A MECHANISM FOR THE GENERATION OF ACOUSTIC-GRAVITY WAVES DURING THUNDERSTORM FORMATION

By A. D. PIERCE and S. C. CORONITI
AVCO Corporation, Research and Advanced Development Division, Wilmington, Massachusetts

DURING the past three decades, a number[1-7] of investigators have reported experimental evidence which would seem to indicate that thunderstorm activity may be related to ionospheric disturbances and, in particular, to sporadic *E*. Roberts *et al.* have provided more recent evidence in their data of path losses of 21·6 Mc/s radio waves transmitted from Panama and received at Stockbridge, New York[8]. They report a noontime disturbance which was detected on various days of August and September, 1964. This noontime disturbance represented a marked decrease in absorption below normal levels. Onset tended to occur between 1115 and 1215 E.S.T. The disturbance duration was about 1 h. We find this evidence particularly suggestive as the path passed over a portion of Florida especially noted for intense thunderstorm activity. One of our colleagues, W. J. Breitling, has checked on thunderstorm activity on August 19 (which was one of the two dates explicitly cited by Roberts *et al.* for which the noontime disturbance was observed) and found that a thunderstorm did exist in a region near the propagation path. Furthermore, the fact that thunderstorms tend to occur during the summer months and during the early afternoon[9] would seem to corroborate the reported times of the noontime disturbance occurrence. Although this evidence is highly circumstantial (as is also that of the previous investigators), it does tend to reinforce our belief that further investigation should be devoted to possible mechanisms by which thunderstorms can exert an influence on the ionosphere and that additional experiments should be carried out that would provide more conclusive evidence.

In this article we shall suggest a mechanism by which energy can be propagated from a thunderstorm during its early stages to the ionosphere and by which an ionospheric disturbance can be created. The mechanism involves the generation of acoustic-gravity waves by air movements in the thunderstorm and the propagation of these waves to ionospheric levels.

The belief that acoustic-gravity waves propagating upwards from the troposphere may be responsible for a number of types of ionospheric disturbances has become increasingly widespread in recent years. Hines[10] has shown that many or most of the observational data pertaining to irregularities and irregular motions in the upper atmosphere can be interpreted on the basis of atmospheric gravity waves (that is, acoustic-gravity waves) and has discussed the possibility that these waves may originate in the troposphere. Gossard[11] has investigated the propagation of these waves from the troposphere and has found that a window can exist for wave periods between 10 min and 2 h through which fairly large amounts of energy can sometimes flow out of the troposphere. Although Gossard discussed several mechanisms by which such waves could be generated, he did not suggest any mechanism by which a thunderstorm could generate acoustic-gravity waves.

In describing our suggested mechanism, it is convenient first to review certain known features of thunderstorm formation. During the initial stage of the thunderstorm cell[9] (that is, the cumulus stage) an updraught extends throughout most of the cell. These updraughts are generally of the order of 10 ft./sec, but may locally (particularly at times early in the mature stage) exceed 100 ft./sec. The driving force for the updraught would seem to be an instability of the lower atmosphere. If this instability occurs in a region near the ground where locally the potential temperature decreases with height, then the air in the lower layer rises, causing the updraft, until a level is reached where the potential temperature (which will not change in an adiabatic expansion) is equal to that of the ambient air at the same altitude. The cooling of the air as it rises may cause condensation of water vapour and this condensation gives up energy to the air which in turn tends to increase the potential temperature and cause the driving force of the updraught to be more intense. The equilibrium height of the unstable air then increases due to the fact that the potential temperature in a stable atmosphere increases with height.

As the unstable air rises to its equilibrium height, it will overshoot this and then be pulled back. The net result will be an oscillation of the air at an altitude approximately the same as that of the cloud tops. The period of the oscillation should be about the same as the local Brunt period[12] (that is, that predicted for free vertical oscillations of the atmosphere).

