctuations far from active thunderstorms and squall lines.

Possible causes of the conductivity minimum--Despite the lack of agreement between Idrac's observations and those by Gish and Sherman as to the altitude of the base of the region of low conductivity , their agreement as to the presence of such a region in the lower stratosphere would seem to justify some attempt to find an explanation for its existence. Atmospheric conductivity is almost entirely controlled by the small-ion density of the air, and this density is in turn controlled jointly by the rate of ion formation (by cosmic-ray-produced ionizations followed by molecular attachment) and by the rate of destruction (by recombination processes and by attachment to Aitken nuclei, forming relatively immobile large ions); hence one must search for some phenomenon capable of locally altering one or both of these rates in the stratum under consideration. There would appear to be no basis for believing that there might be any local decrease of cosmic-ray bombardment here, nor any local anomaly in the molecular attachment rates or in the recombinative processes for small ions, so one is led to seek an explanation for the low conductivity in terms of the effect of some local concentration of nuclei in the lower stratosphere. GISH [1939], in first discussing this type of explanation, suggested the possible role of nitrogen pentoxide which has been detected spectroscopically in the region from 16 to 40 km. GISH [1951] has also noted that ozone was found to be unusually abundant near the top of the Explorer II sounding, but he has not indicated how either of these substances might ever appear in the form of particles large enough to serve as large-ion nuclei.

Convective transport of nuclei--The writer has been led to consider quite a different hypothesis which seems, at first inspection, qualitatively more probable than those advanced by Gish. This hypothesis would account for the presence of a stratum of Aitken nuclei in the lowest portion of the stratosphere in terms of injection of nucleus-rich air into the base of the stratosphere by thunderstorm updrafts that sweep the air up through the troposphere from the lower levels of higher nuclear density and then expel this air into the stable base of the isothermal region. The nuclei so added from time to time by thunderstorms around the world would not remain forever in the lower stratosphere but would slowly leave this region by virtue of the joint action of fall-out and turbulent diffusion. The critical test of the hypothesis thus becomes that of inquiring whether the processes of addition and removal might reasonably be expected to come to balance with a steady-state nuclei count at the base of the stratosphere sufficient to explain the sort of decreased electrical conductivity found by Idrac and by Gish and Sherman.

Thunderstorm heights--First it may be noted that the heights to which thunderstorms extend are in reasonable agreement with the convective hypothesis, at least for the Idrac observations of a low-conductivity layer with its base near 13 km. The average heights of the tops of thunderstorms observed by radar during the Thunderstorm Project [BYERS and BRAHAM, 1949] was slightly over 11 km, and 40 pct of all observed storms built up to 13 km or above. It is, of course, no mere accident that the base of the stratosphere coincided closely with the maximum altitude reached by thunderstorm updrafts since the stable density distribution above the tropopause precludes appreciable growth into the stratosphere.

The location of the low-conductivity layer in the Explorer II sounding is higher than can be accounted for in terms of average thunderstorms of middle latitudes, and particularly so for the November date on which the flight was made. Examination of the temperature distribution prevailing during the flight [BROMBACHER, 1936] reveals that a double tropopause existed over South Dakota on that day. The lower inversion began at 11.5 km, and the upper at about 18.7 km. This plus the fact that the winds near the top of the flight were southwesterly suggests that the balloon may have been in air that had recently come from lower latitudes of the Pacific area where thunderstorm convection is better able to transport air to heights approaching those at which the Explorer II encountered the decrease of conductivity. However, this necessity of an appeal to a tropical origin of the nuclei over South Dakota must be regarded as a weakness of the thunderstorm hypothesis and if further measurements of stratospheric conductivity should reveal that the average level of the minimum agrees more closely with that found by Gish and Sherman than with that indicated by Idrac's work, one could not even consider the convective explanation here proposed.

