Cloud physics

Growth of large hailstones

Anthony Illingworth

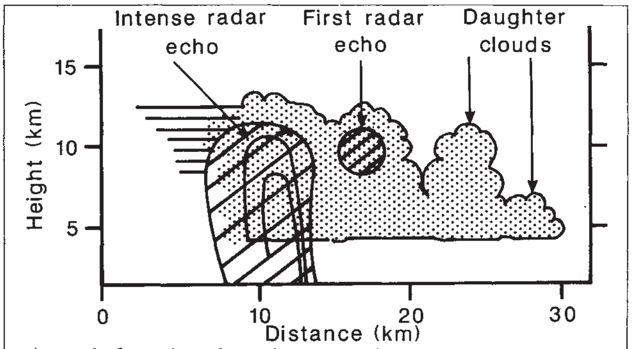
HAIL causes considerable damage to agriculture: for example, in France losses are estimated at £100 million per annum and in Italy the damage in the Po valley alone is even greater. Although hail storms originate in cumulonimbus clouds, not all large thunderstorms produce hail, and a cloud has to perform a delicate balancing act if it is to grow hailstones more than 1 centimetre in size. Many people have been tempted to try to upset this balance and suppress the hail by firing cannon or rockets into the clouds. But our knowledge of hail growth is incomplete and because we cannot precisely predict what would have happened to the storm without any interference, these hail-control techniques are untested. L. Cheng and D.C. Rogers (*J. atmos. Sci.* **45,** 3533–3545; 1988) report observations of radar data, time-resolved surface collections of hail and cloud photographs of a storm in Alberta, Canada, which confirm earlier suggestions that the growth of large hail is a two-stage process.

The main problem is to explain how the embryo of a hailstone can be confined in a region dense with liquid cloud droplets for sufficient time to grow to a hailstone. A falling hailstone grows by sweeping out these droplets which freeze as soon as they hit the hailstone. The maximum amount of cloud water produced by cooling and condensation of moist, warm surface air as it is lifted to −20 °C is about 4 g m^{-3}, and a hailstone needs to spend about 20 min in such a cloud if it is to grow to 1–2 cm in size.

Such hailstones have a terminal velocity of about 20 m s^{-1} or so, but updraught velocities of this magnitude occur in thunderstorms, and so the final stage of growth to the larger size can occur as the hailstone is balanced against the updraught within the cloud and then descends to the ground. The difficulty arises in the early stages of growth. It takes several minutes to achieve a size of a few millimetres, and during this time the embryonic hailstone will have a low terminal velocity, and if it finds itself in a 20-m s^{-1} updraught, it will pass straight through the cloud.

In Alberta, three vehicles chased the storm and collected hailstones underneath the regions of high radar reflectivity. At any one place the large fall lasted only a few minutes. The maxima in the radar reflectivity of the cloud could be traced backwards in time for 20 minutes to the new growth regions of the storm 30 km away from the main hail-producing updraught. Airborne photography confirms the existence of a series of these small but rapidly growing cumulus clouds, called daughter or feeder clouds, in the form of a staircase (see figure).

The picture emerges, then, of hail embryos which can be in the form of raindrops or small ice pellets, growing to about 5 mm while suspended in the weak updraughts of the growing daughter cells. The daughter cell then grows to become the principal updraught, or merges with the main storm, and the final growth stage occurs in a region of much higher vertical air velocity.



A vertical section through a typical hailstorm showing the daughter clouds on the storm's right flank. Stippled shading represents cloud, hatching the highest radar reflectivity. (After Dennis, A.S. *et al. J. appl. Met.* 9, 127–135; 1970.)

Problems do remain. First, why does the succession of daughter cells form with a separation of about 3 km? Cheng and Rogers note that the line of daughter cells was oriented along a line approximately parallel to the environmental wind shear, consistent with the resonance-mode theory of shear-induced instability proposed by D.P. Lalas and F. Einaudi (*J. atmos. Sci.* **33,** 1248–1259; 1976).