Such an oscillation has been observed by C. E. Anderson[13], who gives an example of a curve of the vertical velocity of a cumulus cloud top versus time derived from measurements on photographs of developing clouds. The particular example given by Anderson shows an oscillation with a velocity amplitude of 330 ft./min and a period of 11·8 min superimposed on a steady rise of the air. Anderson's measurements are particularly suggestive as an 11·8-min period is of the correct order of magnitude for Brunt's period in any realistic atmosphere at an altitude below the tropopause.

The total energy associated with the oscillation observed by Anderson can be readily estimated. Taking $\frac{1}{2}\rho_0 V^2$ as the order of magnitude of the energy per unit volume, where ρ_0 is the ambient density and V is the peak oscillation velocity, we find the energy per unit volume to be of the order of 1 erg/cm^3. (The value of ρ_0 used in this estimate was 5×10^{-4} g/cm^3.) If we next assume the oscillation to extend over an area roughly 10 km by 10 km and over a height interval of 3 km, we can estimate the total energy of the oscillation to be 3×10^{17} ergs. Even if this estimate were too large by a factor of 10^3, an energy of 10^{14} ergs would still be considerable.

Because viscosity has negligible effect on oscillations of such a long period, the principal mechanism for the dissipation of this energy should be in its transport by wave motion (that is, by acoustic-gravity waves). These waves should have a period roughly equal to the local value of the Brunt period at source altitude.

The attainment of realistic estimates of the amplitudes of the resulting disturbance at distances removed from the source altitude is difficult because of the complicated manner in which atmosphere temperature gradients affect the propagation. Although we are at present considering this problem, some very rough estimates can be made which indicate that the effects on the ionosphere may be considerable. To make these estimates we consider the oscillation of the air at cloud top heights as producing waves which propagate according to the laws of ordinary acoustics. In the example reported by Anderson, the fluctuations in pressure at cloud top heights would be estimated as being of the order of 7 per cent ambient. If we ignore gravitational dispersion, reflexions, refraction, etc., the ratio of the fluctuations in pressure to the ambient pressure of a travelling wave will vary inversely to the square root of the ambient pressure. Thus the ratio should increase by roughly a factor of ten as the wave travels upwards by 40 km. Even at ground level, the oscillation should be significant, as an oscillation of much less than 0·1 per cent can be detected by microbarographs. (However, the wave oscillations at ground-level may be obscured by the pressure fluctuations due to turbulence created by the thunderstorm formation.)

If these simple estimates were valid, then the wave would be a shock by the time it reached the ionosphere. We do not expect this to be the actual case for reasons which will be discussed later. However, even a pressure fluctuation of 1 per cent ambient at ionospheric levels would have a significant effect on radio wave propagation as the relative fluctuations in electron density will tend to equal those of the pressure—especially in the lower ionosphere where the collision frequency is much greater than the wave frequency.

A more careful analysis of this mechanism will have to take into account the propagation characteristics of acoustic-gravity waves—which are considerably different from those of ordinary acoustic waves. It is possible that considerable reflexion can occur at intermediate altitudes. This reflexion is particularly large at wave periods close to the local value of the Brunt period. Because the wave period at the source altitude is virtually identical to the local Brunt period, the reflexion process will be particularly strong there. However, because at frequencies near the Brunt frequency propagation is more favourable in the direction of increasing Brunt frequency and as, near tropopause altitudes, the Brunt frequency is increasing with height, the propagation should be predominantly upward. The group velocity of the wave near the source altitude may be expected to be very small and also to be nearly horizontal. Considerable geometrical spreading should be expected at ionospheric heights which would tend to reduce the magnitude of the effect from that expected for a wave propagating vertically upwards. It is possible also that some ducting may occur at intermediate altitudes. All these considerations make it difficult to say with any certainty that the mechanism we suggest will cause appreciable ionospheric perturbations. Nevertheless, it does show considerable promise and merits further investigation.

We thank Dr. R. M. Cunningham of AFCRL for several helpful discussions in relation to this problem.

