CLOUD PHYSICS DIVISION CSIRO

RESEARCH ACTIVITIES

July 1979

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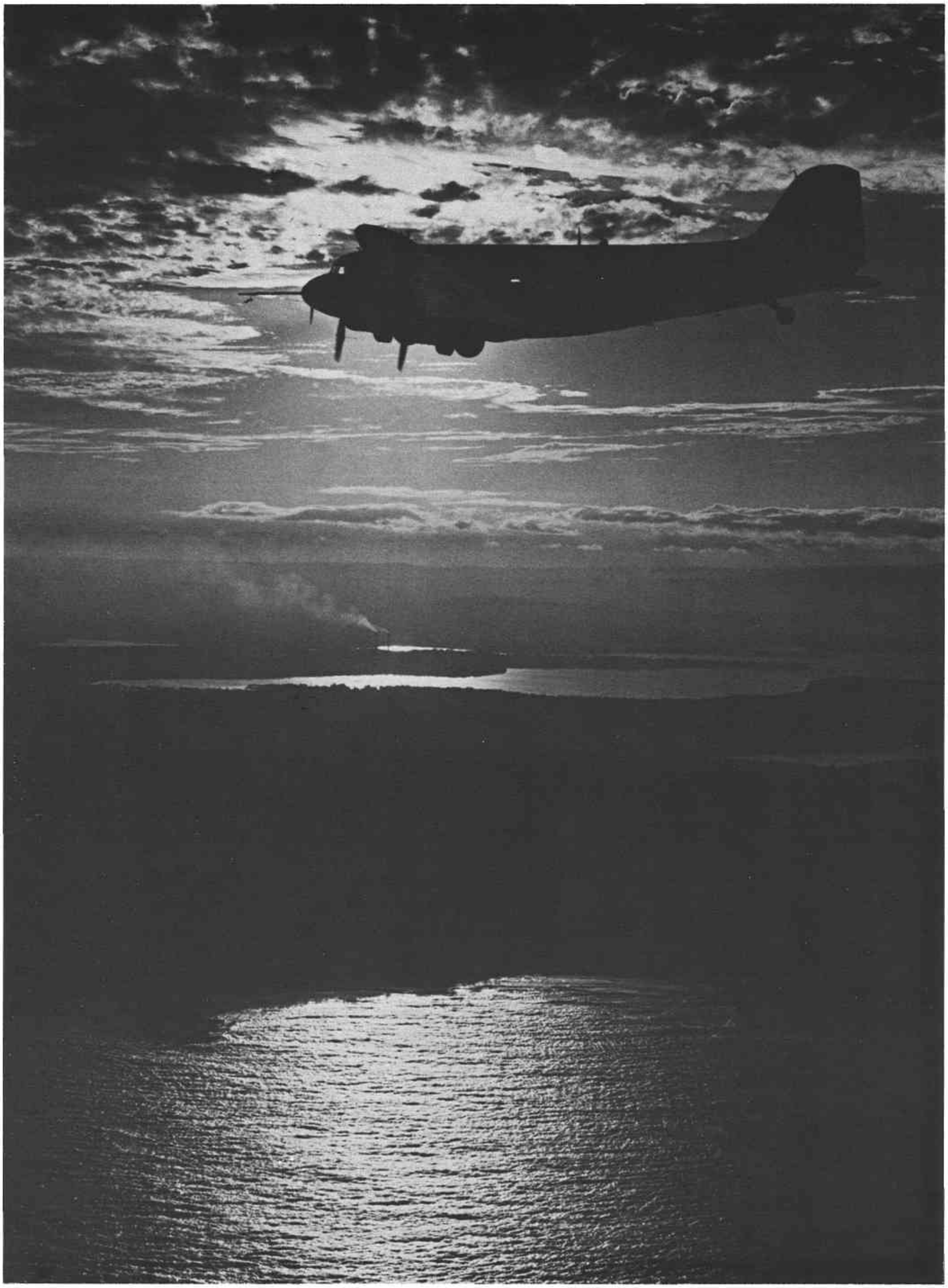
The painting on the front cover, John Constable's "Boat and Stormy Sky" (reproduced by permission of the Royal Academy, London) is a fine example of a squall line as seen by a skilled artist. Constable was a keen observer of the sky all his life and painted many cloud scenes.

Much can be learned by an acute observer about the nature of clouds. However, as a means of predicting what will happen next such observations are of little value unless they are supplemented by theoretical studies of cloud behaviour.

Mathematical models of clouds can be developed from the equations which represent the physical laws governing atmospheric motions. The solution of these equations is only possible with the aid of modern high-speed computers. The back cover shows the cloud shape (white), air motions (black arrows) and changes in air temperature (red, warmer; green, colder) which one such model developed by the Division predicts would occur some 40 minutes after a moist parcel of air commenced rising in an initially cloud-free environment.

The Division uses its instrumented research aircraft to observe and measure cloud properties which can be compared with model predictions. The aim of this activity is a more comprehensive understanding of the physical processes in clouds which lead to rain.



FOREWORD

Mankind has always been concerned about weather and climate; however, it is only in the last few decades that it has come to be recognized that Man, through his agricultural and industrial activities, has the power to affect the weather, perhaps adversely. During the same time span it has also been realized that beneficial changes might be achieved by deliberate intervention at critical stages in weather processes.

The extensive grazing and agriculture in historical times have changed the nature of the land surface over wide areas of the globe, with consequent changes in its heat and water budget. Present-day agricultural and industrial activities, and the vehicles used for transporting the products of these activities, release vast quantities of material into the earth's atmosphere. The character and magnitude of the changes in land usage and in atmospheric pollution in their turn can have a marked bearing upon changes in local and even global climate.

Clouds often play an important intermediary role in these changes. In addition to their obvious role in generating rain, clouds are important in that they can reflect much of the incoming solar radiation back to space. The amount and depth of cloud are clearly significant parameters in determining how much rain will fall or how much radiation is reflected, but it may not be so obvious that the size distribution of the droplets of which the cloud consists is of equal importance. We know that the size and concentration of the cloud droplets depends upon the character and concentration of submicroscopic particles in the atmosphere; since a significant proportion of these particles originates in Man's activities we can see the important link between those activities and weather.

The Division of Cloud Physics is concerned with all aspects of cloud behaviour. Its research covers the chemical nature of the particles upon which the cloud droplets form, the properties of those rare particles which stimulate the freezing process, the way in which droplets and ice crystals interact to produce rain, and the cloud-scale or larger-scale processes responsible for cloud formation. It uses a variety of techniques and observing platforms for its measurements. Laboratory facilities ranging from electron microscopes to wind tunnels are used to study the properties of atmospheric particles and cloud elements. Large balloons are used to send recoverable instrument packages up to stratospheric levels and instrumented aircraft are used to penetrate the clouds and measure their properties.

The overall aim of the research work of this Division is to understand the degree to which Man's activities are affecting weather and climate through the effect of those activities upon cloud properties and to exploit this knowledge by modifying cloud behaviour — for example, in order to increase rainfall.

The Division is located some 16 km north-west of the city centre in the Sydney suburb of Epping, where it shares a building complex and many facilities with the Division of Radiophysics.

This booklet describes the recent work of the Division and the current status of its research into cloud physics, cloud seeding and the atmospheric aerosol.

The Division of Cloud Physics is one of four CSIRO Divisions which are largely concerned with atmospheric problems. These four Divisions, along with six others, constitute the newly formed Institute of Physical Sciences.

RADIATIVE TRANSFER IN CLOUDS

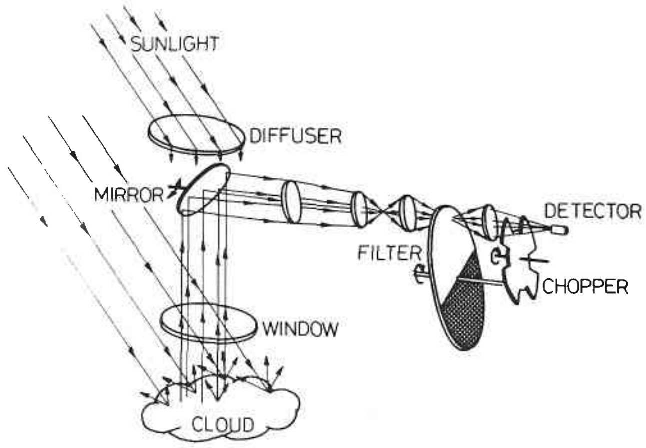
Solar radiation is the driving force which governs all atmospheric motions and weather processes. Only about 50% of the incident radiation is absorbed by the earth's surface, the remaining fraction being either absorbed in the atmosphere itself or reflected back to space. A major factor in determining the fraction reflected is the presence and abundance of cloud and the cloud microstructure. Since reflected energy is lost to space, a high albedo (i.e. where a large fraction of the incident radiation is reflected) tends to lower the temperature and to increase the humidity at the earth's surface. Energy which is absorbed by cloud layers can produce both horizontal and vertical temperature gradients which affect the dynamic and thermodynamic balance of the atmosphere. Thus solar radiation and its interaction with cloud play an important role in the determination of our climate and weather.

When solar radiation is absorbed there will be subsequent emission of radiation by the atmosphere and the surface. Since the mean temperature of the earth is less than 300 K while the effective temperature of the sun is 6000 K, the energy spectra for the radiation emitted by the sun and by the earth are widely separated; in particular, radiation from the sun is a maximum at a wavelength of 0.5 μm and from the earth at about 10 μm. Because the spectra are essentially distinct it is possible to treat the solar and terrestrial (or infra-red) radiation fluxes separately. The two types of radiation are affected differently by clouds: solar radiation tends primarily to be scattered and infra-red radiation to be absorbed and emitted by cloud.

Theoretical work carried out within the Division has indicated that the microphysical structure of a cloud has a marked effect upon the way in which the scattered solar radiation varies with wavelength. This suggests that remote sensing of solar radiation reflected from cloud tops can yield information on the structure of the clouds. Information of this nature is a prerequisite when deciding whether the clouds which occur in a particular region would be suitable for cloud seeding undertaken with a view to increasing rainfall. In the past when this type of survey has been conducted over a defined area instrumented aircraft have been used and many months of observation have been necessary to assess a single site. Large-scale surveys by this method would clearly be impossible because of the high cost and the long period of time involved. However, if remote sensing, from a satellite for example, were possible, many sites could be examined simultaneously. At the present time therefore the Division is engaged on a research program designed to assess the potential of such remote-sensing techniques. If the program is successful it is hoped that the equipment under development will be placed in a satellite, thus permitting surveys on a national, or even global, scale.

The program initially involves measurements from our research aircraft of scattered solar radiation above cloud. From these measurements our theoretical work allows us: (1) to determine whether a cloud consists of ice or liquid

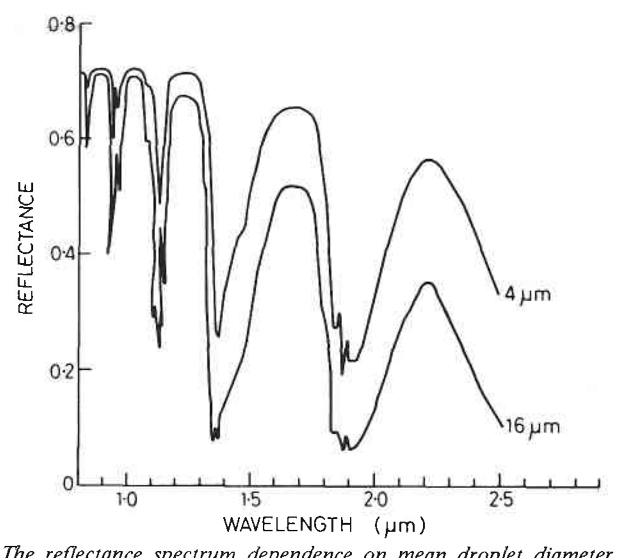
The cloud in the middle of the photograph is brighter than that in the foreground because: (i) sunlight is being scattered from it at closer to grazing incidence; (ii) its upper surface is smoother; (iii) its droplets are smaller and there are more of them per unit volume.



Schematic illustration of the spectrometer used to measure the reflectance spectrum of clouds. A reference spectrum of the incoming solar radiation is periodically recorded by viewing the diffuser.

water; (2) to infer the mean droplet radius of the liquid water distribution. Measurements are also made from the research aircraft of the microphysics within the cloud which can be compared with the predictions.

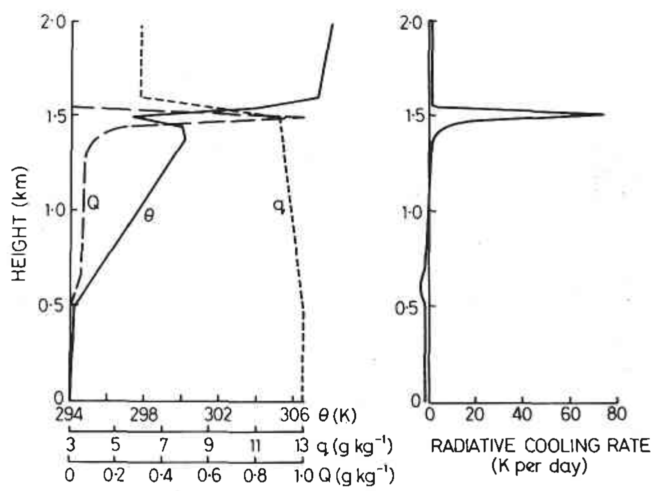
Observations are obtained with a spectrometer and a radiometer, both of which have a field of view of 2°. The spectrometer records a spectrum of the solar radiation every few seconds in the wavelength range 1.2 to 2.4 μm with a resolution of about 0.01 μm. The radiometer measures the solar radiation at four wavelengths. The incoming and reflected solar radiation are measured just above cloud top, and the reflectance spectrum (i.e. the ratio of the reflected to the incoming radiation at each wavelength) is computed. Whether the cloud is composed of liquid water droplets or ice crystals can be determined from the precise positions on the wavelength scale of the absorption lines near 1.5 and 2 μm. If the cloud is composed of droplets then the mean radius can be inferred from the ratio of the reflectance at two wavelengths near maxima in the reflectance spectrum — that is, at wavelengths where absorption is small. The



The reflectance spectrum dependence on mean droplet diameter is illustrated for a stratus cloud with an optical depth of 32. Using the ratio of reflectances at 0.9 µm and 2.2 µm, it is possible to infer the mean droplet diameter.

measurement program is also intended to determine whether the reflectance is affected significantly by inhomogeneities in the clouds; in particular, the scattering of solar radiation from cumuliform cloud is to be considered.

