CHAPTER 18 FURTHER OUTLOOK

** Not Completed*

18. FURTHER OUTLOOK

There are said to be more scientists alive on earth today than the total of those who have gone before in the entire history of mankind. Progress in both pure and applied science is consequently now very rapid by any standards and this is no less true in meteorology than in other fields. Because of this great scientific effort it is hazardous to anticipate developments over the next one or two decades. However, there are certain trends which can be extrapolated with a reasonable expectation of their continuing over the period, and there are new discoveries, hypotheses or techniques which will be developed or tested in the coming years. In this chapter I give my opinion of the direction in which developments will move over the next two decades in the fields of detection, prediction and modification of tropical cyclones and community preparedness against them.

18.1 Detection

Improvements in our ability early to detect the formation of tropical cyclones will come primarily from the system of geostationary meteorological satellites which will be watching the entire globe, almost continuously, using visible and infra-red wavelengths. High and low level winds near suspect areas will be determined from satellite observed cloud motions and will enable the developing process and associated cloud formations to be monitored by day and night. In addition, it is probable that most long range commercial passenger aircraft will be fitted with equipment to automatically transmit wind velocity, temperature and other meteorological data as they fly. This information will be collected by satellite and passed to the relevant weather forecast centres. Some ships may be similarly equipped with automatic observing and transmitting stations. The extra wind data collected from these mobile stations will be merged with that obtained directly from satellite observations and so permit the near continuous monitoring of suspect cloud clusters. Satellite observations of sea temperature and vertical stability and the combined information on winds from satellites, aircraft and ships wind permit the early location of areas where cloud clusters will be likely to develop into tropical depressions. The delineation of these suspect areas will also be made by computer computation both from dynamical forecast models and from computations of the prevailing distributions of vorticity and other relevant variables.

Many developments in instrumental methods of detection should be expected. Satellite imagery will be more accurately gridded with lines of latitde and longitude to permit the centres of storms to be more precisely located. The use of microwaves will enable the central area at the storm to be defined by rainbands at times when the eye is obscured by cloud. Sky-wave radar and satellite born radar will provide information on sea state from which the maximum surface winds will be derived. Coastal radars equipped with a Doppler facility will indicate when rainclouds, within range, move with higher than normal velocities, so giving warning to coastal stations of the formation or approach of strong wind areas associated with developing tropical depressions.

18.2 Prediction

Part of the error in 24 h forecasts of tropical cyclone movement is attributable to uncertainties in the initial position of the storm. The improved methods of detection just described, should therefore make a small contribution to the improvement of the 24 h forecasts which now (1976) average about 200 km in the Western Pacific.

The prediction of the future intensity and location of tropical cyclones will be done by dynamical computation using large computers and nested grids as described in section 16.5 . The large quantity of wind data provided by satellites and mobile platforms, together with satellite derived sea and upper air temperatures will be used to improve the definition of the initial conditions - a necessary preliminary for improved forecasting. If aerial reconnaissance is not available, the size of the eye will be determined from satellite observations. The maximum wind speed in the storm will be determined either by Doppler radar, if within range, or from the characteristics of the cloud cover and peripheral winds as derived from satellite observations. The maximum winds will also be determined from radar observations of the sea state as described in the previous section.

There are practical computational limits to the size to which even a nested grid can be reduced and there are small topographic and oceanographic variations which cannot be fed into the numerical models, for these and other reasons, mean errors in 24 h forecasts of storm position are unlikely to fall below 100 km. However, significant improvements should be expected in the 48 h and 72 h forecasts which, in the Western Pacific and Atlantic, now (1976) average about 500 km and 800 km respectively. It is possible that by dynamical prediction and improved tracking these average errors might be almost halved. This large improvement will derive mainly from the expectation that the very large errors now attributable to frequent failures to predict major changes in the broad-scale wind fields - particularly those associated with possible recurvature situations - should be reduced in magnitude and number. The improved prediction of these changes in the synoptic pattern around a typhoon - which will include changes due to the storm itself - will also contribute to the reduction of errors associated with the 24 h forecasts.

The prediction of storm surge is critically dependent both on storm characteristics and on the location and time of landfall. It will not therefore be possible to predict water levels much further ahead than at present. However, the improved definition of the eye and maximum winds to be achieved by Doppler radar, the improved forecast of position over 24 h and the use of computers to calculate the surge in susceptible areas should improve the precision of the 24 h forecast water levels. Computer derived probability statements for the cases when the storm lands to either side of the most probable landfall position, or ahead or behind forecast time, will be used with the storm surge model to give probabilities of various water levels occuring along a coast.

It is probable that the development of nested grid numerical models will substantially improve rainfall forecasts over large areas for periods of 24 and 48 hours. It is these forecasts which are important for reservoir and flood control.

