substance, e.g. ions, atoms, or molecules must be specified. It thus represents a fixed but imperfectly known number of elementary entities. Avogadro’s number is equal to this fixed number, whose estimated value is currently set at \((6.02252 \pm 0.00028) \times 10^{23}\) per mole (ISO 1979). The mole is not widely used in atmospheric science, possibly owing to the availability of more familiar alternatives and to confusion over its definition and over the exact meaning of the word ‘amount’. One of its main virtues lies in its relating and scaling of the world of atomic entities to the more accessible world of macroscopic amounts.

**REFERENCES**


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(Received 27 May 1981)

By J. W. TELFORD

I was quite interested in the survey of thunderstorm electrification by Latham (1981). The discussion of material published after the address was delivered was a welcome update. I agree that the material related to the negative charge accumulation between \(-10^\circ \text{C}\) and \(-20^\circ \text{C}\) and given in his Fig. 7, is very important (Krehbiel et al 1979).

I am somewhat amused, however, at the conclusion he was able to reach from these facts; that the ice-ice collision process was compatible with these data, and, that the ‘strongest reason for concluding that this convective process is unlikely to be of primary importance in thunderstorm electrification is its incompatibility with Fig. 7’, since I have reached the opposite conclusions (see Telford and Wagner 1979, and Wagner and Telford 1981).

While the discussion of the convective mechanism is somewhat vague there is a clear reference to ‘penetrative downdraughts’, and readers could well assume the author had seriously considered the problem. In Telford and Wagner (1979) it is explained why the downdraughts carrying the negative charge will tend to come into equilibrium between \(-10^\circ \text{C}\) and \(-20^\circ \text{C}\). The parcels descending from higher regions will be ice filled and so will have the advantage of the latent heat of freezing in increasing their buoyancy relative to the rising air currents, which will often contain mostly supercooled liquid water, and hence will be biased towards a greater density because in them the latent heat of freezing has not yet been released.

Thus the descending downdraughts with the negative charge will tend to accumulate at the observed level. On the other hand it is not explained how the falling negatively charged particles stop falling at the \(-10^\circ \text{C}\) level. I submit that this fact, that the negative charges do not fall lower than the \(-10^\circ \text{C}\) level, should be considered a major problem for falling particles charge generation (separation) theories.

The reference to Wormeli (1953) apparently refers to a comment in that paper (page 25) in regard to the Wilson capture process ‘... charge production would correspond to the 10ion cm\(^{-3}\) s\(^{-1}\) which normally appear in the lower atmosphere. This is equivalent to 6Ckm\(^{-3}\) h\(^{-1}\). Since, further, the process is far from being of such perfect efficiency, it is impossible therefore that of itself it can separate the observed charges during the lifetime of a typical cell’.

Now at 10km altitude we have 125 ions cm\(^{-3}\) s\(^{-1}\) (Israel, 1973). If we use 30ion-pairs cm\(^{-3}\) s\(^{-1}\), as found at 6km, as an average, and the charge on the electron is 1.6 \times 10^{-19} \text{C}, and if this charge is separated, we have a current,
\[ i = (100)^2 \times 10^{-5} \times 301.6 \times 10^{-10} = 4.810^{-9} \text{amps m}^{-2} \] per kilometer depth of cloud.

If the cloud is 5 km deep and 5 km square we have in 15 min,

\[ Q = 4.810^{-9} \times 10^5 \times 12515 \times 60 = 540 \text{C}. \]

Thus the basis for the conclusion 'it is impossible therefore', or Latham's '... the rate of ion production by cosmic rays is far too small', quite escapes me. Furthermore the reduction in efficiency argument is a tenuous one, since once a field is established corona mechanisms are available which will provide large quantities of ions.

I think readers should consider the possibility that the whole basis for the particle theories of thunderstorm electrification lies with imaginary clouds which are not turbulent, so that what seems to be obviously necessary may turn out to be impractical, and vice versa. It may be hoped that further measurements will help sort out these divergent viewpoints.

**References**


Wagner, P. B. and Telford, J. W. 1981 Cloud dynamics and an electric charge separation mechanism in convective clouds. Accepted for publication, J. Rech. Atmos., 15, No. 2, 97–123


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Reply by J. LATHAM

I am pleased to have the opportunity of responding to Dr. Telford's interesting comments—particularly since I had not read his papers when mine was written.

The charging processes described in his two papers are somewhat different—the evaporation of large and small ice particles in penetrative downdraughts (1979) and the separation of ions produced by cosmic ray activity (1981). Both are open to question and need to be examined further. In the former case the initial separation of charge has to be produced by some other mechanism, and it is not clear that undersaturations relative to ice will occur in downdraughts except at temperatures very close to 0°C. In the latter case it remains to be established whether ions can be separated with sufficient efficiency in the face of recombination and capture by cloud particles into whose vicinity they move, as a consequence of turbulent motions.

I am afraid that I cannot understand Dr. Telford's arguments leading to the conclusion that the downdraughts will come into equilibrium at temperatures between -10 and -20°C. Recent field and theoretical studies by several workers, including Telford, have demonstrated that negative buoyancy generated at cloudtop by the evaporation of hydrometeors can give rise to powerful downward motions which penetrate the clouds to a level determined by the initial conditions, the turbulent energy within the cloud, the scale of the entrainment, the liquid water content and other parameters. There is no particular reason for equilibrium to be achieved between the -10 and -20°C isotherms. Thus the findings, referred to by Telford, that in clouds of very different vertical depth, total water content, total energy and dynamics (in Florida, New Mexico and the Sea of Japan) the negative charge centre is located within the same narrow temperature band, is suggestive, in my estimation, of a strongly temperature-dependent charging process which, for reasons given in my paper, seems likely to involve ice-ice collisions.

However, one cannot rule out the possibility that the mechanism advanced by Dr. Telford is primarily responsible for charge separation in thunderstorms. His record of innovation and imaginative insight into major problems in cloud physics is such that his ideas must be carefully examined. To do this we need more detailed studies of the interlinking of the microphysical, dynamical and electrical processes occurring within thunderclouds than have been performed to date. However, in my view, the existing evidence points strongly to a precipitation-based charging mechanism in which ice plays the major role.