the era of molecular biology — that the proper interpretation of cellular function benefits greatly by placing them within a whole-animal context and this applies especially to cellular functions involved in whole-animal physiology. By not enquiring of the role of adrenergic responses *in vivo*, an important and unexpected aspect of cellular pH regulation would not have been discovered. Yet again

HCO₃ has confused researchers, thereby emphasizing Thomas's advice in his recent News and Views article⁹ that "he who works in HCO₃-free media risks studying cellular pathology rather than physiology". □

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THUNDERSTORMS

Electrification of anvil clouds

Anthony Illingworth

In a thunderstorm, the heaviest precipitation and most of the lightning are found in the main convective core. When the vigorous updraught reaches the stable stratosphere it spreads out horizontally forming a characteristic flat-topped anvil-shaped cloud which can extend downwind for tens or hundreds of kilometres. Recent balloon measurements by T. C. Marshall *et al.* (*J. geophys. Res.* **94**, 2171–2181; 1989) and G. J. Byrne *et al.* (*J. geophys. Res.* **94**, 6297–6307; 1989) reveal that these anvil clouds also contain large amounts of charge and extensive regions of high field.

For the main convective core of a thunderstorm, where the radar reflectivity is a maximum, the electrical structure is well established. It consists of a vertical dipole with a positive charge several kilometres above a lower negative charge (Fig. 1). An intracloud lightning flash neutralizes about 20 coulombs (C) of the charge in the dipole; a flash to ground brings some of the lower negative charge down to Earth. It is believed that the active charge separation occurs in the main updraught: small ice crystals are swept upwards by the rising air and are charged positively as a result of rebounding collisions with larger hail pellets. Because of their different terminal velocities the positively charged ice crystals accumulate towards the top of the cloud, while the negatively charged precipitation falls to lower altitudes.

The active core of a thunderstorm is a highly turbulent region with hail and frequent lightning, posing an obvious

threat to aircraft. In contrast, conditions within the anvil cloud are much more placid: small ice crystals are found and turbulence levels are low. It had long been suspected that some crystals, charged by collisions in the main updraught, would end up in the anvil, but the new *in situ* measurements reveal that enormous

50 km from the core. The charge layer was 1–2 km thick so that each square kilometre of cloud contained about 1 C.

All the balloon flights found direct evidence of a screening layer of negative charge at the cloud boundary both above and below the positive charge in the anvil. This screening layer has a similar charge density to the inner positive charge layer and forms when negative ions in the clear air are driven into the cloud by the field, but very rapidly attach themselves to cloud particles and lose their mobility. In one case, the authors could estimate the optical visibility at the cloud edge (450 m) and the screening layer thickness (1,100 m), confirming theoretical predictions that the screening layer at the conductivity gradient of the highly insulating air and the clear air should have a thickness about 2.5 times the optical visibility.

During the past few years, systems for detecting and locating cloud-to-ground lightning have been installed in several countries. Most such flashes bring down

IMAGE UNAVAILABLE FOR COPYRIGHT REASONS

FIG. 2 A lightning flash running along the underside of an anvil cloud as recorded by Marshall *et al.* (Courtesy of David Rust, National Severe Storms Laboratory, Oklahoma.)

amounts of positive charge, perhaps several hundred coulombs, are stored in anvil regions, and over large regions the electric fields are over 50 kV m⁻¹.

Two different types of field-measuring apparatus were mounted on the balloons in the new studies. Byrne *et al.* measured the corona current flowing through a conducting-wire probe exposed to the field. Marshall *et al.* devised an ingenious arrangement involving a set of rotating dumb-bells; the charge flowing from one sphere of the dumb bell to the other providing a measure of the field in the cloud. The vertical field profiles observed by the balloons had a similar structure, indicating an extensive horizontal layer of positive charge in the anvil cloud. The inferred charge densities of about 1 C km⁻³ are of similar magnitude to the value in the main convective core, and persisted up to

negative charge to ground, but occasional flashes bringing positive charge from the anvil down to ground are observed. These flashes are amongst the most dangerous, having the highest currents, and extending horizontally for many kilometres. Lightning flashes in anvils are relatively infrequent, and they are especially unexpected, because they tend to occur during the dissipative stage of the storm (Fig. 2). A much higher percentage of positive ground flashes is observed in thunderstorms during the winter but the reason for this is not clear. It may be that in the mobile winter airstreams there is more windshear and the anvil is separated more efficiently from the core of the storm. □

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FIG. 1 Charge distribution in a thunderstorm deduced from balloon measurements, showing the electrical dipole forming in the main updraught and positive charge accumulation in the anvil. A negative screening layer forms at the top and bottom of the anvil cloud.