18.3 Modification of typhoons

In England during World War II fog was dispersed from selected airfield runways by using a system of petrol burners known as "fido". Shortly after the war, in America, selected clouds and fogs were spectacularly modified by seeding them with dry ice. These limited experiments in weather modification caught the imagination of meteorologists and encouraged them to consider other ways of controlling the weather. They began to look for weather systems in which it was possible that man's intervention might trigger a chain reaction or upset a balance of natural forces or processes, and this led to attempts to modify hurricanes.

It is often mistakenly reported that meteorologists hope to prevent the formation of tropical cyclones. There are two reasons for not attempting to do this. In the first place, in many countries in South East Asia tropical cyclones account for between 25% and 35% of the total rainfall and this additional rainfall is essential for the maintenance of life there. Secondly, Landsberg (1960) has shown that tropical cyclones form part of the process by which excess heat and water vapour are exported from the tropics into temperate latitudes (see also sect. 11.6). If tropical cyclones were prevented from forming then it is probable that the heat that they would normally have exported would tend to accumulate in the tropics and the climate there and in temperate latitudes might change in some way which cannot yet be predicted. The balance, at some new level, would probably be restored by the intensification of existing heat transport processes or the formation of new ones - and these might have effects as bad or worse than those due to typhoons.

18.3.1 Why attempt to modify typhoons?

Increasing population and costly development in areas affected by typhoons make it clear that even if warnings are perfect, human suffering and economic loss will increase with time. For example, in the U.S.A. hurricane damage over the 50 years 1920-69, adjusted to the 1957-59 U.S. dollar as base, has increased from an annual average of $40 million in the nineteen-twenties to $355 million in the sixties (Gentry 1973). During the period 1965-69 the annual average (to the same base) was $480 million and was rising rapidly. Intense hurricanes in the U.S.A. cause damage up to 3 times the annual average. For example, hurricane Camille 1969 caused damage equivalent to 1 500 million dollars at 1969 prices. In the countries of Asia and the western Pacific damage and loss of life is greater than in the U.S. because of the much higher frequency of typhoons - particularly of the more intense storms - and the greater coastal population densities. Complete statistics on hurricane damage are almost impossible to obtain but the American Red Cross has collected statistics on residential damage for 21 hurricanes which enables a crude differentiation to be made between wind damage and other (e.g. precipitation flooding). This data is plotted in figure 18.1 (a) and shows that wind damage - direct and indirect - increases greatly as the maximum sustained surface wind speed increases. The reduction in this type of damage which would result if the surface wind speed could be reduced is shown in Fig. 18.1 (b). The total rewards which would accrue if destructive tropical cyclone winds could be lessened by 20% or so without significantly reducing the rainfall, are so enormous as to justify the spending of large sums of money on any experiment in modification which has any hope of success. There are grounds for believing that typhoons may be susceptible to modification - there is hope.

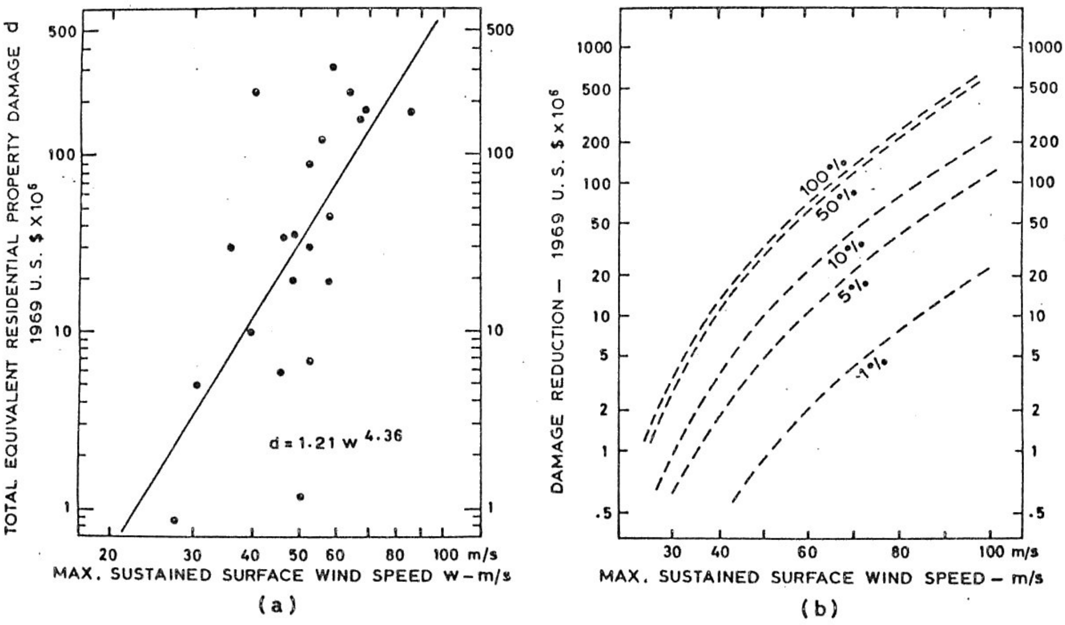

Fig. 18.1 Wind damage to residential property in the U.S.A. attributable to hurricanes is shown plotted against the maximum sustained surface wind speeds (after Howard et al (1972). The corresponding reduction in damage which would result if the winds could be reduced by specified percentages is shown in (b) (after Gray 1973).