Rate of convective transport of nuclei--The first step in a quantitative check of the convective hypothesis consists in estimating the average worldwide rate of thunderstorm transport of nuclei up to the base of the stratosphere. Using data on the average vertical distribution of Aitken nuclei based on 28 balloon flights in the troposphere [LANDSBERG, 1938], and combining these with some recent estimates of the vertical distribution of thunderstorm inflow rates [BRAHAM, 1952], one finds that, during the entire lifetime of an average thunderstorm cell of the middle-latitude type considered by Braham, about 3×10^{20} nuclei may be expected to enter the updraft. Of this total, almost three-fourths of the nuclei are found to enter the cell in the 0-1 km layer. At greater heights, where the mass of air entrained is larger than in the surface layer, the nuclei count has fallen off so much that the weighted average inflow of nuclei is much less than in the 0-1 km interval.

Not all of these 3×10^{20} nuclei are to be regarded as reaching the outflow region at the very top of the storm, however. A certain number will serve as condensation nuclei and will thus be largely removed by the precipitation process, but this number is so small compared to the total number of Aitken nuclei (most of which are too small to be activated for growth) that it may be ignored here. Second, relative motions of nuclei and cloud drops will remove some nuclei by accretion, but this mechanism will also be ignored here on the ground that the collection efficiency for this capture process will be very low in view of the small size of the nuclei. The third process, which cannot be ignored, is that of horizontal outflow of updraft air prior to its reaching the tropopause. Again Braham's data on mass exchange in thunderstorms provides a basis for an estimate. BRAHAM [1952] finds that of the total of 9.0×10^{10} kg of air entering an average storm throughout its duration, only 1.8 by 10^{10} kg flows out at the 200-mb level (about 12 km). Thus, one may regard only 1.8/9.0 of the total of 3×10^{20} nuclei, that is, about 7×10^{19} nuclei, as being expelled from the storm top into the lower layers of the stratosphere. It must be admitted that present ignorance of the details of the kinematics of the outflow pattern at these levels leaves doubt as to whether even this latter number of nuclei may safely be assumed to remain at the outflow level rather than to subside back into the upper troposphere, but this assumption will be made here.

Taking the average lifetime of a thunderstorm cell as about one hour [BYERS and BRAHAM, 1949], and using the estimate by GISH and WAIT [1950] of 3×10^3 storms as the average instantaneous rate of occurrence of thunderstorms over the entire globe, one finds an average rate of stratospheric addition of 6×10^{19} nuclei per second for the whole world. Overlooking the fact that this rate of transport must certainly decrease rapidly with increasing latitude to nearly zero values in both polar regions, one finds that for the entire area of the Earth, 5×10^{18} cm^2, the average rate of thunderstorm injection of nuclei into the base of the stratosphere may be of the order of ten nuclei/cm^2 sec.

Rate of fall-out of nuclei--Having estimated the rate of addition of nuclei, the next step is to estimate the rate of removal in order to compare these two rates as a test of the convective hypothesis. GISH and SHERMAN [1936] have given estimates of the density of nuclei required to account for the low conductivity in the 19-22 km interval of their Explorer II measurements, so in spite of the fact that this interval lies several kilometers above the level to which one may expect thunderstorms to penetrate in middle latitudes, and in spite of the authors' warning that not too much quantitative significance should be attached to their nuclei estimates, these values will be used here as the only available estimate of the nuclear densities in the lower stratosphere. Certain additional deductions can be made from Idrac's data, and note will be taken of these later.

Most Aitken nuclei are less than about 2×10^{-5} cm in diameter [JUNGE, 1951]; therefore, Stokes' law may be applied with reasonable accuracy. Assuming a mean density of 2 gm/cm^3 for the nuclear substances, the particles may be expected to have a maximum fall velocity of only about 10^{-3} cm/sec, that is, less than a meter per day for even the largest. The average instantaneous rate of fall-out per unit horizontal area of the stratosphere is then given by the product of this velocity and the prevailing nuclear density, which we may take as 2×10^3 nuclei/cm^3 [GISH and SHERMAN, 1936]. Thus the downward gravitational flux of nuclei is only about two nuclei/cm^{2}sec. This is almost an order of magnitude less than the estimated rate of addition of nuclei by updrafts, so if fall-out were the sole mechanism capable of removing the nuclei from the stratosphere, one could conclude that the convective hypothesis was confirmed by the above estimates; but in addition, downward turbulent diffusion must be considered.