In a separate program of investigation measurements of the radiation, microphysical and dynamical properties of cloud are analysed and interpreted through the use of mathematical models. Calculations using a model which predicts the temporal development of a boundary layer show that the absorption and emission of infra-red radiation in stratus cloud greatly affect the dynamics of the cloud. Emission from the surface, which is warmer than the cloud, is absorbed by water droplets in the lower regions of the cloud. The consequent radiative warming evaporates some of the liquid water in the lower half of the cloud. On the other hand, the cloud top emits infra-red radiation to space and cools; this allows additional vapour to condense on existing droplets, thus increasing the liquid water content. Thus infra-red radiation in stratus cloud tends to produce an observed liquid water profile which increases almost linearly with height above cloud base. The radiative cooling at cloud top is much stronger than the warming at cloud base, and so the main dynamical effect of the radiation is to induce convection driven from the cloud top. The fluid motion associated with this convection has been measured from our research aircraft.



Profiles of potential temperature, total specific humidity, liquid water and infra-red radiative cooling rate in a stratus cloud, as predicted by a mathematical model.

Calculations of the radiation in stratus cloud show that continental cloud, with a high droplet concentration, reflects much more of the incoming solar radiation than maritime cloud, with a low droplet concentration. Since natural and man-made pollutants are expected to modify the droplet distribution in cloud, they may also modify its albedo and consequently the amount of radiant energy reaching the earth's surface. In order to measure such modifications we are observing the solar radiation above clouds in air contaminated by the plume from a copper smelter and in clean nearby air. Although these measurements are straightforward above stratus cloud, the interpretation of measurements above cumulus cloud fields is difficult because radiant energy is exchanged between the sides of the individual clouds.

MODELLING AND THE DYNAMICS OF CLOUDS

Clouds of their nature can significantly affect weather and climate, so that any reliable predictions that can be made about their behaviour will be extremely useful. Indeed the aim of atmospheric science in general is to gain an understanding of the processes which drive the atmosphere in order that predictions can be made regarding the future behaviour of these processes. On a large scale the predictions may represent forecasts of future weather or climate; on a small scale they may relate to the behaviour of a single cloud.

Such scientific predictions involve the use of mathematical equations or models which represent the various physical laws that are observed to govern the atmosphere. Since our understanding of the atmosphere is as yet incomplete it is important to compare the predictions with what actually occurs. Thus there needs to be strong interaction between research programs which provide measurements and the development of models which use the measurements.

All the Division's activities involve some modelling but the main emphasis in modelling at present is in the study of the dynamics of cloud.

Both cumulus and stratus clouds are dynamic, in the sense that the air motion is turbulent and that cloud droplets evolve from condensation nuclei less than 0.1μm in diameter to precipitation particles with diameters of some millimetres. The turbulent motion of clouds causes them to interact with the clear, ambient air, increasing its heat and moisture content at their own expense. Indeed one of the main effects of cloud is the stirring-up of the atmosphere in such a way that heat and moisture are distributed throughout the troposphere (i.e. the region up to a height of about 10 km).

The particulate nature of clouds has two important effects on conditions at the surface of the earth. Firstly, clouds tend to reflect a large fraction of the solar radiation and thus the ground in cloudy regions tends to be cooler and more moist than it is in areas beneath clear skies. Clouds therefore can significantly affect the weather and climate of a particular region. Secondly, clouds are concentrated sources of water which are carried by the wind and so transport water from one geographical location to another. Cloud-seeding projects often attempt to exploit this property by triggering the release of precipitation at a given location. Quantitative predictions of weather and of the effects of weather modification programs therefore require the development of models of cloud processes.

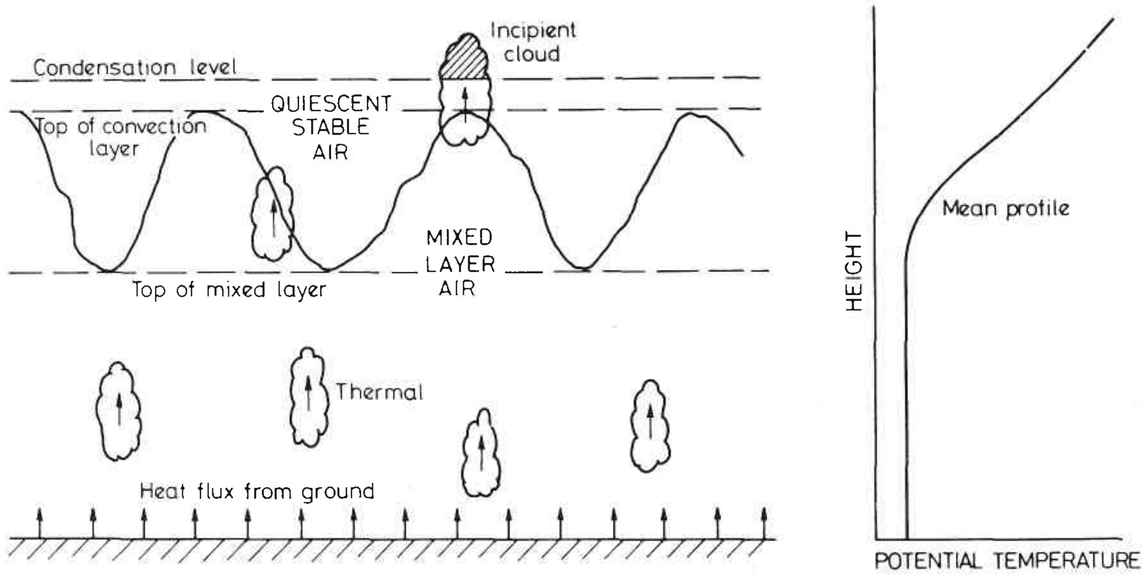
ORIGIN OF CUMULUS CLOUDS

The cumulus cloud field is one of the most prevalent types occurring over both the land and sea. Cloud fields at sea tend to be approximately steady-state, whereas clouds over land suffer large diurnal variations because of the low thermal capacity of the ground. The study of these variations is rewarding in that they can give insight into the origins of cumulus clouds.

On a clear night the land cools by the radiative transfer of heat to space. This cooling causes the lowest few tens of metres of the atmosphere to become quite stably stratified with a temperature several degrees less than that of the overlying air. After sunrise the ground absorbs solar radiation and it becomes hotter than the air above it. The resulting heat flux from the ground generates convection driven by buoyant elements (or thermals) which warm and mix with the ambient air as they rise. The thermals intrude into the overlying stable air, mix with it and so increase the depth of the mixed layer.

Both observations from our research aircraft and theoretical considerations imply that the mixed layer and the quiescent stable air above it are not flat; rather, patches of mixed-layer air extend up some hundreds of metres into the stable region. Thermals cannot penetrate far into the overlying stable air and so the convection layer is deepened only by those rare thermals that rise through the top of a mixed-layer patch.

The development of a typical field of fair-weather cumulus cloud over land is traced from mid-morning (top left), through noon, to a maximum in the early afternoon and to the onset of decay in mid-afternoon (bottom right).



Physical model of a convection layer mixed by thermals.

Thermals transport moisture as well as heat up from the ground. Incipient cumulus cloud forms when the moisture in a thermal condenses as it rises above the top of the convection layer. It is clear from observations that each cloud in a developed cloud field does not consist simply of an isolated thermal which has risen coherently from the ground, as is the case with incipient cloud. On the other hand, the convection layer below cloud base is the source of moisture for cumulus clouds. A complete model of a cumulus cloud field therefore requires some specification of the sub-cloud region from which the clouds originate.

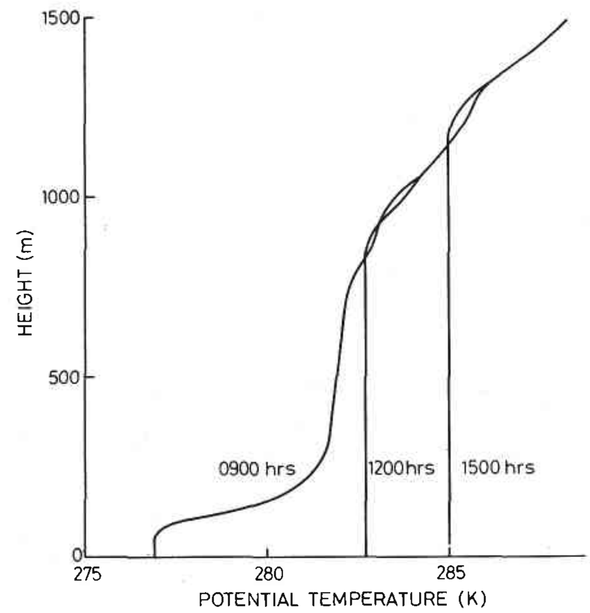
In modelling it is simplest just to consider convection in the absence of moisture. A model of the dry convection layer has been developed in order to predict the profiles of potential temperature which develop when thermal elements penetrate into a stable layer. Given an initial state of the atmosphere, and making well-based assumptions regarding the structure of the thermal elements, the model predictions are found to be in good agreement with field observations. The observed extent of penetration of thermals into the overlying stable region is explained by assuming that when they become negatively buoyant they detrain or lose fluid into their environment; this detrainment is associated with internal forces within the thermal which cause some of the fluid to decelerate until it moves with the environmental air.

The model has been extended to predict both the properties of the convection layer where moisture is present and the time interval from the onset of convection to the development of the first traces of cumulus (incipient cloud). For this development of the model the penetration region, which caps the mixed layer, is assumed to consist of intermittent patches of mixed layer air. Comparison of model predictions with laboratory and field observations gives good support for the theory.

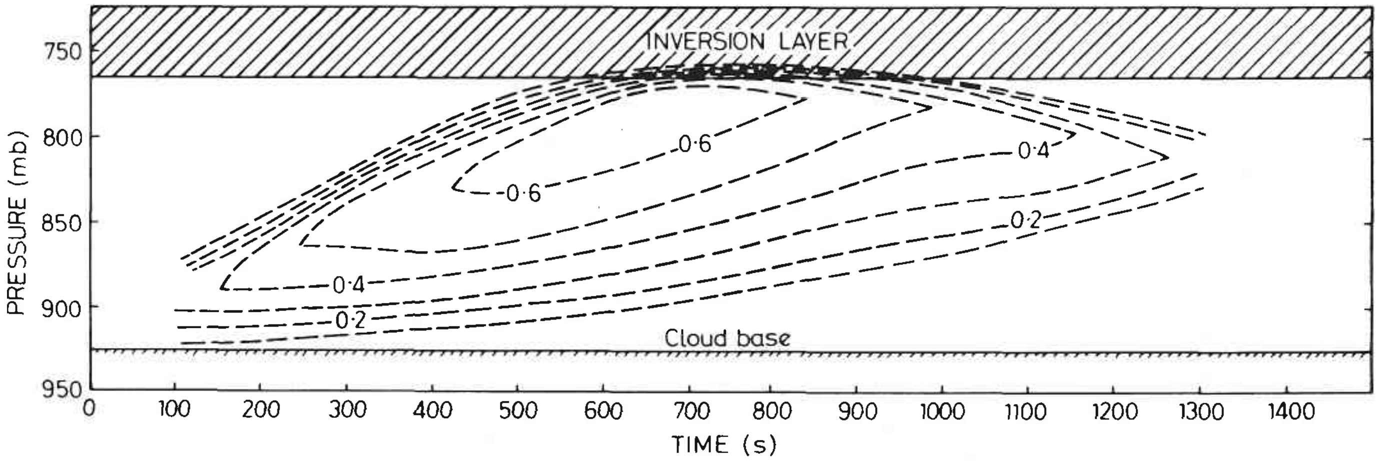
INDIVIDUAL CUMULUS CLOUDS

In order to analyse the detailed behaviour of cumulus clouds it is common practice to develop a mathematical model of an individual cloud growing in a specified environment. Such models involve non-linear partial-differential equations which we solve numerically on a CDC 7600 computer. Cloud models can be put into categories determined by the number of spatial dimensions that are resolved.

A one-dimensional model predicts the temporal development of the mean properties averaged over the horizontal cross-section of a cloud at a given level. Our model allows the cloud radius to vary with height and time, and downdraughts can be induced in the clear air through which the cloud grows. The relatively simple specification of the model ensures that its solution will not tax the run-time or storage-space resources of the computer. Thus a one-dimensional model is convenient for use in numerical experiments involving many solutions of the model equations in order to determine the dependence of some cloud parameter upon another. Such models also seem to be suitable for the study of the detailed effects of the microphysical properties (such as



Temporal behaviour of the potential temperature profile of the air above a heated surface, as predicted by a mathematical model.



Contours of liquid water density (g m⁻³) as a function of time for a cloud growing in an environment capped by an inversion, as predicted by a one-dimensional model.

the effect of droplet growth) on the behaviour of clouds.

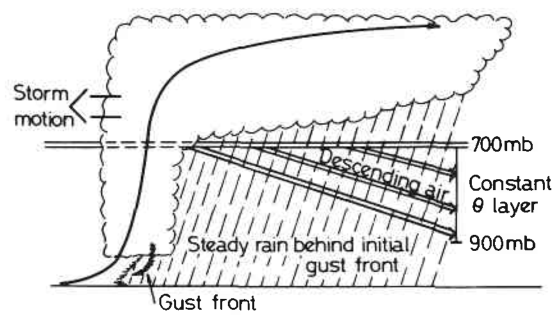
Observations from our research aircraft show that the liquid water density in a cumulus cloud tends to be considerably less than that which would result from lifting saturated air from cloud base under adiabatic conditions. This means that the entrainment of dry environmental air into the cloud must be modelled carefully. A further observation is that cloud base *remains essentially constant throughout the active* lifetime of a cloud. Solutions of the one-dimensional model imply that this result can be achieved only if there is a continuous source of moisture at cloud base. This is contrary to the usual initialization procedure for cloud models, in which a large saturated mass of air is arbitrarily injected into the environment. It would appear that a cumulus cloud is not formed by a single large thermal rising above its condensation level; rather, a cloud requires a steadier but weaker moisture source to be provided from the convection layer beneath cloud base.

We have developed a two-dimensional cloud model in which the motion is assumed to be axisymmetric. This model resolves both the radial and vertical structure of an individual cumulus cloud, and the solution method is *devised to avoid errors arising from the numerical* approximations to the actual differential equations. There is some saving in computer storage and run-time by solving the model on a non-uniform horizontal grid such that the grid-spacing increases away from the cloud axis.

The two-dimensional model is less constrained than the one-dimensional model and so it can be used to test some of the assumptions that are made in the derivation of the one-dimensional model. The two-dimensional model takes account of the pressure field induced by a cloud: this is generally neglected in one-dimensional models. The two-dimensional model is also used to study the conditions under which a cloud grows in a manner consistent with observations. As with the one-dimensional model, it is found that a realistic cloud *cannot be initialized* by a single large moisture or heat perturbation. A steady flux of moisture or heat from the surface provides an appropriate source for a cumulus cloud.