The energy of a typhoon, equivalent to 400, 20 Mt (megatonne) bombs per day, is so very great that man's relatively puny efforts are unlikely to have any significant effect on the intensity of a typhoon unless an "Achilles heel" can be found. Typhoons do not form readily. However, once formed, the storm as a whole shows great stability but the high energy portion near the centre does show signs of instability in so far as the crucial eye wall can go through great variations in structure and intensity in relatively short periods of time. These facts suggest that some critical balance or instability may be involved in both the formation and maintenance of the eye wall and this makes this region a promising subject for experiments in modification.

18.3.2 History of seeding hypotheses for modifying typhoons

Vincent Scheafer first proposed in 1947 a hypothesis on which to base attempts to modify hurricanes. At that time he was working in "project Cirrus" seeding clouds (sect. 3.6.3) and was able to arrange for 80 lbs of dry ice to be dropped into a hurricane off Georgia. After seeding, the hurricane apparently changed direction markedly and struck the Georgia coast. It was at first thought that this change in movement was due to the seeding but it was subsequently shown that the change had begun to take place before the seeding experiment began. However, as can be imagined, the many people who suffered losses were inclined to blame the seeders. This experience led to restrictions on the areas in which experiments could be made.

Schaefer's hypothesis (Riehl 1963) was based on recognition of the fact that the release of latent heat through condensation will not warm the interior of a hurricane unless the condensate falls out as rain. By seeding with dry ice the large convective clouds near the centre of the hurricane it was hoped that the water drops above the freezing level would change to ice. In this way it was hoped to interfere with the rain making process in such a way that less water would fall out as rain and the many ice crystals would persist in the air, move out of the tops and sides of the cloud and evaporate. This evaporation would cool the core of the storm which would reduce the temperature difference between the inside and outside of the hurricane so reducing its intensity and the strength of the winds. However, there are many uncertainties in this chain of reasoning, for example, changing cloud particles to ice crystals will release some heat of fusion this will cause some warming and might cause further growth of clouds and further release of heat of condensation, the rainfall might be intensified and most of the ice crystals would be carried away from the central regions by the storm outflow. It is now generally thought that any cooling due to evaporation of ice crystals would be small compared to the heating effects attributable to seeding and, for this reason, the hypothesis is no longer in vogue and has been replaced by one due to R.H. Simpson and first proposed in 1961 (Simpson et al 1963).

Simpson proposed that silver iodide be used to seed the convective clouds just upwind of the most active or "chimney" region of the eye wall. It is in the tall convective clouds or "hot towers" in this region that most heat is released by condensation. Supercooled water drops are known to exist at high levels in these hurricane clouds. Simpson's hypothesis was that these drops would change to ice on seeding and release heat of fusion (334 kJ/kg) which would not otherwise be available. This released heat would make the eye wall warmer and further reduce the pressure below. Joanne Simpson (1966) has calculated that temperature rises of about 1°C to 2°C are to be expected with surface

