



THE METEOROLOGICAL MAGAZINE

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STATIONERY
OFFICE

August 1983

Met.O. 958 No. 1333 Vol. 112

THE METEOROLOGICAL MAGAZINE

No. 1333, August 1983, Vol. 112

551.501.795:551.501.815:551.508.21

The WPL Profiler: a new source of mesoscale observations

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Summary

A ground-based system being developed at the Wave Propagation Laboratory in Boulder, Colorado, is able, unmanned, to provide atmospheric profiles up to tropospheric heights. The output from this system is continuous in time and thus is potentially a useful source of information for short-period forecasters.

1. Introduction

A system to obtain frequent atmospheric profiles, known as the WPL Profiler (Little 1982), is being developed at the Wave Propagation Laboratory in Boulder, Colorado, under the overall direction of Dr C. G. Little. This article is a summary of a more detailed paper study made in order to familiarize the Meteorological Office with the potential capabilities of the Profiler (James 1983).

2. Background

There is currently much interest in very-short-range forecasts (0 to 12 hours ahead). However the existing upper-air observational networks are largely geared to providing input data for synoptic scale models which are designed to produce forecasts for periods of multiples of 12 hours ahead.

Forecasters in the UK produce local forecasts using hourly surface observations, 12-hourly radiosonde profiles, and satellite images, all interpreted in the light of the general synoptic situation. The UK Weather Radar Network pictures are now becoming more widely available and provide frequent information on weather patterns associated with precipitation. In fact, radar rainfall pictures and half-hourly satellite images from Meteosat are the principal inputs to the FRONTIERS† system which is intended to produce simple very-short-range forecasts by extrapolation (Browning 1979, 1980; Browning and Collier 1982).

*Now at Bracknell

†The acronym FRONTIERS embodies the following key elements: Forecasting Rain Optimized using New Techniques of Interactively Enhanced Radar and Satellite images.

Mesoscale dynamical models are also being developed for short-period forecasting but the principal restriction on their use is the lack of suitable observations. The observations for very-short-range forecast models must be available rapidly and on a fine enough mesh so that important mesoscale features are not missed.

One possible source of such information is the TOVS (Tiros Operational Vertical Sounder) temperature sounding data from the polar-orbiting Tiros-N series of satellites. The Satellite Meteorology Branch of the Meteorological Office are planning to process such data in near real time (Eyre and Jerrett 1982). Information is available over an area within 2 500 kilometres of the UK every six hours. The horizontal resolution of the data is 40 and 200 kilometres for the infra-red and microwave sounders, respectively. The satellite measurements allow vertical temperature profiles to be estimated at points on a 40 kilometre mesh and the derivation of thickness and thermal wind charts over a large area (for example see Fig. 6, Eyre and Jerrett 1982). A problem with polar orbiter data is that, although they are of good horizontal resolution, they are only available at intervals of six hours from a pair of satellites. In addition the resolution is worse (200 kilometres) in the cloudy areas where much of the interesting weather occurs because the infra-red sounder cannot penetrate cloud. Geostationary satellite sounding techniques developed in the USA (Smith *et al.* 1982) are able to provide data at one-hour intervals but they are restricted at present to infra-red soundings in clear or partly cloudy conditions. Further problems with satellite data are that the vertical resolution and accuracy of the temperature and humidity data become worse near the surface, and that information on the wind field is inadequate.

3. The WPL Profiler

The WPL Profiler is an alternative system to obtain frequent atmospheric profiles. The Profiler is a ground-based system consisting of three elements; a clear-air Doppler radar, a six-channel vertically pointing microwave radiometer and a set of surface sensors that monitor surface pressure, temperature and humidity. The Doppler radar measures a wind profile above the Profiler site and the radiometer provides information which can be processed to produce temperature and approximate humidity profiles. The wind, temperature, and humidity profiles are available continuously in time. A unique feature of the system is that information from the radar sub-system can be used to improve the temperature profiles obtained from the radiometer measurements alone.