Second, why are so few embryos introduced into the main updraught? The concentration of raindrops in mature clouds is several thousand per cubic metre, and if they all found their way into the main updraught they would collect cloud droplets so quickly that the supply of cloud water in the updraught would soon be exhausted. Instead of a few large hailstones, many more smaller hail pellets would be produced.

My recent polarization radar measurements of developing cumulus clouds (*Nature* **336,** 754–756; 1988) suggest that the first detectable radar echo consists of just a few large raindrops in concentrations of less than one per cubic metre. If this is so, then these raindrops would form natural embryos for large hailstones without invoking any elaborate mechanism for size sorting. But we still cannot predict whether any attempt to introduce artificial nuclei such as silver iodide into daughter cells would enhance or diminish the hail risk, or whether such efforts at modification are futile. ☐

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Oceanography

Are rising and falling particles microbial elevators?

J.R. Toggweiler

A CASUAL survey of sediments from the deep-sea floor reveals that most of the sedimentary material consists of the remains of tiny plants and animals that once lived near the surface. Not long ago it was widely assumed in oceanography that particulate material sinking from the 'euphotic' upper layers of the ocean was composed of fairly indigestible organic particles and mineral precipitates, like $CaCO_3$, which slowly settled through a dark and largely lifeless abyss. Since sediment traps were developed in the late 1970s to catch the sinking material in mid-water, it has become apparent that material sinking through the abyss is composed not of inert, slow-settling particles, bur rather of fast-sinking, nutritious material which can feed a rich assortment of deep-dwelling animals, both in the water column and at the sea floor. Now we learn that the flow of particulate organic material goes both ways: K.L. Smith Jr, P.M. Williams and E.R.M. Druffel report elsewhere in this issue (*Nature* **337**, 724–726; 1989) that the deep-dwellers of the abyss are generating buoyant organic particles which ascend toward the surface. Their data show that the upward flux may be 15–20 per cent of the sinking flux on average.

Smith *et al.* hung moored sediment traps, both in the usual upward-facing mode and upside down, at 600 m and 1,600 m above the sea floor at two locations in the Pacific Ocean. Besides finding a surprisingly large amount of material in the inverted traps, they found that ascending material is distinctly different from the sinking material at the same depth. The ascending material consists of egg masses and amorphous gelatinous material, and includes none of the skeletal tests and clay particles common in the sinking flux (K. Smith, personal communication). Furthermore, the upward flux seems to have a distinct seasonal signal, with larger fluxes observed in the spring at both locations.

The sinking flux of organic matter 3,000 m or so below the surface is a small fraction of sinking fluxes in the upper kilometre (Martin, J. H. *et al. Deep-Sea Res.* **34**, 267–285; 1988). What remains to be determined is whether the 0.15–0.20 ratio of upward to downward transport identified by Smith *et al.* is representative of the upper kilometre. Should this relationship hold where downward fluxes are high, then the upward flux would have to be considered a significant component of global carbon and nutrient budgets. Smith *et al.* did hang a set of normal and inverted traps just 500 m below the surface, but strong upper-ocean currents bent the mooring line so severely that the catches in both traps were completely compromised.

The composition of the ascending material in the traps of Smith *et al.* and its apparent seasonal cycle suggest very strongly that the upward flux forms part of the life cycles of certain deep-sea animals. We do not know whether the ascending egg masses caught 3,000 m or more from the surface actually travel all the way up and develop into planktonic juvenile forms. The eggs could stop rising at some depth and develop in mid-water.