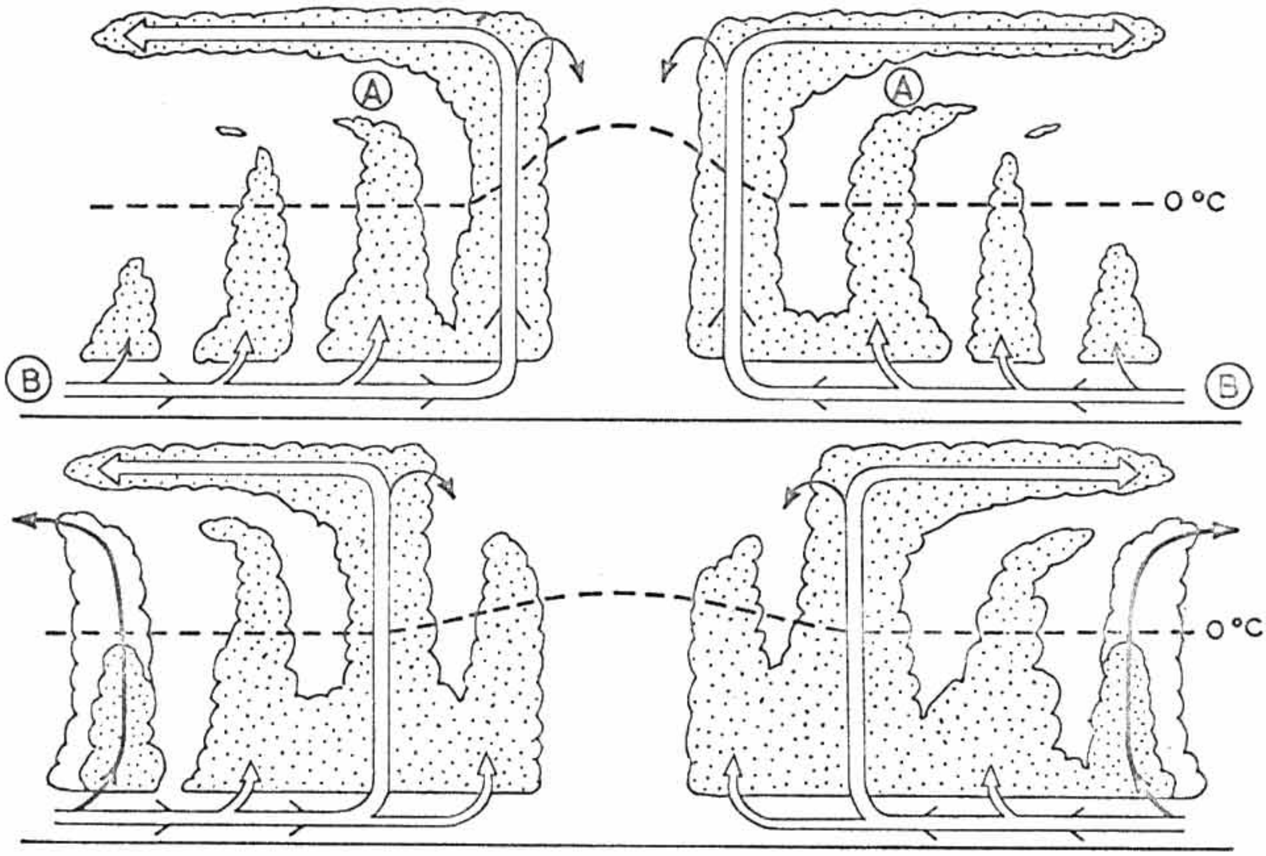

Fig. 18.2. Schematic diagram to illustrate how seeding (top) might cause the clouds to grow (bottom). Seeding with silver iodide at A causes increased convection in the larger clouds outside the eye wall. Seeding with carbon at B causes increased convection in the outer clouds. Both methods reduce the supply of moisture and angular momentum to the eye wall region.

pressure falls of 6 to 7 mb. If the pressure at the boundary of the hurricane remained unchanged, the pressure fall under the seeded areas would have the effect of reducing the gradient of pressure in the region of the eye wall; the region of greatest pressure gradient would then be moved further from the storm centre and the associated ring of maximum winds would also move outwards and - by analogy to the ballerina who extends her arms and a leg to slow down a pirouette - decrease in speed. The hypothesis becomes more attractive when it is realized that convective clouds form only about 1 to 6% of the total volume of a hurricane or typhoon (sect.) and that only a susceptible fraction of them need to be treated. Again, there are weak links in the chain of reasoning in this hypothesis. Through lack of both physical data and detailed models we can be sure of neither the direction nor the magnitude of some of the expected changes. This is a reason for resorting to experiment.

The hypothesis has been modified in recent years as the result of flights tests and numerical modelling. It is now proposed to seed just outside the eye wall where the clouds have not attained the height of those nearer the storm centre. The supercooled water drops in these clouds freeze and release latent heat of fusion (~ 334 kJ/kg) so warming the upper part of the cloud and increasing its buoyancy. As a consequence of the increase in buoyancy the cloud grows higher releasing latent heat of condensation (~ 2 501 kJ/kg) and sublimation (~ 2 834 kJ/kg) which is additional to, and greater than, the heat released during the initial fusion. The growing clouds reach the outflow level, as shown in Fig. 18.1, so providing a path for the inflowing air in the boundary layer to rise in the newly grown clouds further from the storm centre and exit in the storm outflow thus effectively "short-circuiting" or cutting off much off the inflow to the eye wall where, consequently, the circulation weakens and so decreases the subsidence in the eye. The maximum wind speeds at the new outer location are reduced, due to the partial conservation of angular momentum and the decreased temperature and gradients in the inner region. The surface pressure distribution adjusts to the wind and temperature fields and finally, after some period, probably in the range 6 to 18 h after final seeding, the storm returns to its original state. This hypothesis has been tested by numerical simulation and is currently the hypothesis upon which Project Stormfury is based.

18.3.3 Project Stormfury

In 1961 aircraft from the United States Navy and the Weather Bureau jointly seeded hurricane Esther, and in the following year "Project Stormfury" was initiated as a continuing joint effort to obtain a better physical understanding of hurricanes with a view to ultimately finding a method to modify them so as to reduce their maximum winds. In the seeding experiments pyrotechnic silver iodide generators - about as large as a king size beer can - are dropped from high-flying jet aircraft along a radius of the storm and outside the eye wall. Typically, five aircraft might be used each carrying 200 cannisters containing 0.16 kg of silver iodine. On explosion each cannister is estimated to produce 10^{12} to 10^{14} nucleating particles. Before and after seeding a massive observational programme is carried out by aircraft flying at different levels.