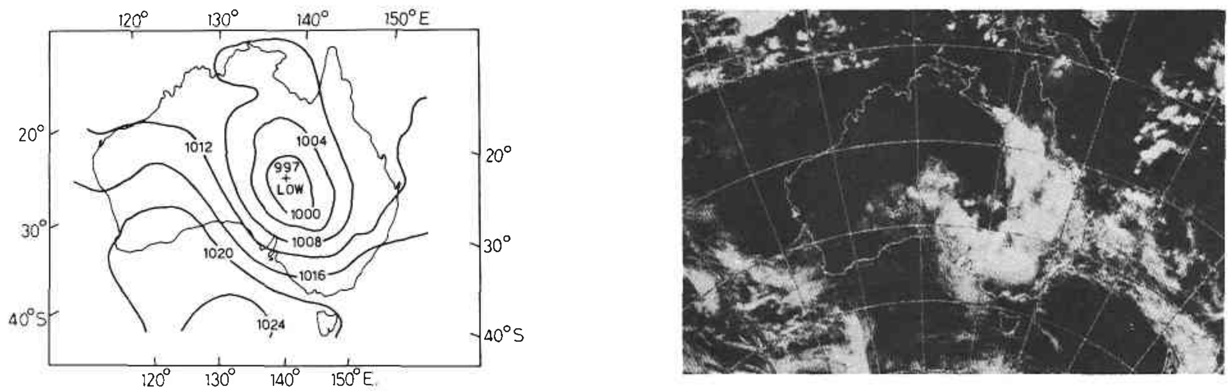
DOWNDRAUGHTS BEHIND SQUALL LINES

Fields of individual cumulus clouds represent only one of several types of cloud affecting the troposphere. Cumulonimbus clouds often develop in regions of strong convection and the consequent storms sometimes propagate horizontally if the wind profile is appropriate. Travelling storms not only produce significant amounts of precipitation but also tend to modify the air in the lower atmosphere as they pass over a region. Our analysis of some published observations of tropical squall lines in Venezuela suggests that downdraughts generated by the precipitation cause air from the middle troposphere ahead of a squall line to descend to beneath cloud base behind the line. This descent produces a layer of sub-cloud air in which the equivalent potential temperature is constant.



Air flow relative to a travelling squall line. Descending air produces a sub-cloud layer of constant equivalent potential temperature.

The profiles of potential temperature and specific humidity in the sub-cloud region are affected by evaporation of precipitation from the cloud. We find that the observed profiles of potential temperature and specific humidity can be reproduced by solving a system of equations which represent the evaporation of rain in a descending parcel of air. This physically straightforward situation provides a suitable test for simplified models — i.e. the parameterization of the microphysical processes in clouds. Parameterization of the microphysics must be used in dynamically complex cloud models because of computer limitations.



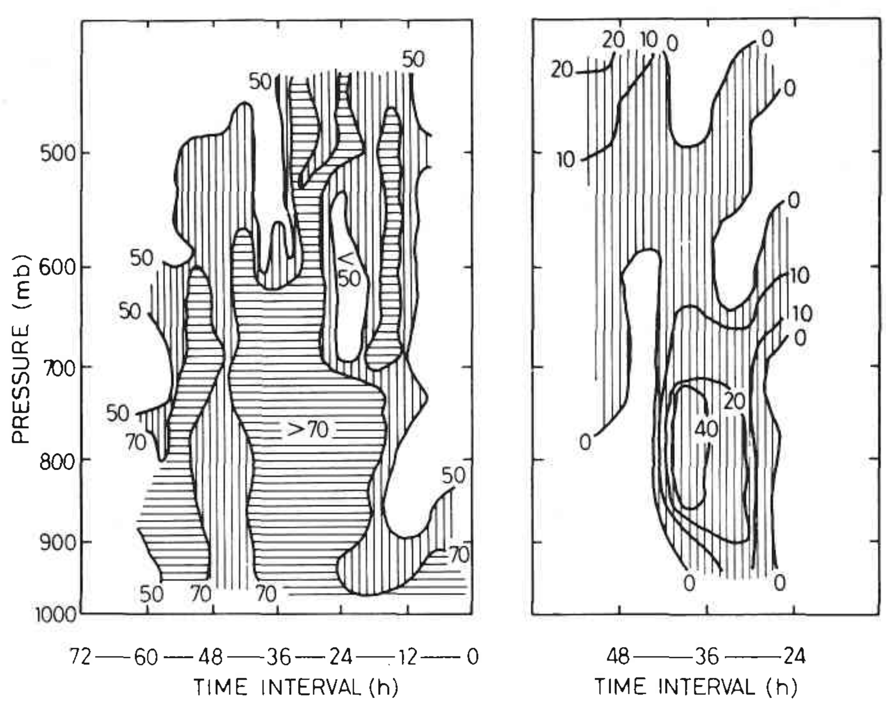
Surface pressure map showing a low-pressure system moving over Victoria and producing deep stratiform cloud. The satellite photograph was taken on the same day.

STRATUS CLOUD

While cumulus and cumulonimbus clouds are formed basically by convection some clouds are associated with the lifting of an air mass by a synoptic-scale low-pressure system. Under these conditions the resulting stratus cloud has horizontal length scales of many hundreds of kilometres. Preliminary observations suggest that during our cloud-seeding experiment in western Victoria, described later in this booklet, the most suitable conditions for seeding with silver iodide will occur in the deep stratiform cloud of synoptic-scale systems. These systems produce about 30% of the spring rainfall in the region, and contribute significantly to the general circulation by transporting heat and moisture to high latitudes.

Although a low-pressure system has a lifetime of several days, the intense rain at a given location on the ground falls over a period of about 12 hours. Information about the rain process can be derived from data, collected during frequent rawinsonde ascents, which reveals the general structure of the system as it passes a ground station. By estimating the large-scale horizontal gradients of heat and moisture it is possible to calculate the vertical velocity field required to obtain the observed temperature and humidity profiles. The rainfall at the ground can then be predicted. The calculation takes into account the effects of both cloud water, which moves with the air, and rain water, which falls relative to the air motion. This one-dimensional model of a synoptic-scale system is useful for studying the consequences of varying the microphysical properties of stratus cloud, and so it is relevant to our current cloud-seeding experiment.

The precipitation from a low-pressure system is maintained by synoptic-scale lifting of the air mass, but studies in the U.K. and the U.S.A. imply that the rain is intermittent and is associated with mesoscale rain bands having horizontal scales of 50 to 100 km. Any detailed analysis of low-pressure systems must therefore take into account these mesoscale features of the motion. Research into these matters is planned for the future.



Contours of relative humidity (%) measured during the passage of a low-pressure system over Victoria (left) and the contours of vertical velocity (cm s⁻¹) for the same system derived by a one-dimensional model.

AIRBORNE PARTICLES, WEATHER AND CLIMATE

Much of the Division's work is concerned with deliberate attempts to increase rainfall by adding ice-forming particles to clouds, but attention is also paid to the possibility that rainfall may be altered inadvertently as a result of Man's activities.

The ability of a cloud to rain is influenced not only by the number of ice-forming particles in the air in which it is growing but also by the size and concentration of its cloud droplets, which in turn are influenced by the size distribution and concentrations of the soluble particles suspended in the air. When large numbers of such airborne particles are present, cloud droplets are more numerous and hence smaller than if the cloud had been formed in cleaner air. The chance is correspondingly reduced that the small drops will collide, coalesce, and form raindrops. As we know, many of Man's activities produce very large numbers of soluble particles that remain suspended in the air until caught up in cloud drops or washed out by rain. Therefore any increase in the concentrations of such particles originating in industrialized areas upwind of agricultural land would be a cause of concern, since any changes in average rainfall can have important economic consequences.

Any large-scale change in concentrations of water drops in clouds can affect not only rainfall but also the fraction of the sun's radiation which reaches the earth's surface. Increasing the concentration increases the fraction of sunlight reflected by the clouds. On a large scale, the amount or distribution of energy available for driving the world's weather systems could thereby be affected, with repercussions for global climate.

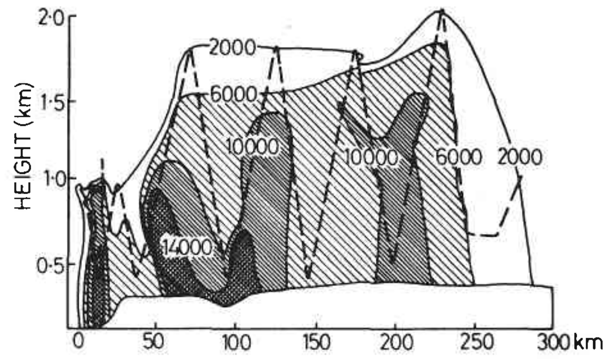
There are three main questions to be answered about airborne particles:

(1) Are the particles active in cloud droplet formation mainly natural or are they man-made?
(2) Are their numbers likely to increase with increasing industrialization?
(3) What are the overall effects of the particles on rainfall production and climate?

The ways in which the Division is attempting to answer these questions are as follows.

First, we have made airborne surveys over as much of Australia as possible to find the nature and sources of existing particles. Of course the conditions change with time — bushfires, droughts and floods cause natural changes, while increasing population leads to a change in the balance between natural and man-made particles. Repeated surveys are therefore required.

The Cessna 402 aircraft used for aerosol research.



Isopleths of Aitken particle concentration measured 167 km down-wind of Perth on Sunday 22 May 1977 at 1300 hrs local time.

Secondly, in order to observe more closely changes in particle concentrations long-term measurements are being made at Cape Grim, a remote site on the west coast of Tasmania. At the same time measurements are being made of other quantities that might influence climate. The results should give some insight into the extent to which particles from the populated regions of the southern hemisphere can penetrate towards the South Pole.

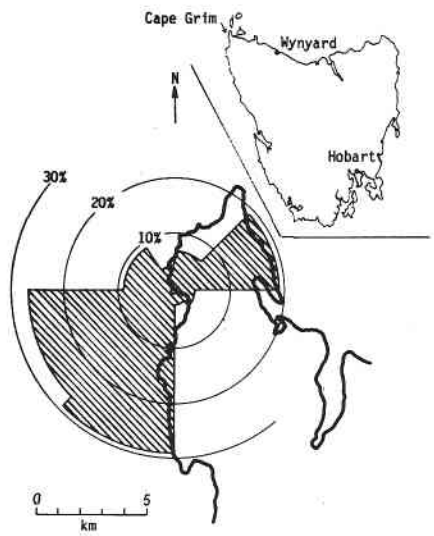
The third question is undoubtedly the most important and will certainly be very difficult to answer. We know for certain that increasing the concentration of airborne soluble particles increases the cloud droplet concentration, thus reducing the probability of rain in an individual cumulus cloud in a period of say 30 min. However, the effect upon clouds with longer lifetimes is not quite so certain. The effects are likely to be even more complicated when as well as an increase in small particles there is a simultaneous addition of very large soluble particles and ice-forming particles, both of which may accompany certain particle-emitting processes. In an attempt to solve this problem we are comparing the rain from clouds which form in the plume of particles from a very strong isolated source with that from clouds which form in clean air nearby. Many preliminary measurements have been made of the concentration of particles present in the plume at different distances from the source.

SURVEYS FROM AIRCRAFT

A Cessna-402 aircraft was fitted out with an air intake on the nose and a variety of particle counting and collecting devices, and flown long distances, sampling at levels ranging from close to the ground to above the cloud tops in a sequence of ascents and descents. Centres of population were avoided, except for special studies of large sources such as Kwinana-Fremantle-Perth, Newcastle-Sydney-Wollongong, and smaller isolated sources such as Broome and Carnarvon.

There are many possible sources of small particles in the atmosphere and our aim has been to find their relative importance. Smoke from fires, wind-blown dust, sea spray, particles exuded by forests or other vegetation, rotting seaweed and combinations of reactive gases — all these have been suggested as important natural sources. Our surveys have so far shown that while wind-blown dust and sea spray provide the majority of very large (>2 μm diameter) particles, they provide a negligible proportion of the much smaller (0.02 to 0.2 μm diameter) and far more numerous particles active in cloud formation. Most of the small particles seem to be ammonium sulphate; whether of natural or industrial origin these small particles probably come from reaction of sulphur dioxide with water vapour to form sulphuric acid, followed by combination with ammonia. Of the natural sources, fires (many of which are not really "natural") probably provide the greatest number of particles. However, the output from urban or industrial areas where fuel containing sulphur is burnt or refined, or where sulphide ores are processed, is so great that it is probable that most sulphate particles are man-made. A city complex such as Kwinana-Fremantle-Perth produces in excess of 10^{19} particles per second which are detectable at immense distances downwind of their origin.

This work has shown clearly that the *potential* for weather modification through industrialization is present. It remains to be shown whether such modification is on a large scale or insignificant, deleterious or beneficial.



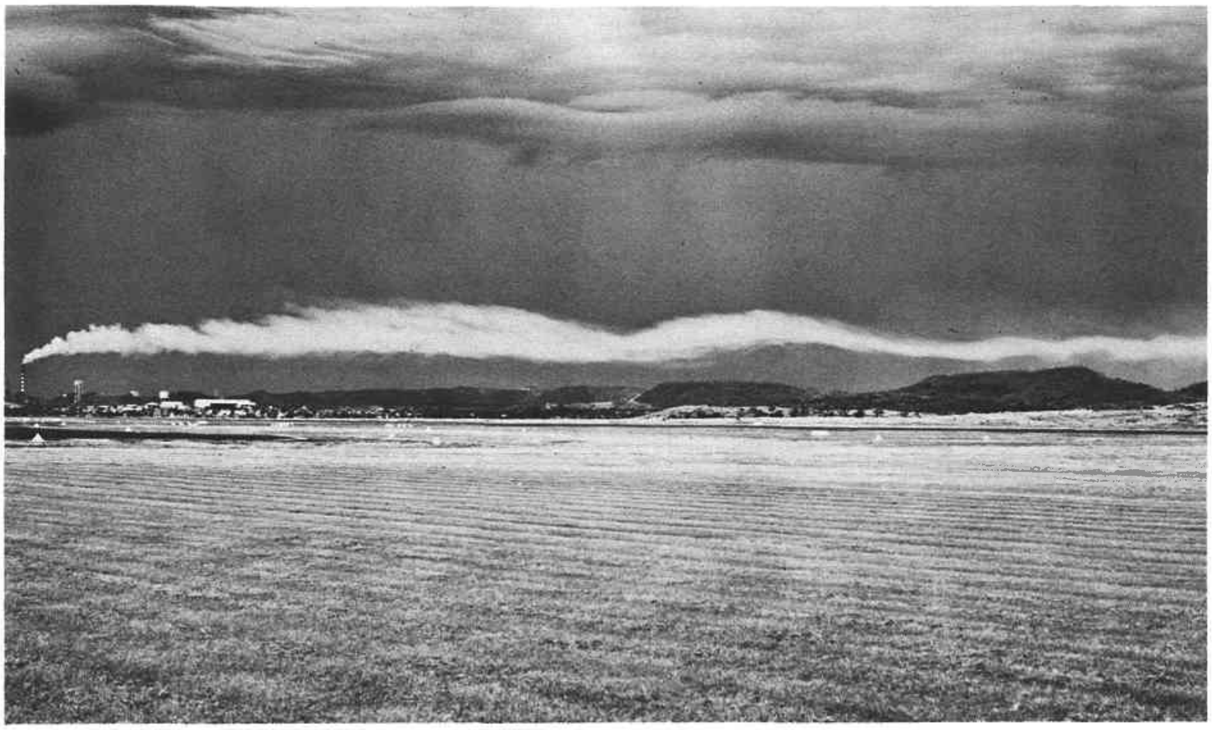
Annual wind direction frequency distribution at Cape Grim. Note that winds from between west and south are those most likely to be free of local pollution and that these winds occur nearly 60% of the time. The inset shows the location of Cape Grim at the north-west tip of Tasmania.