Turbulent diffusion of nuclei--The rate of vertical turbulent diffusion of nuclei in a layer depends on the eddy diffusion coefficient D, and on the vertical density gradient of the nuclei, dn/dz. LETTAU [1951, Fig. 2] gives 10^5 cm^2/sec for the diffusion coefficient at the 15-km level, and from GISH and SHERMAN [1936, Fig. 7] one finds the density gradient in the layer of low conductivity to be about 10^{-2} nuclei/cm^4. Hence for this combination of data the turbulent flux is

$$D\,dn/dz = (10^5\ \text{cm}^2\ \text{sec}^{-1}) \times (10^{-2}\ \text{cm}^{-4}) = 10^3\ \text{cm}^{-2}\ \text{sec}^{-1}$$

downward. This rate is three orders of magnitude greater than the rate of fall-out, so it appears that one may quite safely neglect fall-out as compared with diffusion. But more pertinent to the present discussion is the fact that the estimated rate of downward diffusion of nuclei is some 100 times greater than the estimated rate of addition of nuclei by thunderstorms (10 nuclei/cm^{2}sec). One seems forced to conclude that the convective transport hypothesis is quantitatively inadequate for accounting for a uniform, worldwide stratum of high enough nuclear density to fit the Explorer II conductivity measurements.

Discussion--Having found this negative result in the effort to check the convective hypothesis, it is interesting to note that if one seeks points in the computations where some modification might be made, these appear to be almost entirely changes that only strengthen the evidence against the hypothesis.

First, the data on nuclear densities in the troposphere [LANDSBERG, 1938] were obtained from balloon flights made over well settled areas where industrial pollution tends to give counts unrepresentatively high for the world as a whole, so any revisions here would certainly lower the estimated convective transport rate.

Second, the assumption that all of the air diverging from the thunderstorms at the 200-mb level remained, along with its suspended nuclei, at the level of outflow cannot be defended too well. A thunderstorm that builds up to the tropopause probably succeeds in locally pushing up the stable overlying stratospheric air but complete intermixing of the outflow with stratospheric air, as assumed above, is a rather unlikely extreme. If any corrections could be made here, they would undoubtedly lower the effective rate of convective addition of nuclei.

Third, an attempt to incorporate Idrac's findings into the estimate of the downward diffusion of nuclei from the underside of the stratum of low conductivity yields an even higher rate of removal than was found above from the data of Gish and Sherman. Idrac reports a nearly twenty-fold increase of field strength between eight kilometers and about 14 km, which implies a roughly equal factorial decrease of conductivity in this interval. GISH and SHERMAN [1936, Fig. 4], on the other hand, found a conductivity decrease of a factor of only two in the interval from 19 to 22 km. This difference in implied nuclear gradients is thus seen to amount to about a factor of five, making it correspondingly more unlikely that thunderstorm updrafts are steadily counterbalancing downward diffusion of nuclei.

Fourth, one might choose to use the eddy diffusivity value corresponding to the interval in which the conductivity decreased in the Explorer II sounding (19-22 km)rather than to use the value for the 15-km level as was done above in an effort to simulate conditions prevailing just above the tropopause. LETTAU [1951] gives 10^3cm^2/sec for D at this level (down a hundred-fold from D at 15 km), so combining this with the previously considered value of the density gradient one obtains an estimated diffusion rate of 10 nuclei/cm^{2}sec. This is just the estimated transport rate, so this fourth revision is the first one to favor the convective hypothesis. But since this revision requires that one deal with altitudes too great to match observed thunderstorm heights for any but tropical latitudes, it provides no real support for the convective hypothesis anyway. It is, however, interesting to note that LETTAU [1951] has suggested that the very rapid decrease of D with height just above 15 km must tend to produce what he terms a "dust horizon" at this level, and cites some light-scattering observations in support of that contention. This theoretical and observational evidence for some sort of zone of accumulation just above the tropopause does give further support to the view that a layer of high nuclear density and hence low conductivity is the rule rather than the exception in the lower stratosphere, but does not clarify its ultimate origin.