The organization necessary to get all the aircraft to the right place at the right time for a seeding experiment is immense and limits the area in which hurricanes can be seeded to a radius of about 1 300 km from bases at Jacksonville, Florida and in Puerto Rico. Futhermore, following the 1947 seeding fiasco, the area was further limited by the political restraint that no hurricane could be seeded if it was in a position from which a recorded hurricane has struck a highly populated coast within 36 hours. These restrictions reduced the available hurricanes to about one per year. After the seeding of Esther in 1961 no suitable storm moved through the area until Beulah in 1963. This hurricane was seeded twice. There were no seedings in 1964, 1965 or 1966 because of shortage of both key aircraft and suitable hurricanes. In 1967 the seeding area was enlarged and experiments were permitted if the chance was 10% or less of the hurricane centre passing within 90 km of a populated area within 24 hours after seeding. In spite of this relaxation, and others, no suitable hurricane met the requirements in 1968. After 5 years of waiting a hurricane - Debbie - was at last seeded on the 18th and 20th August 1969 when it was to the northeast of Puerto Rico. In 1970 the guidelines were again relaxed so that seeding was to be completed 18 hours before possible land fall but no eye-wall experiments were possible in 1970, 1971 or 1972 although some limited experiments were carried out in the rainbands of hurricane Ginger on 26th and 28th September 1971.

After only 14 seeding flights in 3 hurricanes in 12 years plans were made in 1971 to move the experiments to the Pacific where the chance of encountering a suitable storm within 1 300 km of the proposed base at Guam was about three times better than from the Caribbean bases. However, this decision was followed by the recession of the mid-nineteen seventies and flying operations had to cease until new and better instrumented aircraft could be provided later in the decade. In the interim, numerical models of tropical cyclones were improved and experiments were carried out on them to determine the probable effects of different seeding techniques.

The results of the flight seeding experiments up to and including Debbie are shown in Table 18.1. They tend to indicate support for the stormfury hypothesis in so far as the changes in wind speed are all in the direction anticipated and, in both Debbie seedings, the magnitude of the wind speed change was also of the same order as that indicated by the hypothesis. The wind profiles obtained by Doppler techniques from aircraft flying at 3.66 km are shown in Fig. 18.3. Note particularly how the wind speed maximum on the right of the storm on the 20th August fell from 99 kn to 83 kn and moved outward by about 10 n miles (18 km). The question of whether these changes were natural occurrences or man induced remains to be answered. The project hopes to be able to determine which effects are man-made by repeatedly seeding typhoons and hurricanes and monitoring the changes in the many physical variables involved, if the changes are frequently of the same nature and occur at about the same time after each of many seedings then, in time , it should prove possible to identify the small man-made changes in the larger "noise" or natural variability within the tropical cyclone. However, many years of experimentation will be required before a generally acceptable answer will be obtained. Although operating from Guam will provide greater oportunities for these experiments most of the typhoons in that region are in the deepening or developing stage and this will be the source of a further difficulty in the way of interpreting the experiments.

Table 18.1. Results of experiments in seeding hurricane clouds near the eyewall (from Gentry 1973).

Name	Date	No of Seedings	Approx Max Wind Speed Change (Percent)
Hurricane Esther	16 Sep 1961	1	-10
Hurricane Esther	17 Sep 1961	1	0*
Hurricane Beulah	23 Aug 1963	1	0*
Hurricane Beulah	24 Aug 1963	1	-14
Hurricane Debbie	18 Aug 1969	5	-30
Hurricane Debbie	20 Aug 1969	5	-15