In any event, the adult forms must eventually descend to the near-bottom environment to complete the cycle. M.W. Silver *et al.* (*Nature* **309**, 246–248; 1984) discovered large populations of ciliated protozoa associated with sinking detritus in the upper 2,000 m of the Pacific. They found distinct species changes among these populations at different depths. Silver (personal communication) believes that the protozoa locate and colonize detrital particles in mid-water and feed as they ride the particles down. Rather than ride completely out of their habitats they release themselves and ascend back to their original depth range. The behavioural strategies which are suggested by the studies of Smith *et al.* and Silver *et al.* define a conceptual model for the transport of organic matter which makes the upward flux seem not so mysterious after all. ☐

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Physiological ecology

Species borders and metabolism

Jared M. Diamond

WHAT limits the distribution and abundance of species? Different answers have been suggested: food abundance, habitat structure, interspecific interactions such as competition and predation, and physiological limitations imposed by abiotic factors such as temperature. Temperature is one putative controlling variable that cannot be manipulated experimentally at large outdoor study sites. Thus, Terry Root (*Ecology* **69**, 330–339; 1988) has made an important advance by her discovery of a temperature-dependence of some species borders that is strikingly consistent and closely tied to physiological mechanisms.

The northern boundary of distribution around Christmas for the Eastern Phoebe (solid line) lies very close to the −4 °C isotherm of January minimum temperature (dashed line).

Root has analysed the Christmas bird counts organized annually since 1900 by the National Audubon Society. (Each year on a day within 2 weeks of 25 December, at 1,317 sites throughout the United States and Canada, hordes of fanatical bird-watchers count all birds observed within a 15-mile-diameter circle.) For each species and site for the decade 1962–63 to 1971–72, Root (*J. Biogeogr.* **15**, 489–505; 1988) calculated the average number of bird individuals seen per hour per group of bird-watchers, and plotted this measure of abundance on contour maps for comparison with contour maps of six environmental variables.

One of these variables is winter temperature, taken as average minimum temperature at the site during January. Root finds that more than half of the bird species analysed (60 per cent) have the entire length of their northern range border during Christmas counts closely associated with a particular isotherm. The Eastern Phoebe, for example, winters in the south-eastern United States northwest to a limit coinciding closely with the −4 °C minimum January isotherm (see figure).

Published measurements of resting metabolic rate are available as a function of ambient temperature for winter-acclimatized individuals of 14 species of songbirds whose northern border thus coincides with an isotherm. Above a certain critical temperature characteristic of each species, resting metabolic rates of birds remain at the basal metabolic rate and are independent of ambient temperature. Below this critical temperature, resting metabolic rate increases linearly with decreasing temperature to supply the extra energy needed to balance heat loss. Root examines the resting metabolic rate measured for each species at the minimum January temperature of its northern boundary. Ratios of this rate to the basal metabolic rate of the same species vary tightly around 2.49 with a standard error of only 0.07. She obtains virtually the same ratio for 36 other songbird species whose metabolic rates, though not measured directly, can be estimated from the dependence of metabolic rate on body weight.

Thus, these 50 North American songbird species are limited to wintering in areas where they do not have to raise their resting metabolic rate beyond 2.5 times the basal level in order to stay warm — the '2.5 rule'. This strikingly consistent value applies to songbirds from wrens to crows, ranging in weight from 5 to 448 grams and in diet from seed-eaters to insectivores, and with winter northern borders ranging from Florida to Canada. Now recall G.E. Hutchinson's definition (*Cold Spring Harb. Symp. quant. Biol.* **22**, 415–427; 1957) of the fundamental niche as the set of environmental conditions under which a species would be physiologically capable of maintaining itself, if it were not for restrictions imposed by interspecific interactions such as competition and predation. Root's discovery in effect suggests an operational definition of the fundamental niche for temperature-limited songbirds. It thereby allows several questions to be formulated in terms of physiological ecology.

First, what is the physiological basis of the 2.5 rule? Does it imply that an organism can synthesize only enough extra intestinal nutrient transporters or enzymes of intermediate metabolism to process nutrients at a rate 2.5 times the resting rate?

Second, does a similar rule apply to