GROUND-BASED MONITORING FOR CLIMATIC CHANGE

Climate is very variable in time and space, and the reasons for this, of which there are probably many, are largely unknown. There is unfortunately little chance in the short term of finding a cause-and-effect relationship between changes in the type or concentration of atmospheric particles and changes in climate. However, by long-term monitoring of many probable causes of climatic change in a region well-removed from sources of pollution, we may eventually be able to separate out those causes that are significant. With this in mind a small network of stations has been established under the guidance of the World Meteorological Organization, with Australia providing a base at Cape Grim in north-west Tasmania. Early in 1979 the Government announced that a permanent station would be built to replace the temporary trailer used since April 1976.

The CSIRO Divisions of Atmospheric Physics and of Cloud Physics are both investigating the potentially important sources of climate change. The Atmospheric Physics program aims at measuring and interpreting

The baseline station is situated on the highest point of the headland at Cape Grim.



The plume from the Mt. Isa copper smelter photographed during a field trip in May 1977. Chimney height is 150 m; approximately 5 km of the plume's length is shown.

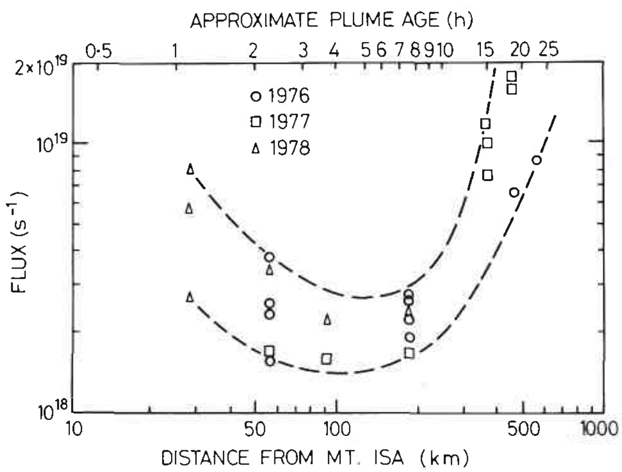
changes in the concentration of important atmospheric trace gases, including carbon dioxide, ozone, nitrogen oxides, and freons. This program will be extended to include sulphur dioxide. Our own work is principally concerned with atmospheric particles. The number, nature and size distribution of atmospheric particles are investigated routinely and studies are made of the short-term and long-term variations. In addition we have commenced to measure the concentration of ammonia gas — data which is important in determining the sources of particles produced in remote locations.

Most of the large particles observed at Cape Grim are sea-salt — as might be expected for a site on the edge of a cliff overlooking the sea and exposed to fierce gales — whereas most of the smaller particles are ammonium sulphate. Occasionally however urban pollution from Melbourne, about 400 km to the north, is very obvious, becoming the dominant aerosol.

EFFECT OF POLLUTION ON RAINFALL

In the course of our aircraft surveys of particles it became clear that the copper and lead smelters at Mt. Isa in Queensland were a remarkably rich source of particles in an otherwise clean environment. Mt. Isa is in generally flat terrain which extends out to great distances. Orography therefore plays no part in the rainfall distribution. The area is thought to be particularly suitable for comparing rainfall in a polluted zone with rainfall in nearby unaffected air.

We first studied the way in which the plume disperses, by flying through it at different levels at a sequence of distances from the chimney stacks and constructing contours of particle concentration for each distance. The most important features to emerge were that at distances of 50-500 km the angular plume width stayed more or less constant with a spread of 20-30° irrespective of distance from the source and that the total number of particles per second crossing a plane perpendicular to the wind (particle "flux") at first decreased with distance and then increased. The initial decrease was due to collision and coagulation of the highly concentrated particles. As the plume spread through an ever-increasing volume the importance of coagulation decreased in comparison with particle generation from the sulphur-containing gases in the plume.

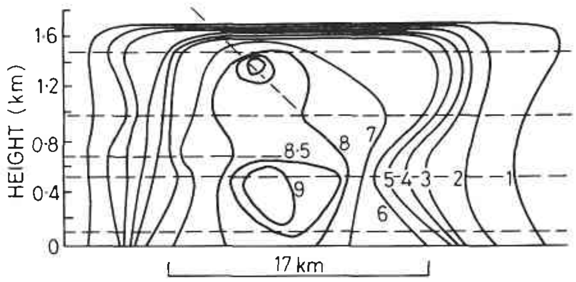


Variation of Aitken particle flux in the plume as a function of distance from Mt. Isa. The measurements were made in June 1976, May 1977 and February 1978.

Near the stacks the particles were mostly sulphuric acid, which has a very distinctive appearance when captured on a surface and viewed by an electron microscope; this material was gradually transformed to ammonium sulphate as it drifted downwind, presumably through reaction with the traces of ammonia which are always present in the atmosphere.

Preliminary observations have been made in clouds forming in the area. The clouds examined so far have been all small to medium cumulus, generally containing more and smaller drops when growing in the plume than in the clean air nearby. An increase in drop concentration and decrease in drop size would be expected to delay the onset of precipitation, as was in fact observed in the only clear-cut case of precipitation so far studied.

The overall effect on precipitation will require a lengthy observation program. Much of the rain that falls in the area is in the form of heavy storms; therefore, just as with cloud-seeding, it will not be easy to determine whether an observed increase or decrease in rainfall is directly attributable to the man-made particles — unless of course the differences are large and consistent.

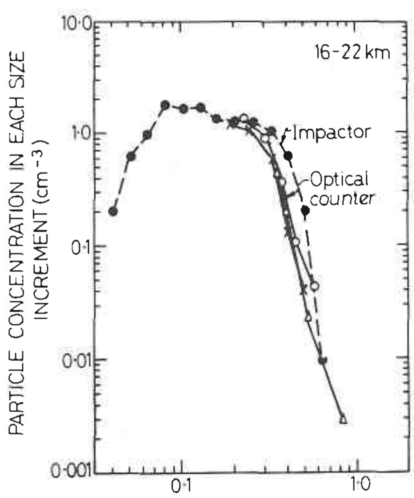


Isopleths of Aitken particle concentration, in thousands per cubic centimetre, measured by traversing the Mt. Isa plume. The measurement was made 185 km downwind of Mt. Isa on 16 June 1976 at 1045 hrs local time. The aircraft paths are shown by broken lines.

OTHER CAUSES OF CLIMATIC CHANGE: STRATOSPHERIC PARTICLES

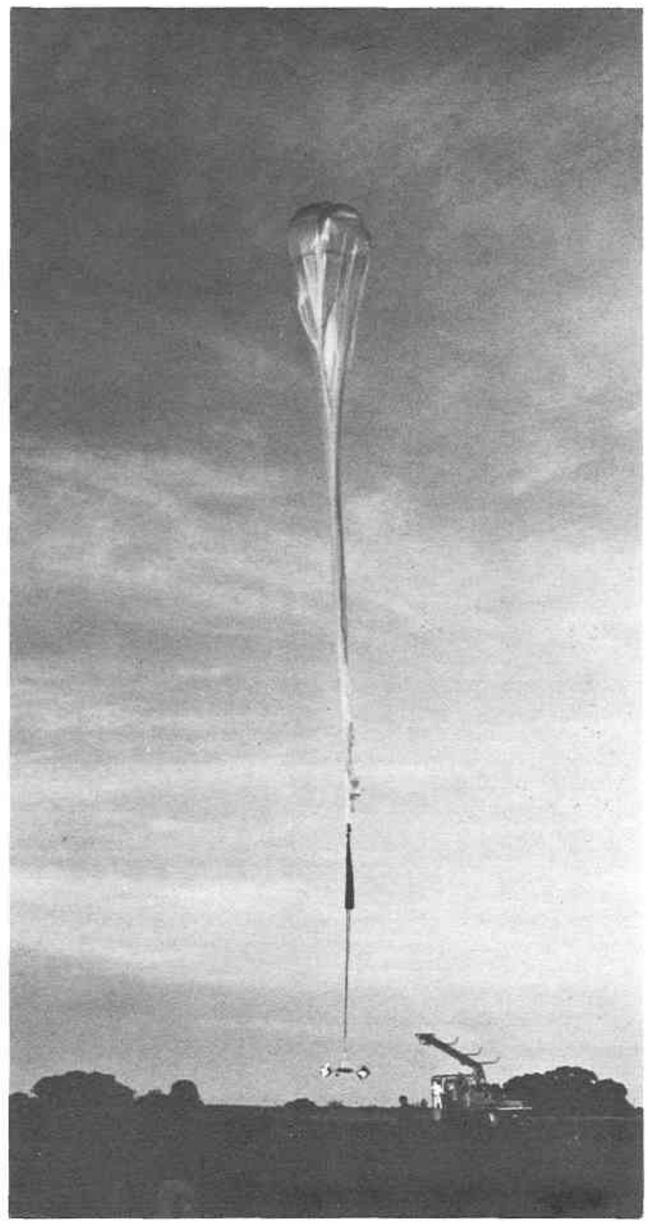
While particles in the lower atmosphere have a potential for influencing climate through their effects on clouds, those suspended above the weather regions can affect ground temperatures. By absorbing more radiation than they emit stratospheric particles increase the temperature of the air around them and correspondingly reduce the net amount of radiation available at the ground. For example, general cooling at ground level usually follows major volcanic eruptions, which greatly increase the load of particles in the upper atmosphere.

For many years the primary means of studying stratospheric particles has been by direct collection, using



Size distributions of stratospheric particles determined using impaction and in-situ photo-electric detection techniques.

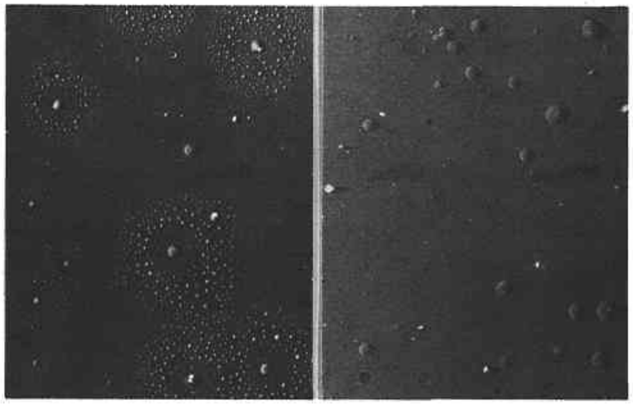
equipment carried on balloons and later retrieved. More recently we have also used methods of counting and sizing the particles while they are still in the stratosphere by using their light-scattering property. This method avoids the possibility inherent in the direct-collection method that the particles could evaporate or undergo change between collection and examination. Impaction techniques are, of course, still necessary to allow us to study the chemical nature of individual particles. The light-scattering method has allowed direct assessment to be made of the efficiency with which impactors collect



A large helium-filled balloon starts its ascent carrying particle-sensing equipment to about 30 km altitude.

particles in the stratosphere in place of laboratory-based or theoretical values of this quantity.

Changes that occur in the stratosphere can be monitored from the ground by optical radar ("lidar") or by light scattering observed from a satellite. However, such results can be interpreted only when the particle size distribution and composition are known in detail. For example, remote-sensing procedures might result in misinterpretation or failure to detect the very obvious differences in nature of the aerosol particles shown in photographs (a) and (b) (below), even if they scattered light differently.



(a) (b)

Particles with very different appearances collected in February 1977 (a) and July 1977 (b), from approximately the same altitude (18 km).

THE CHEMISTRY OF AIRBORNE PARTICLES

In our interpretation of the origin and importance of particles we rely heavily on our knowledge of their chemical nature. The larger particles — salt spray and dusts (which constitute the greater part of the total mass of suspended material in the atmosphere) — are usually quite different in nature from the smaller, more numerous particles which are of significance in cloud and rain processes. If we wish to obtain information about the chemical nature of the small particles it would be misleading to collect a large sample containing a mixture of all the particles present and analyse it by conventional chemical techniques. To determine the importance of the atmospheric particles for their effects upon weather we need to be able to identify a few particular substances, notably sulphuric acid and ammonium sulphate — the major components of most atmospheric particles. We also need to be able to obtain some estimate of the mass of these substances in individual particles weighing no more than 10^{-15} g. Such tests have now been fully developed and are routinely used.

The particles are collected on an electron microscope grid that has been precoated with a thin layer of silicone oil; the particles are then "shadowed" by vacuum evaporation of barium chloride, followed by silicon oxide, at an angle such that the "shadows" (where no chemical is deposited) are twice as long as the particle is high. Next the grid is exposed to a high humidity for an hour or so and the particles re-examined under the electron microscope. Sulphates leave tell-tale rings of barium sulphate around the outline of the particle and its shadow of inert insoluble silicon oxide. The ratio of the size of the rings to the size of the original particle allows the proportion of sulphate to be estimated.

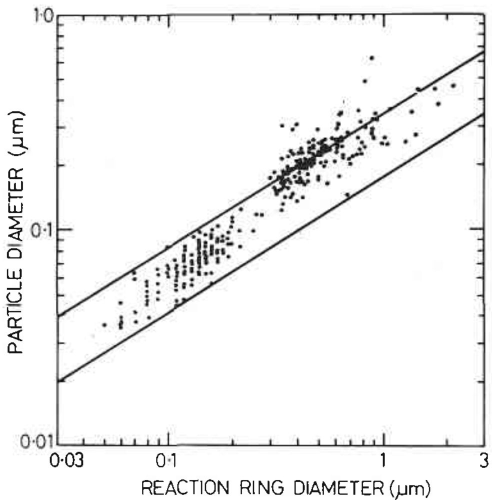
Even though the accuracy limits are wide by some standards, the estimation of the proportion of sulphate in such tiny particles is still a remarkable achievement. Masses of as little as 10^{-17} g of sulphate can be determined to within about 40%. A similar test has been developed for nitrate, but it has not proved easy to make quantitative. Further development work on other tests would be of great benefit in the study of small airborne particles, even though the sulphate test covers such a high proportion of them.