In all, it would seem to have been shown here that the convective hypothesis for transport of nuclei to the stratosphere, though qualitatively quite plausible, is not quantitatively compatible with such observations of the conductivity minimum as exist at present.

Concluding remarks--That Idrac's observations of the vertical variation of the electric field intensity should constitute the only check on the decrease of conductivity with height in the lower stratosphere found in the Explorer II flight, and that even this check should have gone so long unnoticed, seems regrettable. Present-day balloon-sounding techniques should be readily capable of providing data on the behavior of the field up to almost 30 km. Hence the writer recommends that repetitions of Idrac's measurements be carried out at enough different localities and times to determine whether a layer of low conductivity is in fact always present just above the tropopause, and if so to determine at what heights it lies and whether it is uniform or patchy in nature. A series of such soundings might clarify many of the questions raised in the present examination of the convective hypothesis of the origin of such a layer. Such measurements would also shed light on the interesting suggestion [HOLZER and SAXON, 1952] that a layer of minimum conductivity could be responsible for exaggerated surface field fluctuations far from active thunderstorms.

Acknowledgments--The writer would like to express his gratitude to the Office of Naval Research for their support of the cloud physical research in the course of which this paper was written.

References

BRAHAM, R. R., The water and energy budgets of the thunderstorm and their relation to thunderstorm development, J. Met., v. 9, pp. 227-242, 1952.

BROMBACHER, W. G., Wind direction and velocity derived from the travel of the balloon "Explorer II", Nat. Geogr. Soc. Contributed Papers, Stratsphere Ser., no. 2, pp. 144-146, 1936.

BYERS, H. R., and R. R. BRAHAM, The thunderstorm, Rep. Thunderstorm Proj., U. S. Weather Bureau, Washington, D. C., 1949.

GISH, O. H., Atmospheric electricity in Terrestrial Magnetism and Electricity (J. A. Fleming, ed.), Nat. Res. Council, 1939.

GISH, O. H., Universal aspects of atmospheric electricity in Compendium of Meteorology (T. F. Malone, ed.) Amer. Met. Soc., Boston, 1951.

GISH, O. H., and K. L. SHERMAN, Electrical conductivity in the atmosphere to an altitude of 22 kilometers, Nat. Geogr. Soc. Contributed Papers, Stratosphere Ser., no. 2, pp. 94-116, 1936.

GISH, O. H., and G. R. WAIT, Thunderstorms and the Earth's general electrification, J. Geophys. Res., v. 55, pp. 473-484, 1950.

HOLZER, R. E., and D. S. SAXON, Distribution of electrical conduction currents in the vicinity of thunderstorms, J. Geophys. Res., v. 57, pp. 207-216, 1952.

IDRAC, P., Sur des enregistrements du champ électrique de l'atmosphère jusqu'à 20,000 m d'altitude, C.-R., Acad. Sci., v. 182, pp. 1634-1635, 1926.

Editorial Note: We are informed that a later and fuller report of the 1926 work is the following:

IDRAC, P., Recherches sur le champ électrique de l'atmosphère aux grande altitudes à l'observatoire de Trappes, Mémorial de l'Office National Météorologique de France, Paris, Gauthier-Villars et Cie, 1928.

JUNGE, C., Nuclei of atmospheric condensation in Compendium of Meteorology (T. F. Malone, ed.), Amer. Met. Soc., Boston, Mass., 1951.

LANDSBERG, H. Atmospheric condensation nuclei, Beitr. Geophys., (Sup.), v. 3, pp. 155-252, 1938.

LETTAU, H., Diffusion in the upper atmosphere in Compendium of Meteorology (T. F. Malone, ed.), Amer. Met. Soc., Boston, Mass., 1951.

Department of Physics,
Iowa State College,
Ames, Iowa

(Communicated manuscript reviewed October 10, 1952;
open for formal discussion until January 1, 1954.)