[1] Watson Watt, R. A., *Proc. Roy. Soc.*, A, **141**, 715 (1933).

[2] Mitra, S. K., *Nature*, **137**, 503 (1936).

[3] Mitra, S. K., and Kundu, M. R., *Nature*, **174**, 789 (1954).

[4] Rastogi, R. G., *Indian J. Met. Geophys.*, **8**, 43 (1957).

[5] Rastogi, R. G., *J. Atmos. Terrest. Phys.*, **24**, 533 (1962).

[6] Venkateswaru, P., and Satyanarayana, R., *J. Sci. Indust. Res. (India)*, **20**, B, 8 (1961).

[7] Kesara Murthy, M. J., *Curr. Sci. (Bangalore)*, **32**, 206 (1963).

[8] General Electric Co., *Dispersive Characteristics of the Ionosphere, Tech. Doc. Rept. No. RADC-TDR-64-, Interim Report*, No. 3 (November 30, 1964).

[9] Byers, H. R., *The Thunderstorm* (U.S. Dept. of Commerce, Washington, D.C., June 1949).

[10] Hines, C. O., *Canad. J. Phys.*, **38**, 1441 (1960).

[11] Gossard, E. E., *J. Geophys. Res.*, **67**, 745 (1962).

[12] Brunt, D., *Quart. J. Roy. Met. Soc.*, **53**, 30 (1927).

[13] Anderson, C. E., *Cumulus Dynamics*, 57 (Pergamon Press, New York, 1960).

REMOVAL OF MAGNESIUM FROM UNDERGROUND WATERS USING LIME

By Dr. R. J. W. McLAUGHLIN
Department of Geology
AND
Dr. W. T. AGAR
Department of Physiology, University of Melbourne, Australia

THE problem of the production of sufficient fresh water for the needs of mankind is one which has steadily become more pressing, and considerable effort is now expended in research aimed at desalination. In Australia, generally acknowledged as the driest continental land-mass, this difficulty has always been acute, especially for the watering of domestic animals, and much marginal land is always in a state of hazard. The position is sometimes so critical that large areas may be dependent on waters whose concentration of salts lies close to the toxic level, and certainly well in excess of tolerated maxima of city supplies anywhere in the world. It is hardly surprising that authorities have hesitated to give decisions on maximum tolerable levels, but it is interesting to note that the better-watered areas have much lower 'suggested tolerable levels' than the semi-arid regions[1]. Such waters, in the dry regions, nearly always have their source in underground aquifers. These waters contain variable quantities of soluble salts, depending on the nature of the aquifer, and the rate of fill and movement in this porous layer. The most common ions in solution are sodium and chloride, but there are others also. One of these, magnesium, is especially harmful to animals. For this reason it is unfortunate that many hydrological authorities report their chemical analyses merely as chloride. From this they calculate the percentage of sodium chloride present, assuming quite arbitrarily that all the chloride is balanced by sodium. Using this type of calculation, many waters which appear safe are in fact highly dangerous to stock, especially to young animals.

It is surprising that so little attention appears to have been given to the magnesium content of underground waters. We have on several occasions found underground waters, from bores in Western Victoria, Australia, which have contents of from 400 to 1,000 parts per million magnesium after a long period of dry weather. This is within the range toxic for farm animals on dry summer pastures[2,3] and harmful effects were noted in stock drinking these waters, cattle and young sheep being more susceptible than older sheep.

A high concentration of magnesium in drinking-water may have a deleterious effect on animals in a number of ways. Initially, the presence of magnesium salts in water may make the animal disinclined to drink. Peirce[3] found that sheep suddenly presented with water of high salinity showed loss of weight and a marked decrease in food intake, whereas, if the salinity was increased gradually over 3 to 6 weeks, the same levels of salinity could be tolerated without nutritional disturbance. Field observations in Western Victoria confirm that animals moved to waters containing a high concentration of magnesium show at first a marked disinclination to drink.