SMALL-PARTICLE PRODUCTION

We can divide atmospheric particles into two classes: giant particles are those larger than about 2 μm diameter; small particles, including the Aitken nuclei, are those which extend in size almost down to molecular dimensions, or about 0.001 μm diameter.

Giant particles are produced by mechanical disruption of macroscopic objects. For example, large salt particles are produced at the ocean surface by wind-blown spray or by bursting bubbles; crustal weathering on land leads to the large crystalline particles of which wind-blown dusts are composed. Although giant particles often represent the greater part of the mass of airborne material they usually account for only 1% or less of the total number concentration of atmospheric particles. It is the more numerous small particles that determine how many cloud droplets are formed in a parcel of rising air under given environmental conditions.

The special fraction of Aitken nuclei which participates in cloud droplet formation is that fraction of soluble particles with diameters larger than approximately 0.02 μm. The most common of these particles are composed of ammonium sulphate. We would like to know how these particles are formed in the atmosphere so that we can understand why their concentration changes in space and time and the degree to which industrial processes are important in these changes.



Results of the thin film test for sulphate applied to particles collected from the Mt. Isa plume, 370 km downwind of Mt. Isa, on 16 May 1977. Particles composed entirely of ammonium sulphate should give data points which lie between the two straight lines.

It has been known for some time that small particles can be formed readily by nucleation from the gas phase. However, a quantitative description of the process by which ammonium sulphate particles are formed requires a knowledge of the atmospheric concentrations of the gaseous precursors — i.e. ammonia and sulphur dioxide. The latter is oxidized to gaseous sulphuric acid prior to the formation of condensed-phase sulphuric acid or ammonium sulphate particles.

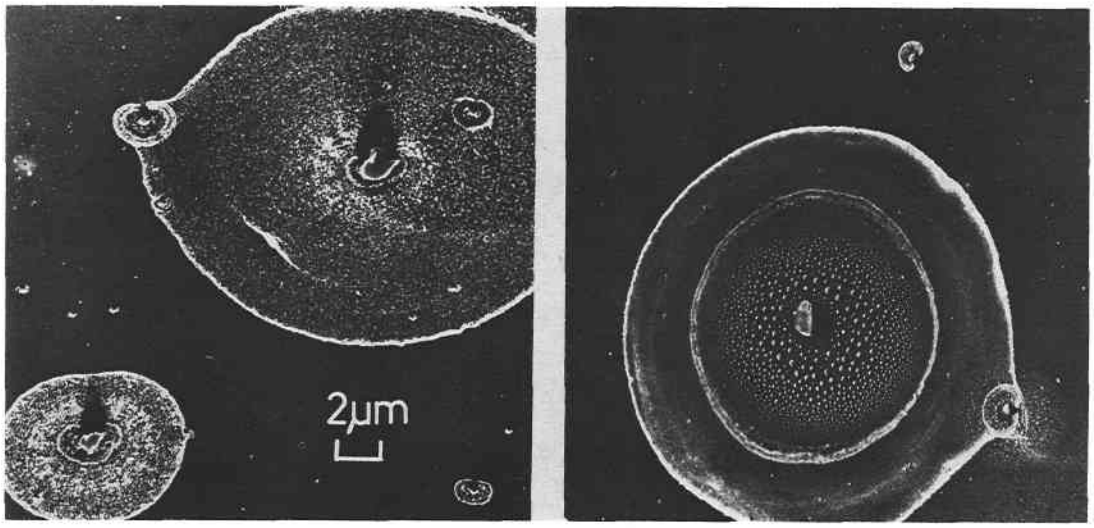
Techniques have been available for some time for measuring sulphur dioxide at the parts-per-billion level usually encountered in unpolluted regions. Until recently however it was possible to make similar measurements of ammonia only in the laboratory. In order to measure the very low ammonia concentrations which occur in the arid continental or remote maritime areas in which we are interested it has been necessary to develop an alternative to the usual ammonia detection methods. In our method air containing ammonia is passed through a filter impregnated with oxalic acid, which reacts with the ammonia. The resulting ammonium oxalate is then concentrated in a thin ring by washing it from the centre of the filter to a heated outer ring, where the solvent evaporates. A specific reagent is applied to the paper to give a dark colour to the ring, the intensity of which depends on the amount of ammonium ion present. The test is made quantitative by comparing the intensity of the ring with that obtained by using standard ammonia solutions. The detection limit depends upon sampling time, and is about 0.05 parts-per-billion by volume for a three-hour sample. The accuracy, although not high, is within about 40%, which is adequate for our purposes. Preliminary results in the field have yielded ammonia concentrations in summer of about 1 ppbV over central Australia in the mixed layer and about one-fifth this value over the oceans south of the continent. In winter these values may be reduced by a factor of three.

A reliable estimate of the vapour pressure of sulphuric acid over concentrated aqueous sulphuric acid solution is required also if the homogeneous nucleation of sulphuric acid particles is to be described quantitatively. Present estimates vary by as much as two orders of magnitude at a specified composition and temperature, so currently we are evaluating several methods of directly measuring the vapour pressure as a function of acid concentration and temperature. One method uses the ring oven technique, this time detecting the sulphate ion rather than ammonia; another involves measuring the change in conductivity of water through which acid vapour has been bubbled; in the third a measurement is made of the pH change in water exposed to a known volume of acid vapour.

The final piece of information needed for our understanding of the particle formation process is the size distribution of the small ammonium sulphate particles in the atmosphere, particularly in the diameter interval 0.001 to 0.2 μm. Reliable measurements have only recently been possible for such small particles. In the method we have developed, measurements are made of the fraction of particles which can penetrate a series of filters having different filtration properties. The transmission characteristics of the filters vary with particle size, and in a way which is well known from theoretical studies. Hence it is possible to use the measured penetration fractions to reconstruct numerically the initial particle size distribution.

LONG-TERM EFFECTS OF PARTICLE POLLUTION

The programs described above are essential to an understanding of the processes by which small sulphate particles are formed, both in remote areas such as Cape Grim and in regions of high sulphur dioxide concentration such as in the Mt. Isa plume. It is estimated that human activities contribute between one-third and one-half of the total 200 million tonnes per year of sulphur at present injected into the earth's atmosphere. This fraction appears to be increasing, and it is clear therefore that an understanding of the particle generation process is essential if we are to assess the effects of human activities on the global environment.



Particles containing soluble sulphate react with a thin film of barium chloride to produce rings of insoluble barium sulphate. Left, ammonium sulphate particles; right, sulphuric acid particles.


CSIRO
VH-CAT
VH-CAT

A NEW CLOUD PHYSICS RESEARCH AIRCRAFT

The Division has recently acquired a Fokker Friendship F-27, which has been modified to enable it to play its new role as a research aircraft. It replaces a DC3 which has been used for cloud physics research for the last 20 years.

An instrumented research aircraft is sometimes described as a "flying laboratory"; a more realistic term might be "flying observatory", because in cloud physics few experiments, in the laboratory sense, are performed in flight. The main function of the airborne system is to make measurements and take samples during flight and store the results for processing and evaluation in the laboratory.

The instrumentation consists of three principal sections.

(i) Sensors mounted externally on the aircraft to detect certain properties of the atmosphere.

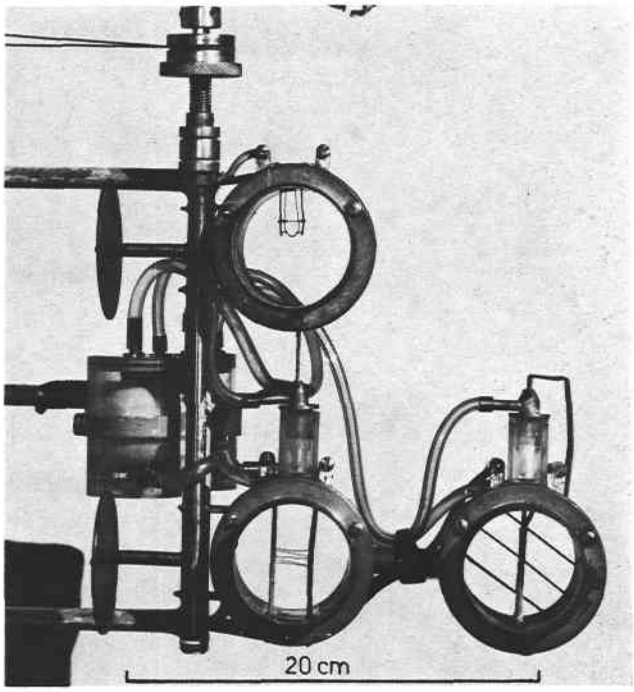
(ii) Processing circuits and devices, carried in the aircraft cabin, to convert the sensor signals and samples to storable form.

(iii) Storage systems for the data and samples.

Much of this instrumentation has been designed and built by the Division.

The purpose of each research expedition is carefully defined and the array of sensors mounted on the aircraft is selected accordingly. An economic and scientific advantage of a large aircraft, like the F-27, is that the equipment for more than one research team may be carried on many flights; joint missions produce more comprehensive data and sometimes yield solutions to problems more quickly and cheaply than individual operations.

It is convenient to describe the instruments in terms of the properties they are designed to measure.



The top circular housing contains a fine-wire resistance thermometer to sense dry air temperature fluctuations; below it another thermometer, covered with a cotton wick, measures wet-bulb temperature. To the right a more robust, wet sensor is used for in-cloud measurements. A constant-water supply to the wicks is maintained by the container with tubes attached.

PRESSURE, TEMPERATURE AND HUMIDITY

Measurement of these fundamental properties of the atmosphere and their variations with height, location and time is essential to almost all atmospheric physics research.

Static pressure, which is a measure of altitude, and dynamic pressure, a measure of forward speed of the aircraft, are both registered by electrical sensors which communicate with orifices on the fuselage, nose and wing tips of the aircraft.

A variety of electrical thermometers is used to determine the temperature of the air at flight level. The mean temperature, averaged over about 5 s, can be determined with high absolute accuracy — a few hundredths of a degree Celsius — but fluctuations in temperature at frequencies as high as 10 times a second are obtainable at, perhaps, only half this absolute precision. At temperatures below the freezing point of water the thermometer housing has to be de-iced by a heater and consequently a lower accuracy has to be accepted.

The water vapour content of the air, or humidity, is measured by the additional use of wet-bulb thermometers or by sensing the temperature at which dew forms on a polished plate.

AIR MOTION

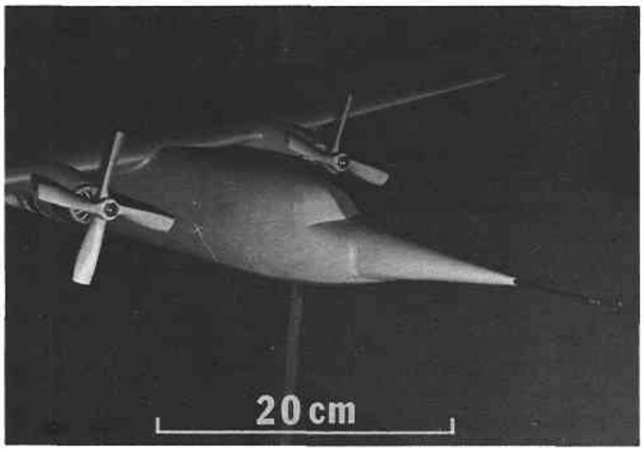
The most familiar is the mean horizontal motion — the wind — which varies with height above the surface and with time.

There is often also a mean vertical motion, generally of much smaller magnitude, and there are small-scale fluctuating eddy-like movements of the air describable by such terms as convection and turbulence.

To measure the velocity of the air from an aircraft in motion the aircraft's own altitude, speed and direction, in a three-dimensional sense, must be determined in relation to the ground. The velocity of the air relative to the aircraft must then also be measured. Three separate systems are in use in the F-27 to satisfy the requirements of the scientific research programs currently in progress.

The horizontal wind at flight level is measured by transmitting a radar signal from the aircraft and receiving the energy reflected back from the ground; this radar operates equally well in clear air and in cloud. The difference in frequency between transmitted and received signals, or Doppler frequency, together with the airspeed measured by the pressure sensors, enables the wind velocity to be computed.

Small-scale air motions due to eddies ranging in size from about 10 m to 500 m are measured by means of a gyroscopically stabilized platform in the cabin and sensitive motion-sensing vanes attached to an extension of the nose of the aircraft. At a distance of several metres ahead of the nose the disturbance to the air by the aircraft itself is negligibly small.



A flow-direction sensor is shown extending from the nose of a model of the F-27 aircraft during wind tunnel tests. The nose of the actual aircraft had to be extended to enable instruments to be mounted in air undisturbed by the presence of the aircraft itself during flight.

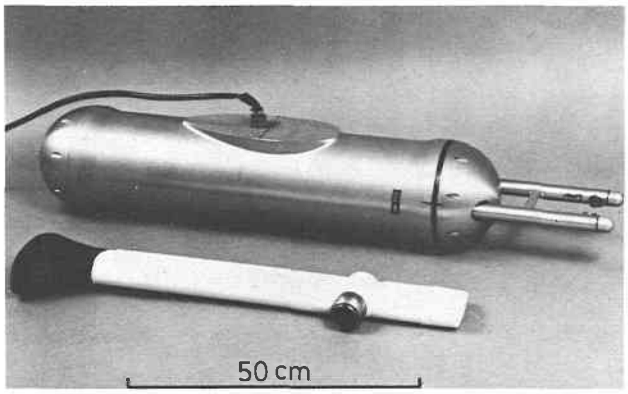
The design of this nose-cone was based on the results of experiments in a wind tunnel during which precise measurements of the air flow around a scale model of the aircraft were made.

In addition, a less accurate gyro-system determines air movements which are on a scale large enough to perturb the aircraft flight path itself; this instrument is adequate for some types of research in turbulent clouds.

CLOUD DROPLETS AND ICE CRYSTALS

Instruments to measure the concentration of droplets in various size ranges are carried by the aircraft. Some of these instruments rely upon the optical effects produced when cloud particles are swept through a laser beam; many thousands of droplets are automatically counted and their sizes estimated in each second as the aircraft flies through cloud.

One recently acquired instrument of this kind is capable of producing two-dimensional images of particles and is particularly effective in determining the shapes of ice crystals.