* Pyrotechnics dropped outside seedable clouds

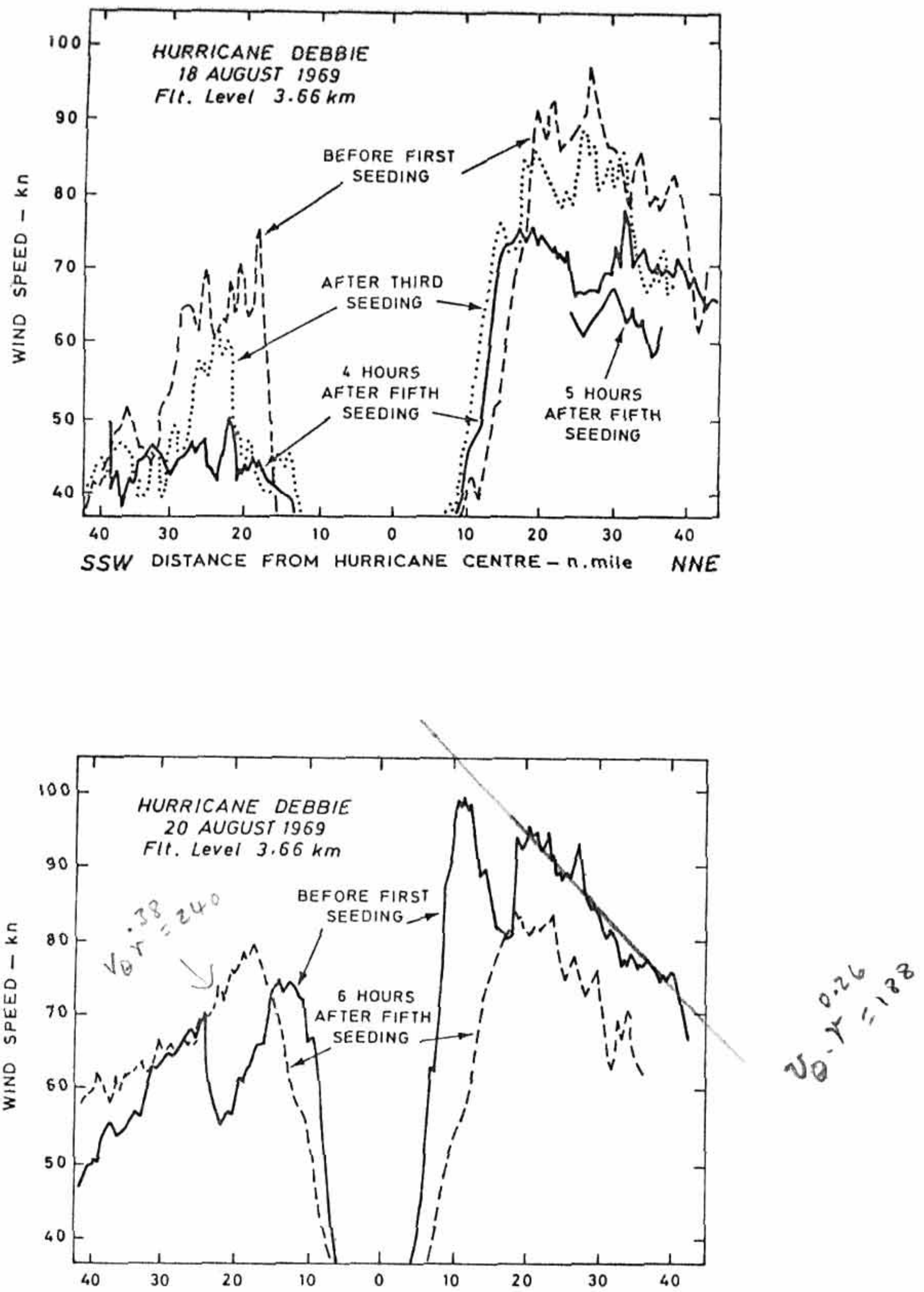

Fig. 18.3. Changes with time of the wind speeds at a height of 3.66 km in hurricane Debbie on the 18th August 1969 (top) and 20th August 1969. (After Gentry 1973)

In 1979 new highly instrumented aircraft were ~~assembled~~ readied for further experiment. These included two P-3 Orions one C-130 Hercules operated by NOAA, one additional Hercules to monitor the low level conditions and the NASA CV-990 Convair to monitor upper levels ~~in the storms. ...~~

These ~~are only~~ five aircraft, being much ~~...~~ ~~to provide ... better information ... was obtained in the 16 air~~ more highly instrumented than the 16 used in Debbie, ~~and they~~ are expected to provide a more definitive and complete picture of the structure of hurricanes and of the processes taking place inside them.

18.3.4 Modification using carbon dust

Gray (1973) suggested that the maximum wind speed in a tropical cyclone could be reduced by distributing carbon dust in the low level inflow in the fine weather outside the cirrus cloud canopy. Solar energy intercepted by the carbon particles would result in the heating of the inflowing air and be accompanied by increased evaporation from the sea surface. As a result, the inflowing air would obtain greater buoyancy and so rise at a greater distance from the storm centre than would otherwise be the case. The low-level inflow to the more central areas of the storm would then be depleted and - as in the case of the stormfury hypothesis - this should result in the reduction of the maximum wind speed near the eye wall. The method is illustrated in Fig. 18.2 where carbon dust introduced at B, outside the cirrus canopy, heats part of the inflow which rises in the peripheral clouds (not stippled). Both the carbon dust and the stormfury methods aim to bypass some of the tropical cyclone inflow away from the eye wall region, they could therefore be used simultaneously.

Gray and collaborators (1974) have studied the carbon dust method in considerable detail and consider it to be more efficient than the stormfury method in all particulars except cost. This contention is supported by tests using Rosenthal's (1970, 1971a, 1971b) numerical model and injecting the expected heating at the appropriate place. It is, of course, aesthetically displeasing to pollute the atmosphere with soot but, if the dust is dispersed in the way intended then the resulting mass density will be about $50 \mu g/m^3$ which is less than the particulate loading found in the atmosphere in most cities.

Carbon black dust consists of fine essentially spherical particles of 95-99% pure carbon formed by the controlled incomplete combustion of fossil fuels. Particles with a radius of about 0.1 micron maximise the solar absorption per unit mass, they are invisible to the naked eye and have a negligible fall speed in the atmosphere. The density of these particles is 2000 kg/m^3 and individual particles weigh about 10^{-14}g. About 3 x 10^{13} particles, weighing 0.3g, can completely cover a horizontal cross section of 1 m^2. Calculations show that maximum heating per unit weight (and cost) is achieved if the carbon dust is dispersed such that about 10% of an area is covered; the absorption rate then varies little with solar elevation above about 30^o so that 9 to 10 hours of nearly constant absorption rate obtain during daylight hours. The carbon dust particles heat the air primarily ($\sim$94%) by direct absorption of solar energy and molecular conduction to the surrounding air. About 6% of the heat transfer is accomplished by long wave radiation. The solar energy incident at the top of the tropical atmosphere amounts to about 33.5 MJ/m^2 per day. Normally, in cloud free air, about 20% of this energy is absorbed or scattered and reflected back to space and 80% is absorbed by the ocean. If carbon dust is scattered at a ten per cent area coverage in the layer between the surface and 950 mb then it is estimated that it will absorb about 15% (5.03 $MJ/m^2/d$) of the incident solar radiation which will heat the dusted atmospheric layer at a rate of about 1^oC per hour. At the optimum dispersal density, 1 kg of dust will cover 40 000 m^2 and intercept about 200 x 10^3 MJ per day - this is 6 000 times more heat than would be released by the complete conbustion of the same mass of coal. Gray (1973) claims that "among the energy souces normally used by man only nuclear energy compares with carbon black as a source of accumulation of energy per unit mass, and no known substance compares as a source of heat per unit cost. A 20 kilotonne nuclear explosion produces about the same amount of thermal energy as can be obtained from 1 tonne of carbon dust in 10 hours of solar heating."

It is proposed that the carbon dust be generated from petroleum in after burners fitted to the jet engines of jumbo-type aircraft; 10-20 such aircraft would be required to dispense around a typhoon, in the fine weather moat, a cloud containing 1-2 thousand tonnes of carbon dust. It is necessary to place the dust sufficiently upstream so that it does not advect under the cirrus shield before 10 hours of heating have been accomplished - two days of heating may be obtained in some cases. The increased evaporation comes about because the extra vertical mixing caused by the increased warming will bring drier air down to the sea surface increasing the water vapour pressure difference between the air and ocean and so increasing evaporation.

What are the uncertainties in the method? It is not the first time that it has been proposed that carbon dust be used as a heating agent to cause cloud growth. Van Straten et al (1958) carried out experiments in which clear air was seeded with carbon dust at the level of the bases of existing clouds. Five runs were made and small clouds were observed to form in all cases although a definite causal relationship could not be established. Similar experiments by Downie (1960) were not so successful. Gray (1974) considers that these experiments were on too small a scale so that diffusion effects diluted or dissipated any heat absorbed. He also considers that the amount of carbon used (5-20 kg) was much too small especially when associated with clumping of the solid material used. The jet engine dispersal method advocated by Gray et al (1974) has yet to be developed and tested. What will happen to the carbon cloud in a natural environment? Will it tend to accumulate in preferred areas or to concentrate in vertical columns? How will the shielding of the carbon dust by storm clouds affect the energy gain? Will the enhanced cumulus convection further intensify the storm circulation in which it is embedded? These and other uncertainties remain and are unlikely to be resolved until field tests have been made. It is probable that such field tests, supported by numerical modelling experiments, will be made by the end of the decade - they will certainly be necessary before the spending of one to two million U.S. dollars on a full scale experiment can be justified. A single C 5A aircraft flight for 8 to 10 hours would cost about US$40 000. This could carry the equivalent of 90 tonnes of carbon dust costing about US$10 000. To these direct operating costs must be added about US$50 000 for aircraft modifications making a total of $100 000 per flight or one to two million dollars per experiment involving 10-20 flights. However, this large cost has to be balanced against the huge potential rewards (Fig. 18.1) which stand to can be gained if the method can be shown to work.

18.3.5 Other hypotheses for modifying typhoons

When a typhoon is considered as a heat engine other possibilities for modification present themselves. Firstly, the effectiveness of the heat source - the ocean surface - could be reduced by cooling it in some way. The towing of icebergs into the path of hurricanes has been suggested as one method of cooling the sea. Likewise, the inflowing air in the storm could be cooled by dropping cooling substances into it from aircraft. However, both schemes require the expenditure of great amounts of energy and, in addition, they suffer from many practical difficulties not the least being the hazards associated with the operation of many ships or aircraft in the dangerous environment of typhoons.

Joanne Malkus (1958) examined whether the introduction of a large volume of water into the eye of a typhoon or hurricane would cool the core air sufficiently - by evaporation - to raise its density and so raise surface pressure. She ~~found that evaporation of about 100 so raise surface pressure~~. She found that evaporation of about 100 times as much water as was raised in the Bikini lagoon atom bomb test, about 10^6 kg, would saturate the eye of an intense typhoon like Marge 1951 but that the pressure would only rise from 890 to 930 mb - still an intense typhoon. The method would be less effective on a more moderate typhoon in which the eye is already relatively moist.