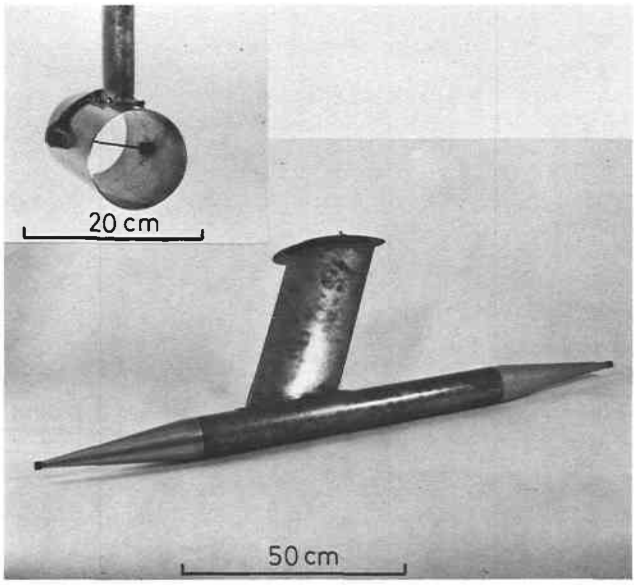


The larger instrument measures the size, shape and number density of ice crystals in clouds. The smaller counts and sizes cloud water droplets. Both instruments detect the light scattered from laser beams as particles pass through them.

For some purposes, particularly in measurements associated with the application of cloud-seeding techniques, it has been found desirable to slow fragile crystals down from flight speed to an extent which permits them to be impacted on an oil-covered film without shattering. They may then be examined visually or imaged with a camera. Special equipment has been built by the Division for this purpose.

CLOUD WATER CONTENT

By adding up the volumes of all the droplets in a given volume of cloud it is possible to calculate the concentration of liquid water, knowledge of which is essential for many research projects. Information about droplet volumes can be obtained from the instruments described above; however, a separate instrument has been devised to measure the liquid water content directly. Another new instrument has been designed to measure the total concentration of water substance, i.e. the sum of that in the liquid and that in the vapour phase.



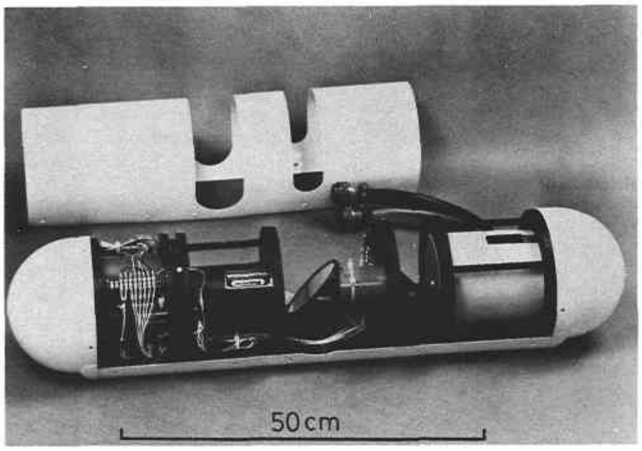
Cloud air enters the conical nose at the left-hand end of the lower instrument, is heated to evaporate all water and ice and is exhausted at the other end. Vapour concentration inside the instrument is measured to determine total water concentration. The upper instrument determines liquid water in cloud from the heat lost from the thin rod seen within the cylindrical housing.

RADIATION

The radiant energy received by the earth from the sun is the primary driving force of nearly all atmospheric phenomena. To understand the ways in which this energy is partitioned between various atmospheric processes we need to measure radiant power per unit area, or flux, at various wavelengths from ultra-violet to infra-red and in various directions.

The aircraft is equipped with several radiometers of different capabilities; one operates in a wavelength band which is not appreciably absorbed by the constituents of the air, and so when pointed downwards it is capable of measuring the temperature of the ground or sea over which the aircraft is flying.

Other radiometers measure the fluxes of radiant energy received from the sun or re-radiated from the earth or from clouds; some measurements give information on microphysical properties of clouds, i.e. droplet size and concentration.



Radiometers mounted inside this pod are exposed to the environment via two mirrors and corresponding slots in the cover. The mirrors rotate to enable radiant flux to be measured in a number of discrete angular directions between vertically upwards and downwards.

AEROSOLS

The atmosphere contains vast quantities of tiny particles some of which are of major importance in cloud processes and all of which have some relevance to the amount of the sun's radiation which reaches the surface of the earth.

The aircraft is equipped with a variety of instruments to detect and collect aerosol particles varying in size over an enormous range — from less than a hundredth of a micron to those visible to the human eye. Samples of air are taken through a carefully positioned orifice on the skin of the aircraft and the particles they contain are impacted on minute grids which are subsequently examined in an electron microscope. Particles collected in this way are analysed by chemical techniques devised by the Division and described elsewhere in this booklet. In-flight measurements of particle size and concentration utilize the optical effects which are observed as the particles pass through a beam of light.

INFORMATION STORAGE

Nearly all the processing and scientific evaluation of the observations collected in any airborne mission is carried out in the laboratory after completion of each field expedition. During the flights however some computation and study of the data may be necessary to adjust tactics according to the prevailing circumstances.

The principal data processing and storage system on board the aircraft is a powerful mini-computer, especially "ruggedized" for the aviation and military environment, which controls the recording of instrument signals on magnetic tape. Some of the instruments have their own individual subsidiary magnetic tape recorders and pen recorders.

Not all of the information can be collected in numerical form; samples of cloud particles and aerosol particles must be returned to the laboratory for further study, and facilities are provided for these purposes. Additionally there is the familiar photographic process for information storage, and cameras carried in the cabin and mounted in pods externally are used to obtain pictorial records of clouds and other meteorological phenomena.

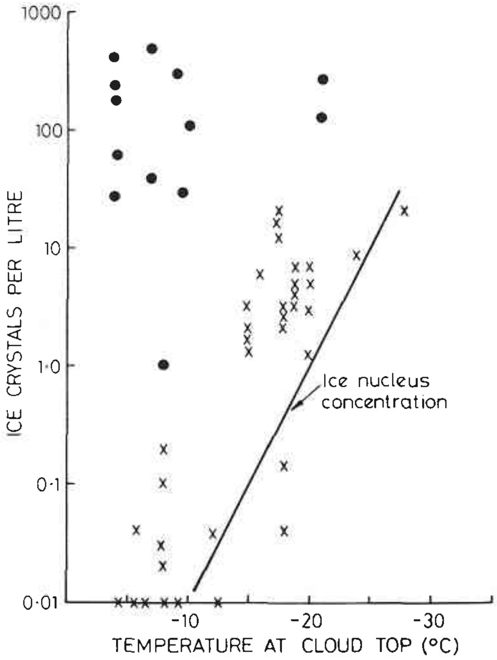
The F27 aircraft as instrumented in 1979. Instruments are located around the fuselage forward of the propellers. The instruments at the numbered positions are listed below:

1. *Ultra-violet radiation transmissometer for measuring average size of cloud particles. Upward-facing radiometer and total temperature sensor are also carried on this mount.*
2. *Raindrops are counted and measured as they sweep through the laser beam in this instrument.*
3. *Scanning radiometer for measurement of visible and infra-red radiant energy in directions from vertically upwards to downwards.*
4. *Sizes and numbers of very small cloud droplets are determined from scattering of laser light in this unit.*
5. *Ice crystals are decelerated before capture in this sampler to prevent shattering.*
6. *Infra-red spectrometer for estimating cloud particle size distribution.*
7. *Optical instrument for counting and imaging ice crystals and water droplets in clouds.*
8. *Assembly of an instrument for measuring liquid water concentration in cloud (part of (1), the U-V transmissometer) and a reverse flow thermometer.*

STUDIES OF ICE CRYSTALS IN CLOUDS

It is a matter of experience that rain only falls from clouds that are reasonably deep. This is particularly true over the land, but even over the sea clouds less than about 1 km deep seldom produce rain. However, cloud depth alone is not a sufficient condition for rain production — there needs to be an active mechanism for producing cloud particles that are big enough to fall to the ground as raindrops. In maritime conditions, for example, big cloud droplets may originate by condensation on giant sea-salt particles. Where the tops of the cloud are cold enough the formation of ice crystals can provide a mechanism for starting the rain process. Ice crystals grow by sweeping up droplets to form small pellets or "graupel" and these subsequently melt and fall as raindrops.

Natural ice crystals are thought to form upon tiny dust particles in the air, the "ice nuclei". Our early studies of artificial clouds in laboratory cloud chambers showed that ice crystals only formed in concentrations of more than 1 per litre at comparatively low temperatures, about -20° C. Their apparent rarity encouraged the belief that artificial ice nuclei, capable of assisting ice crystals to form at temperatures much warmer than -20° C, could be used to enhance the rainfall.



Comparison between ice crystal concentrations found in maritime cumulus clouds which also contain large drops and in continental cumuli from which such drops are absent. In the latter case the ice crystal concentration conforms more closely to that of the ice nuclei.

When we started making measurements of ice crystal concentrations in real clouds, using instruments mounted on an aircraft, we soon found that cumulus clouds forming in moist onshore winds near the Australian coast did not conform to our expectations at all. Concentrations of ice crystals of 100 per litre were found in clouds that had tops no colder than -10° C. This led to the idea that in these clouds a process was at work by which the few ice crystals which formed upon ice nuclei could be "multiplied" many times over.

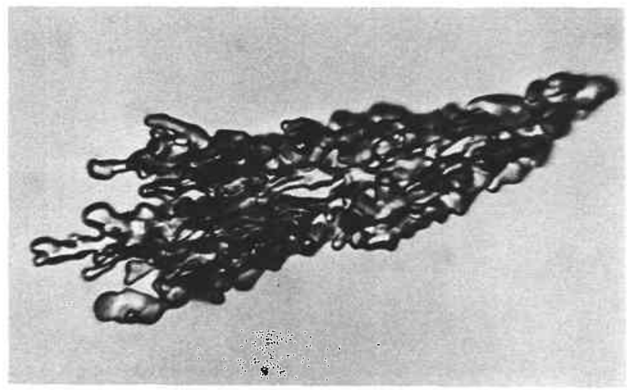
In other types of cloud, in particular shallow layer clouds, we found that the ice crystal population conformed much more closely to that expected from the ice nucleus measurements. Investigators in Israel reported that there was no evidence of ice crystal "multiplication" in their cumulus clouds — which were different from the ones we had studied in that they contained much larger concentrations of much smaller cloud droplets. The contrast in the ice crystal populations is illustrated in the adjoining figure.

LABORATORY EXPERIMENTS IN ICE CRYSTAL MULTIPLICATION

In attempting to understand the multiplication process we have used instrumented aircraft to study natural clouds in order to specify as closely as possible the conditions necessary for the mechanism to function. We have also conducted laboratory experiments to imitate possible multiplication mechanisms.

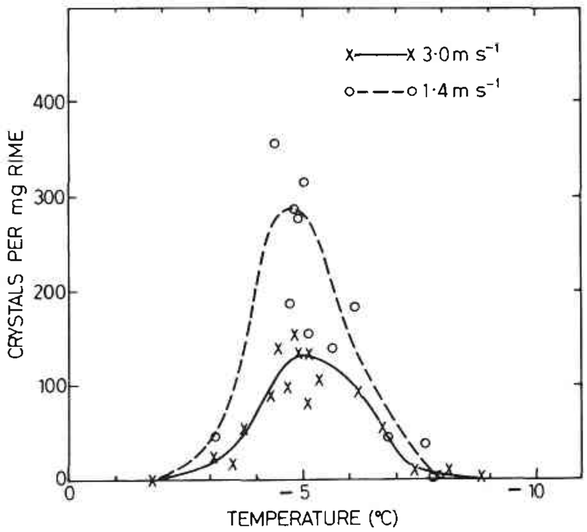
As a result of these experiments it now seems fairly certain that ice crystals falling through a cloud and sweeping up supercooled drops can throw off secondary ice particles ("splinters") when these drops freeze. The growth of ice particles leading to the formation of graupel has been imitated in the laboratory by moving a metal rod through an artificial cloud in a cold room. Drops freeze on to the front of the rod and form a layer of rime ice. As they freeze, ice splinters are thrown off and twinkle as they fall through a light beam.

This multiplication process only takes place under special conditions and this limits its operation to certain types of cloud. Splinters are produced only at temperatures between -3 and -8° C and only in clouds which contain some drops greater than 25 μm in diameter. However, the concentration of drops less than 13 μm diameter also influences the number of splinters that form.



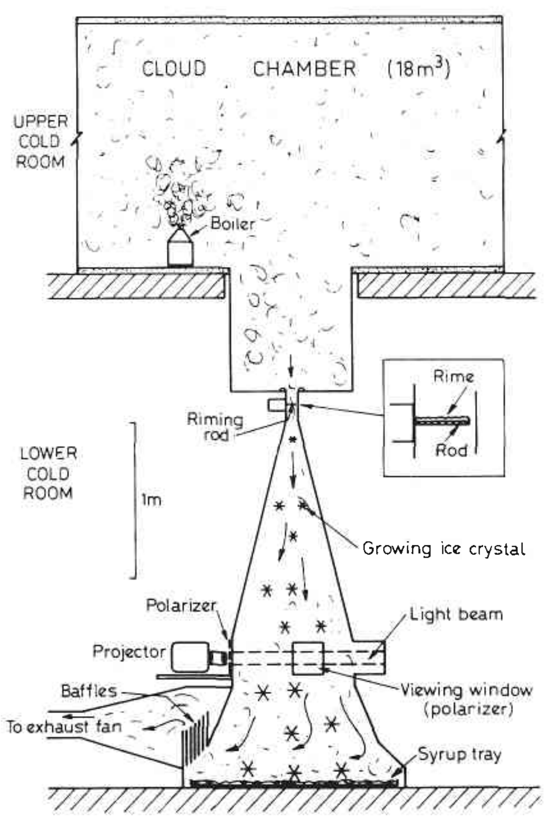
Fragment of rime of length 0.7 mm grown at -7° C. Supercooled drops have been colliding with the left-hand end of the structure at 1.4 m s^{-1} and freezing.

Once a rimed ice particle starts producing splinters these can grow and start sweeping up water drops and ejecting secondary ice particles in their turn. The process then becomes a "chain reaction" which can give rise to the high crystal concentrations we have found in Australian maritime cumuli, which typically contain a wide range of droplet sizes.



Ice splinters are thrown off during the growth by riming of ice particles between temperatures of -3° C and -8° C, with peak production at -5° C. The process is more efficient in terms of crystals produced per unit weight or rime at lower impact velocities.

Present research is directed at discovering the exact mechanism by which these secondary ice particles form. Our most recent experiments use a vertical wind tunnel through which we draw a cloud supercooled to a temperature of about −5° C downwards past a metal rod, so that drops strike the rod and freeze. The ice splinters produced in this process can be counted as they pass through a light beam below the rod. The frozen drops form a white opaque coating of rime on the rod. Examination of fragments of rime under the microscope show that it has an open branch-like structure in which individual frozen drops are seldom distinguishable. The branch tips grow forward into the airstream. So far our studies of the rime structure have not yielded any clue as to how the ice splinters are produced.



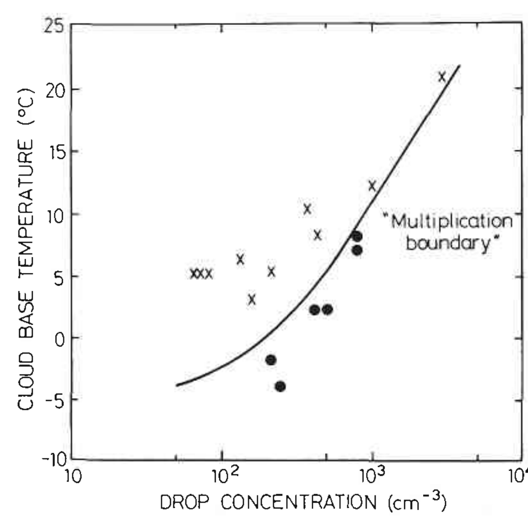
Apparatus for studying splinter formation during the growth of rime. Cloud droplets are drawn down past a riming rod in the narrow neck of a wind tunnel. Ice particles that are thrown off grow and are observed in a light beam lower in the tunnel. They can also be counted when they fall into a tray of super-cooled sugar solution at the bottom of the tunnel.

IMPLICATIONS FOR CLOUD SEEDING

Although the physical mechanism of splintering is not yet fully understood its possible implications for weather modification cannot be ignored. Clouds in which abundant ice crystals are present because of splintering are unlikely to yield more rain when seeded with artificial ice nuclei. This situation is likely to prevail in cumulus clouds forming in clean air that has had a long path over the sea. Here the drop concentration is low (about 100 cm^{-3}) and the large drops that are required for the splintering process can grow by the time the cloud top reaches the −8° C level. Such clouds are well able to produce precipitation naturally, without human interference.

Conversely, artificial stimulation is likely to be more profitable in clouds where drops larger than 25 μm diameter only form above the critical −8° C level. This is often the case in "continental" air that has spent a long time over land and contains many condensation nuclei and therefore many drops (say, 1000 cm^{-3}). Such clouds offer good chances of success in attempts to increase rain by seeding with ice nuclei.

The big cloud drops required to sustain the splintering process can grow in quite shallow clouds if the drop concentration is low, but a much greater cloud depth is required when the drop concentration is higher. This leads to the idea that one can draw a "multiplication boundary", based on observations in actual cumulus clouds, that separates those cloud conditions where multiplication is likely to be active from those where it is not. This could be used as a rough guide to differentiate potentially productive seeding situations from those where the natural production of ice crystals makes seeding unprofitable.

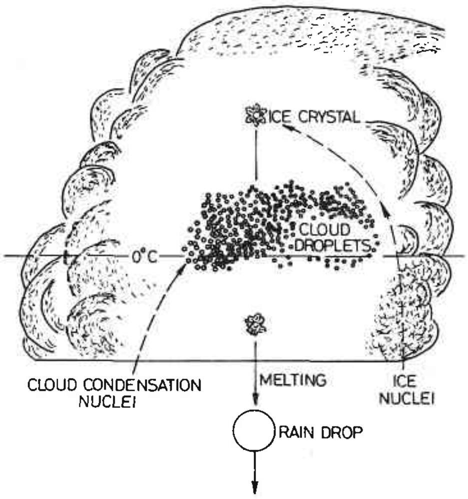


The "multiplication boundary" — only clouds having properties to the right of the boundary are likely to be useful in cloud-seeding experiments. The cross indicates active multiplication and the circle inactive.

CLOUD SEEDING

INTRODUCTION

As producers of rain, clouds can be divided into two categories: those whose main body is colder than 0°C and those whose tops are warmer. In Australia much of our rain comes from the cold type, and on these clouds most seeding experiments in this country have been made. The basic steps that lead to the formation of rain in this type of cloud are illustrated in the figure below.



The process leading to the formation of rain in cold clouds.

In all clouds droplets form on minute nuclei which, in almost every situation, are sufficiently numerous for the available cloud water to be consumed when the droplets have grown to a diameter of only 10-20 microns. Droplets of this size have negligible terminal velocities and are usually sufficiently free of ice-forming nuclei to remain unfrozen even when cooled a long way below 0°C; as a result such a cloud system remains fairly stable. Precipitation occurs only when particles are large enough to fall against the updraft. Such particles grow as a result of collisions with cloud droplets in their path, the speed of fall and number of collisions increasing as the particle falls. Eventually they emerge from cloud base as raindrops.

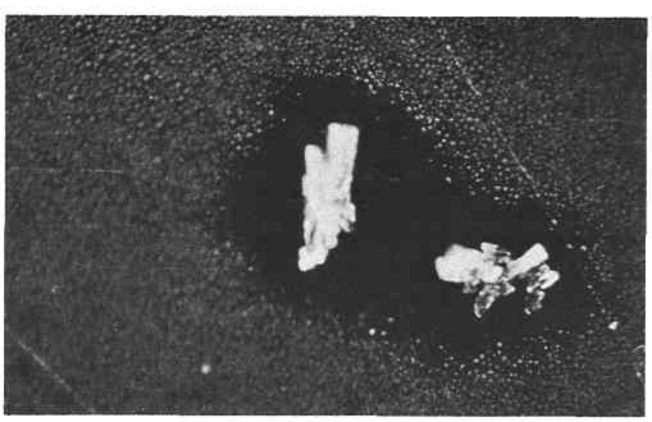
In the case of cold clouds the particles which initiate precipitation are usually ice crystals, and if an insufficient number are present in a natural form they can be introduced by seeding the cloud with artificial ice nuclei such as AgI, or by adding dry ice pellets. The latter cool the air to such a low temperature that large numbers of ice crystals form directly from the water vapour present. In either case the ice crystals so produced are initially very small — of the order of a micron or so. The first stage of their growth occurs by vapour deposition at the expense of the surrounding supercooled droplets. They take only a minute or so to grow large enough to undergo collisions with cloud droplets, and the rain-forming process is under way.

There are three major requirements that clouds must satisfy before being suitable for seeding by this technique:

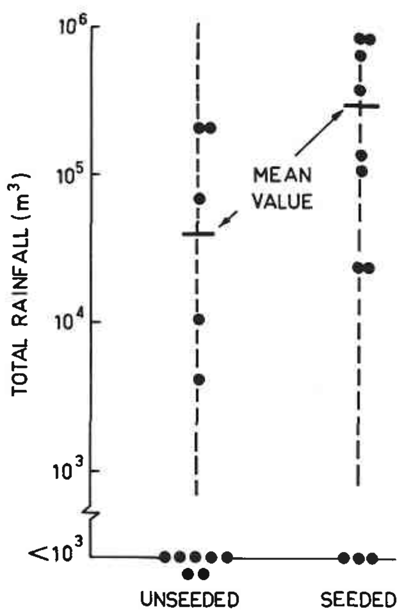
(i) Ice crystal concentrations should be lower than about 0.1 l^{-1} during the natural lifetime of the cloud. If concentrations are much above this level the addition of further crystals by seeding could be detrimental. This is because the same amount of available water would then be divided up amongst a large number of ice crystals, which would then necessarily be smaller, and less likely to reach precipitation size.

(ii) There must be a sufficient depth of supercooled water for large numbers of collisions to take place. About 10^6 cloud droplets are required to make up the volume of a 2-mm-diameter raindrop.

(iii) The region between the cloud and the ground should be neither so dry nor so deep that the raindrops evaporate before reaching the ground.



Ice particles growing from vapour at the expense of surrounding supercooled droplets.



Total rainfall from isolated cumulus clouds.

The de Havilland Twin Otter used for seeding in the Tasmanian experiment.

PAST EXPERIMENTS

Early experiments in Australia demonstrated that single cumulus clouds satisfying the requirements outlined above occurred reasonably often, and that their rainfall could be increased many times by seeding. However, if cloud seeding is to be of economic significance it is important to be able to increase the rainfall over an extensive area, such as a water catchment basin or an area subject to intense agricultural usage. Such areas are hundreds or thousands of times larger than that covered by a single cumulus cloud.

The area-type experiment is not only more difficult to perform than the single-cloud type (the suitable clouds have to occur over the target area at the right time), but, because of the natural variability of rainfall, it must continue for a number of years before a reliable assessment of the results can be made. Five area experiments have been carried out in Australia in the past 25 years. The most recent and best documented of these was carried out in Tasmania from 1964-1971 by CSIRO and the Hydro-Electric Commission. The results of this experiment suggested that rainfall increases as high as 30% could be achieved in autumn. Statisticians analysing such experiments always like to assess the probability that the observed increase was fortuitous — i.e. that it could have occurred just because of random variation in rainfall that happened to coincide with seeding. This probability, or significance level, was about 3% for the Tasmanian experiment.

Indeed the results of this experiment were so convincing that the Hydro-Electric Commission were encouraged to carry out further experiments to test cloud seeding as a water resource management tool. On the basis of the prior experiment it was estimated that for a cost of $300,000 an extra 50 mm could be produced in the autumn-winter period. This additional rain on the Great Lake catchment alone would generate electricity which, the Commission estimated, would cost $776,000 to generate by the alternative means of production — the oil-fired Bell Bay station. Thus the benefit would be more than double the cost per annum, and the potential would be much greater when all the catchments controlled by the Commission were considered. The Commission therefore adopted the practice, from 1972 onwards, of examining the dam levels in the major catchment areas and deciding, in the light of its requirements at the time and of the expected shortfall of water, whether to implement cloud seeding in the following autumn. Because of full storages, and also for economic reasons, seeding did not recommence until 1979.

Given such an attractive economic basis for seeding, it is clearly reasonable to ask whether the same results could be expected in other regions of Australia. Unfortunately we cannot answer this question with any sort of confidence at present, mostly because of the restricted framework in which previous cloud-seeding experiments were of necessity conducted. Because of the difficulties involved in measuring, interpreting, and understanding the basic physics of the rain-bearing clouds, the effects of seeding were measured only in terms of rainfall on the ground. While this type of approach answers the most important question as to whether any extra rainfall can be produced, it severely limits the possibility of applying the results of any individual experiment to other regions where cloud conditions could be different.

A typical wheat field in the area of the seeding experiment.

WESTERN VICTORIA

Against this background the Division has made plans for a seeding experiment in the Wimmera region of western Victoria which will be carried out with support from the Victorian Department of Agriculture. Western Victoria was chosen as the general area for the experiment for several reasons:

(i) A reasonable fraction of the rainfall of that region is associated with the passage of cold fronts, which also dominate the weather patterns of a large portion of southern Australia. Any information that could be gained on the seedability and structure of frontal clouds would consequently be of great interest to cloud physicists and meteorologists.

(ii) The area is a prominent wheat-growing area in which extra rain during the growing season would be welcomed.

(iii) From an aeronautical and logistic point of view, the area is a favourable one in which to base a cloud-seeding experiment: there are several large towns serviced by domestic airlines; there is an adequate ground network in the area; there are good air navigation facilities; and there are no prominent mountain ranges to cause concern to pilots flying under the adverse conditions that always accompany a seeding operation.

The western Victorian experiment is the first conducted by CSIRO in which it has been possible to conduct a scientific investigation of the site before the experiment commenced. In the past, because of economic pressures such as those caused by drought, the tendency was to begin seeding a given area as soon as possible. This left minimal time for planning procedures such as examining alternative target areas, optimizing the use of controls, selecting the best season, or installing extra rain gauges. A further impetus for more detailed planning for the new experiment has come from cloud physics studies of cold clouds showing that opportunities for seeding do not occur as frequently as was thought 10 years ago. It is now recognized therefore that there is an even greater need to optimize not only the seeding treatment but also the techniques used to detect the effects of the seeding on rainfall.

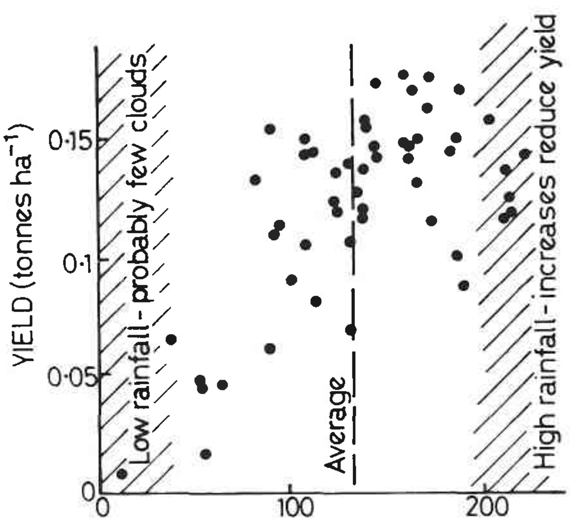
The chief aim of the Wimmera experiment is to increase the rainfall over a fixed target in the centre of a wheat-growing area. The main assessment will be a statistical one based on the rainfall in the target area; this will be supported by a comprehensive physical measurement program in which measurements will be made of the properties of the clouds, the changes due to seeding, the location and concentration of seeding material, possible changes in precipitation downwind, etc. It is only by an intense effort of this nature that the details of the changes wrought by seeding will be uncovered and the chance of transporting the results to other areas enhanced.

Background planning for this experiment commenced in 1974. It consisted of three interrelated programs: economic benefit analyses; cloud observations; numerical simulations of experiment.

(1) Economic benefit analyses

Western Victoria was originally chosen as the potential site because it was a prime wheat-growing area, and there were expectations that yields could be increased if rain in the growing season (August-November) were increased.

Estimates of what this increase in yield might be were obtained by plotting the wheat yield against rainfall for the past 60 years, and allowing for the increases in yield due to improvements in wheat strains, fertilizers, etc. Such a plot is shown in the figure below. Using this information, one can show that in an average year a 10% increase in the seasonal rainfall would increase yield by about 0.01 tonnes ha^{-1}, which in turn would be worth about one million dollars for the target area of some 2000 km^2 which is proposed for the experiment.



Relationship between yield and rainfall during the growing season for wheat in the Wimmera.

This results in a cost-benefit ratio of about 3 or 4 to 1 for the actual experiment. An operation in which a larger area would be seeded more often, and in which the costly cloud physics measurements would not be made, would of course be even more attractive economically.

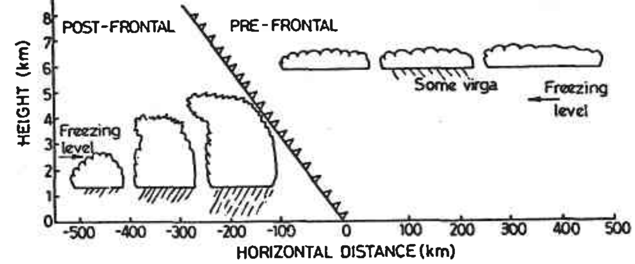
(2) Cloud observations

Four years of observations from an instrumented light aircraft revealed that there were two important rain-causing weather patterns.