It has also been suggested that a film could be spread over the sea surface to reduce evaporation. Theoretical models of tropical cyclones (Ooyama 1969, Rosenthal 1970, Sundquist 1972) all indicate that stopping evaporation in the inner regions of a typhoon would reduce its intensity. The value of monomolecular films for this purpose was tested off Florida in 1972 (Mallinger and Mickelson 1973) and although the test indicated that the energy of the ocean waves was effected the film could not survive strong winds. The search for films that have the characteristics of being tear resistent, spreading easily on the ocean surface and being biodegradable has included the use of hybrid films consisting of thin polymer membranes made from linoleic acid, polyvinyl alcohol and derivatives of polyvinyl acetates. Oleyl alcohol has also been tried and has been dispersed in the form of frozen cubes. So far no film has been found which could survive long enough in the hurricane environment and be acceptable to environmentalists, fishermen and others. However, even if an inocuous substance is discovered which will form a film capable of surviving large waves and wind speeds in excess of gale force then some 2 000 tonnes of it would need to be spread by about 50 cargo-type aircraft over a 200 x 200 km area ahead of the typhoon. The cost of the material used would probably be about half a million U.S. dollars and, to this cost, must be added that of operating the aircraft - in all, a very expensive experiment which would have to be repeated very many times to establish the value of the method.

Heat from the top of a typhoon is lost by radiation into space, this forms part of the heat sink or exhaust system of a typhoon. It has been suggested that this radiation system could be modified beneficially by distributing materials with various radiation properties on top of clouds at selected locations and various distances from the typhoon centre. It has been argued that this would cause changes in the temperature of the top of the typhoon which would affect its intensity. A technique for ejecting plastic bubbles in the exhaust of aircraft jet engines has been suggested as a means of distributing the required materials. However, neither the technique nor the expected effects on the typhoon have yet been fully evaluated.

Although tropical cyclones have so far been seeded with dry-ice and silver iodide there are already available other chemicals which affect the physical processes in clouds. Some inhibit the coalescence of cloud droplets but they have not been used because they are corosive and because there is no satisfactory hypothesis as to how their action might modify typhoons.

18.3.6 Modification prospects

Not all countries welcome tropical cyclone modification experiments near their territory because there are still many unanswered questions. First and foremost what is the chance that the all-important storm rainfall will be diminished? Is it possible that seeding, in some cases, may intensify the storm? Could the effects of seeding cause the storm to change its direction of motion? Is there not a real possibility that by increasing the radius of the maximum winds we will also increase the severity of the dangerous and damaging storm surge (sect.)? Will there be any ecological side effects or pollution problems resulting from the use of the various seeding agents? These and other questions remain to be answered by experiments both in the field and in the computer. Some scientists argue that we should not attempt to modify hurricanes and typhoons until we understand them better and can predict the effects with confidence. However, Joanne Simpson (1966), an eminent Stormfury meteorologist, has pointed out that this philosophy - which requires predictive models to precede experiments - runs counter to that of the great experimental physicists of the past and present. In the history of science there are many examples of exploratory experiments producing results which were later used to formulate models. Rutherford's model of the atom being a case in point. Indeed, scientifically controlled cloud-seeding experiments have produced results which have enabled Joanne Simpson and co-workers to formulate a predictive model for cloud-seeding experiments. It is hoped that a similar procedure will succeed with tropical cyclones. It is important to realise that in this section we are talking only of properly controlled scientific experiments in which many physical variables are measured and monitored, this way lies progress. The uncontrolled, unmonitored seeding of clouds and tropical cyclones is, at this stage of our knowledge, to be deplored.

It is of interest to note that although we have been speaking of man induced modifcation of typhoon intensify mother nature has a whole range of modifcation techniques which frequently protect certain areas from extreme storms. For example, Taiwan and the Philippine Islands greatly weaken intense typhoons which pass over them, from east to west, and so protect the South China Sea and south China coast from extreme typhoons. The land and mountains cut the supply of moisture, heat and momentum to the eye wall region so weakening the winds and destroying the eye itself. When the centre is over the sea the mountains often cause the release of convection in the outer parts of the storm, by orographic lifting, so depleting the inflow to the inner regions of the typhoon. Elsewhere, such factors as areas of cold sea water and adverse upper wind fields tend to weaken storms and offer protection to certain areas.

Finally, Gentry (1969) has estimated that if hurricane or typhoon modification research is supported for 10 years at the same rate as in the late nineteen sixties, and if in that time the winds in one destructive storm are reduced by only 10% then the return on the investment will be more than 1000%. Therefore, although we cannot yet predict whether we will eventually be able to satisfactorily modify typhoons the effort to do so will probably continue because of the enormous rewards which would attend success. Present thinking on this subject by many meteorologists has been summarised by Miller (1967) who wrote "no serious-minded meteorologist yet believes that we can alter the structure or the energetic process of the major hurricane, but it is probably equally true that no serious-minded meteorologist would question the wisdom of trying to do so."

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