(a) Fronts, or front-related weather, accounts for about 50% of rainfall in western Victoria during the spring months. The accompanying figure shows a general picture of the cloud types found in association with the fronts investigated. Ahead of the front, winds are generally north to north-westerly, the air is dry and its aerosol content strongly continental (i.e. with high concentrations of cloud nuclei). The pre-frontal clouds consequently have high bases, with high concentrations of small drops. They tend to be fairly stable, and although there is quite often a reasonable depth of supercooled water that could be released via seeding, this depth is insufficient to produce drops large enough to survive the descent through the dry sub-cloud layer.

The frontal and post-frontal clouds form in a moister south-westerly air stream and are cumuliform in nature with bases of the order of 1.5 km and tops limited by the inversion associated with the following high-pressure system. Most rain from these clouds comes via the ice process. These clouds fall into a special category in which an ice multiplication process commonly occurs. This process manifests itself in the rapid natural glaciation of any turret which rises above −5°C, and ice crystal concentrations as high as 500 to 1000 l^{-1} have been measured in these clouds.

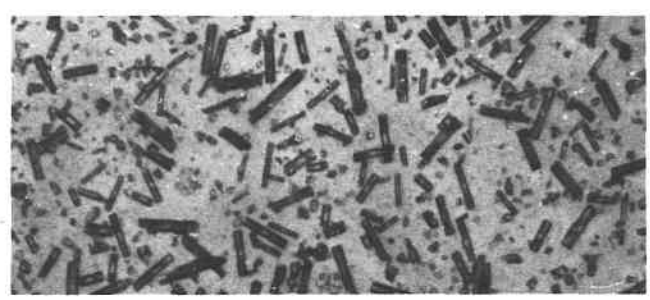
	Post-frontal	Pre-frontal
Cloud type and cover	4/8-8/8 Cu, Sc	8/8 Ac, As
CCN	50 cm^{-3}	500 cm^{-3}
Wind	240/30	350/40
Surface temperature	~15°C	~30°C
D.P.	~10°C	-5°C
Droplet concentration	~50 cm^{-3}	500 m^{-3}
" size	~20 μm	10 μm
Ice crystal concentration	~100 ℓ$^{-1}$	<0.1 ℓ$^{-1}$



Cloud characteristics associated with a typical cold front.

Both classes of clouds associated with fronts of this type are therefore unsuitable for seeding.

(b) Another important but less frequent source of rain for western Victoria is the rain depression or closed low that moves into the region from either Central Australia or the Southern Ocean. Precipitation in these clouds frequently occurs via the coalescence process; rainfall rates are typically less than 1 mm h^{-1} when averaged over the life of the system, which can be anywhere from 24 to 72 h. Rough calculations suggest that for these systems the rainfall rate could be increased by seeding to about 2 mm h^{-1}. This represents an increase of about 100%, but it is probably only practical to consider that increases of the order of 25% to 50% are likely to be realized in a seeding operation.



An example of the high concentrations of columnar ice crystals found in some of the self-glaciating post-frontal clouds.

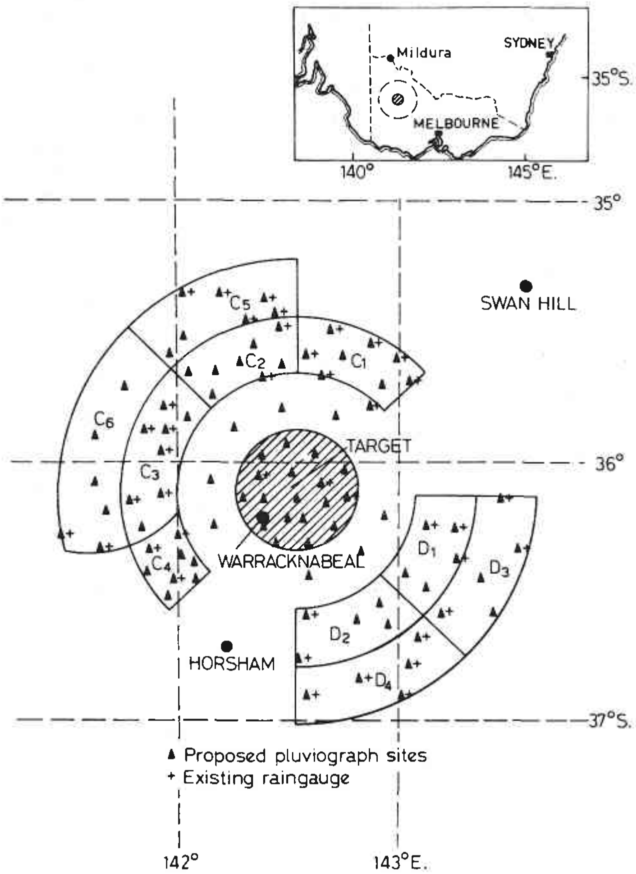
Although these systems occur only five times in each spring season on average, the rainfall associated with them represents about 30% of the season's total. Hence on a seasonal basis the anticipated increases in rainfall due to seeding would be between 7% and 15% for a full 24-h operation, and correspondingly less for a daylight-hours-only operation.

(3) Numerical simulations of the seeding experiment

Our existing knowledge suggests that the number of occasions suitable for seeding each year will be small, and that the likely effects of seeding will be of the order of a

10% increase in total rain for the season. Thus even in an experiment of five years' duration the detection of the effects of seeding against the background of the considerable natural variability of rainfall is likely to be a difficult task.

Before commencing an experiment one would like to know if the variability in natural rainfall is such that there is a reasonable chance of detecting the effects that seeding is expected to produce in an experiment of reasonable



The experimental area. C_1 to C_6 are control areas; D_1 to D_4 are downwind areas in which effects of seeding will also be sought.

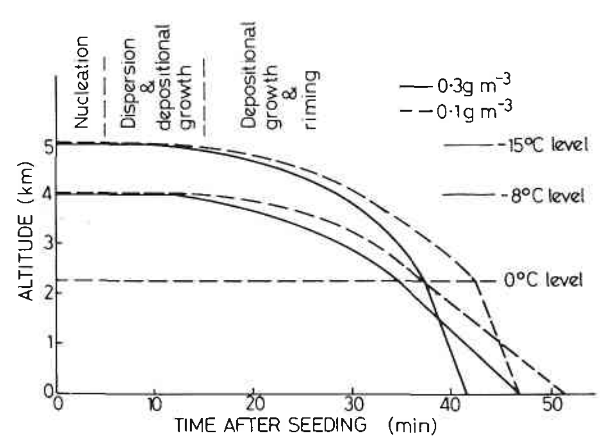
duration. This can be done by simulating numerically the experiment proposed, using historical rainfall records as a source of data. In a simulation of this type, the daily rainfalls averaged over two chosen target and control areas are calculated from the historical records for each day over a five-year period. Knowledge of the cloud climatology is used to exclude those days on which it is unlikely on the basis of synoptic conditions that suitable clouds would have formed. This leaves a set of experimental days for which a random seeding sequence is chosen. On the days designated "seeded" by this sequence, the historical target rainfall is altered according to some hypothesized effect of seeding — e.g. a 20% increase. The rainfall for the experimental days (with the artificially increased "seeded" rainfall in the target area) is then analysed as if it were the data from a real experiment — i.e. an estimate of the increase due to seeding is calculated together with a significance level associated with that increase. If this level is smaller than some preset value (say 10%) the simulated experiment is deemed a "success". This procedure is repeated 100 times, choosing a new random seeding sequence each time. The proportion of successful detections in these 100 simulated experiments is a measure of the probability of detecting such an increase due to seeding in an experiment of five years' duration. Many simulations of this type have been performed in cooperation with members of the CSIRO Division of Mathematics and Statistics. The overall suggestion from these simulations is that at the 10% significance level there is about a 70% chance of success in a five-year experiment, provided the increase in rainfall on our few selected days lies between 25% and 50%. If the increase should be greater than this, the chance of detecting it is correspondingly greater.

It is interesting that the detectability of a given percentage increase does not improve significantly when applied on all rainy days, instead of on just the comparatively few closed-low days. This is because the rain on closed-low days is more uniform and widespread than on other days and allows for better correlations between the target and control area rainfalls.

EXPERIMENTAL DESIGN

The Victorian experiment has several features that have not previously appeared in weather modification experiments. For example, although the target area will be fixed the control areas used will be selected according to the wind direction: the best controls to use are normally those upwind of the target when most of the rain fell. The experiment will be randomized on a suitable-day basis, with cloud suitability to be assessed by the CSIRO aircrew from in-cloud observations. Randomization ensures that some of the days on which suitable clouds occur will be left unseeded, and the rainfall on these days will be used to establish the relationship between target and control area rainfalls.

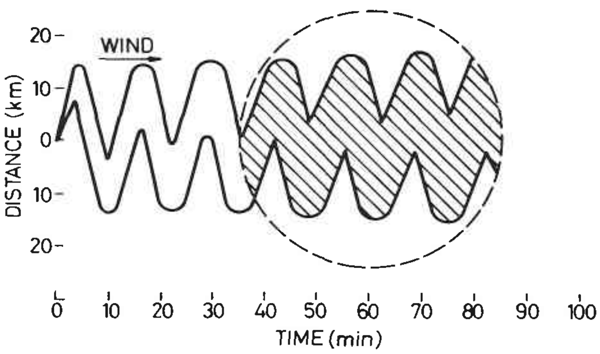
In addition to the two seeding aircraft, an instrumented F-27, the Division's research aircraft, will be used to document the sequence of physical processes that commences with the release of seeding material and finishes with the arrival of precipitation on the ground. The research aircraft will be equipped to measure the cloud water content, the size and shape of ice crystals present and their concentrations, wind speed as a function of height, and the level of turbulence. It should in fact be able to track the plume of ice particles that result from seeding.



Calculated trajectories of raindrops which form on seeding material at two different levels.

The way in which the seeding material is expected to grow and fall out is shown above for seeding at the −8° C and −15° C levels. In both cases it takes about 45-50 min for the particles to reach the ground after they are released and commence to grow; the particles which start higher up grow faster at the colder temperatures and eventually catch up to those that commenced growing at the lower levels. These trajectories are used to decide how far upwind of the target, and at what level, seeding should take place.

During the time that it takes for the "seeded" rain to reach the ground, small-scale turbulence acts to disperse



Coverage of the target area with seeding material released from an aircraft flying backwards and forwards along a line 25 km long.

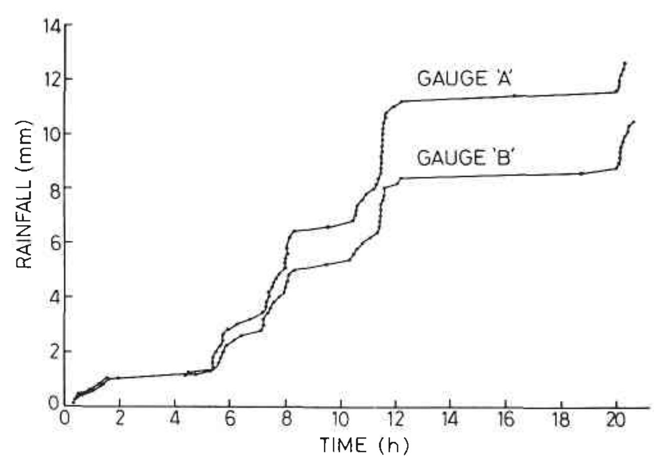
the seeding material in such a way that most of the target area will be covered.

The raingauge network to be installed will consist of 105 automatically-recording gauges of CSIRO design. Most previous experiments have relied on gauges which are read daily, usually voluntarily by local people interested in the experiment. The new network will allow us to separate the "seeded" rain from that which occurred on the same day when seeding was not actually taking place. In addition, the new network is inherently more reliable — the reading from the daily-read gauges invariably included such anomalies as the assignment of a complete week's rainfall to the Monday, or market day, or the day on which the gauge was read. Whilst this sort of error is of little consequence in assessing the total season's rainfall or even weekly rainfall, it can cause havoc in a cloud-seeding program designed around short seeding periods.

The gauge is of the tipping-bucket type: every time 0.2 mm of rain falls, the bucket tips, and an electrical signal starts up a cassette recorder. The date and time at which the bucket tipped are then recorded on the cassette, and the recorder is stopped again. (The time is obtained from a crystal clock accurate to 1 part in 10^6.)· This method of recording requires very little power and the units can be left in the field for up to 30 weeks whilst operating on a single battery. Further, a tape can record up to 900 mm of rainfall. It is expected however that the recorder will be serviced at least once during the three-month period of the seeding experiment.

The automatic raingauge network will be able to record the detailed structure of precipitation in space and time. Its usefulness will not be limited to the seeding experiment alone, but will extend to general meteorology. The spatial and temporal variability of rainfall from fronts, the size and duration of rainbands embedded within large-scale systems, the tracking of rain cells across the area — all of these are topics on which the network should be able to provide previously unobtainable information. Perhaps the most useful feature of the gauges is the ease with which the rainfall information can be retrieved. Automatic gauges currently in use in Australia employ chart recorders driven by clockwork motors. The amount of labour involved in reading these charts is such that the rainfall records for just a few gauges are generally not available until many months after the event. With the CSIRO gauges a tape can be read in less than 60 s, and although the total data reduction will take considerable time, it is envisaged that rainfall averages for the experimental areas, isohyetal patterns, etc., should be available one month after the completion of the seeding season.

Attempts will also be made to detect the presence of silver in target area rainfall. The detection of silver would add substantial weight to any assessment suggesting that seeding with AgI had affected the rainfall, and the time delay between seeding and detection would yield valuable information on the likely trajectories of seeded particles. At a few selected sites within the experimental area, probably one each in the target, control, and downwind areas, semi-automatic collectors of precipitation will be installed. These units will consist of 10 Teflon beakers, each of which will collect the rainfall for a 2-h period. The beaker assembly will be contained within a small unit which will freeze the sample soon after collection to minimize the diffusion of silver to the walls of the beaker. The inlet will be a 20-cm Teflon funnel, so that at a rainfall rate of 1 mm h^{-1} a sample of about 60 ml will be collected. These samples will be concentrated and analysed for silver content by the CSIRO Division of Process Technology using atomic absorption spectrometry.



Rainfall records taken in the area from two automatic raingauges situated 6 km apart. The fine resolution obtainable and the high correlation between the records are evident.

All of these features make the forthcoming experiment unique and of considerable importance for the historyof rain-making in Australia. If offers us an opportunity to make considerable progress in at least one area of weather modification.

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