3.1 *The clear-air Doppler radar sub-system*

The Doppler radar is used to obtain wind profiles under all weather conditions. 'Clear-air' radars observe the very weak returns from inhomogeneities in refractive index present in the air on a scale of half the radar wavelength (see James 1980). The refractive index of air in the upper troposphere is almost entirely dependent on temperature and so clear-air radars detect fluctuations mainly in the temperature field. The radar used is very sensitive in comparison with conventional Doppler weather radars. This sensitivity is achieved by using a large antenna (100 by 100 metres in the case of the Profiler VHF radar developed originally by the Aeronomy Laboratory) and by integrating the returned signal for periods of up to two minutes to make a single velocity measurement. The large antenna is constructed from simple arrays of wires and has no moving parts. Observations are made at a number of different ranges simultaneously; the Profiler radar makes measurements with a height resolution of 1 kilometre at heights of between 2 and 20 kilometres. The radar is normally used to look simultaneously in three different directions, vertically and 15 degrees from the zenith in two orthogonal directions (e.g. East and North). Provided strong wave motions are not present these measurements allow both horizontal and vertical air motions to be calculated.

Other important information can be obtained from the radar measurements. It has been found that a very much stronger signal is observed by the vertical beam (compared with the oblique beams) from stable layers in the stratosphere (Gage and Green 1979). This increased signal results from specular reflection from regions of large refractive index gradient caused by strong vertical gradients of temperature in these stable regions. This allows the height of the tropopause to be measured remotely and continuously from the surface. In addition tropospheric stable layers, in particular the inversion at the top of the boundary layer, give enhanced signals in the vertical beam. The strength of such signals is related to the strength of the inversion; thus the radar is able to detect and measure the height of stable layers and give an indication of their static stability. In any new system every effort should be made to decrease the minimum range to one kilometre or less so as to increase the frequency with which the boundary layer top is detected.

3.2 *The radiometer sub-system*

The Profiler uses a six-channel passive microwave radiometer to provide temperature, water vapour and liquid water observations. Four of the channels are at frequencies between 52 and 58 GHz, on the side of an oxygen absorption band. These four are used to give temperature information. The other two channels are used to provide water vapour and liquid water observations. One is near the peak of a water vapour absorption line at 21 GHz and the other at 31 GHz is removed from any absorption lines but is sensitive to continuum absorption by liquid water. The atmosphere is relatively transparent between 20 and 30 GHz and as a consequence these two channels are able to measure the total column water vapour and liquid.

Individual radiometer channels are sensitive to the atmospheric temperature over a range of heights; the exact sensitivity is described by the weighting function, see for example, Eyre and Jerrett (1982). In the case of the four temperature sounding channels the weighting functions are relatively broad (>100 mb) and none is sensitive to the temperature above 400 mb. In order to recover a useful temperature profile from the radiometer measurements a technique termed inversion is used. The inversion technique employed in the Profiler system is statistical inversion. A climatological set of radiosonde ascents is assembled and for each ascent the measurements the Profiler would have made are calculated. Next these synthetic measurements are correlated with the original radiosonde profiles to form a cross-correlation matrix. This matrix describes statistically how changes in a radiosonde ascent relate to changes observed by the Profiler. When new Profiler measurements become available the cross-correlation matrix can be used to estimate the atmospheric profile. This technique is a form of multiple linear regression. The method is improved by dividing the climatological data set according to the time of year.

Further improvement is achieved by utilizing information from the radar. The climatological data set can be divided according to the height of the tropopause: one set would contain tropopause heights between 10 and 11 kilometres, the next heights between 11 and 12 kilometres etc. By measuring the tropopause height with the radar, the appropriate climatological data set can be used in the inversion. A similar method can be used to handle the boundary layer inversion. Further refinement can be achieved by modifying the calculated profiles in the light of radar measurements of the heights and strengths of other tropospheric inversions.

4. Examples of some results

Fig. 1 shows time changes of the wind observed with the Profiler radar. The diagram shows a series of wind profiles at one-hour intervals over a two-day period (Ecklund *et al.* 1979). Height is shown vertically and the eastward and southward components of the wind are shown separately. Horizontal

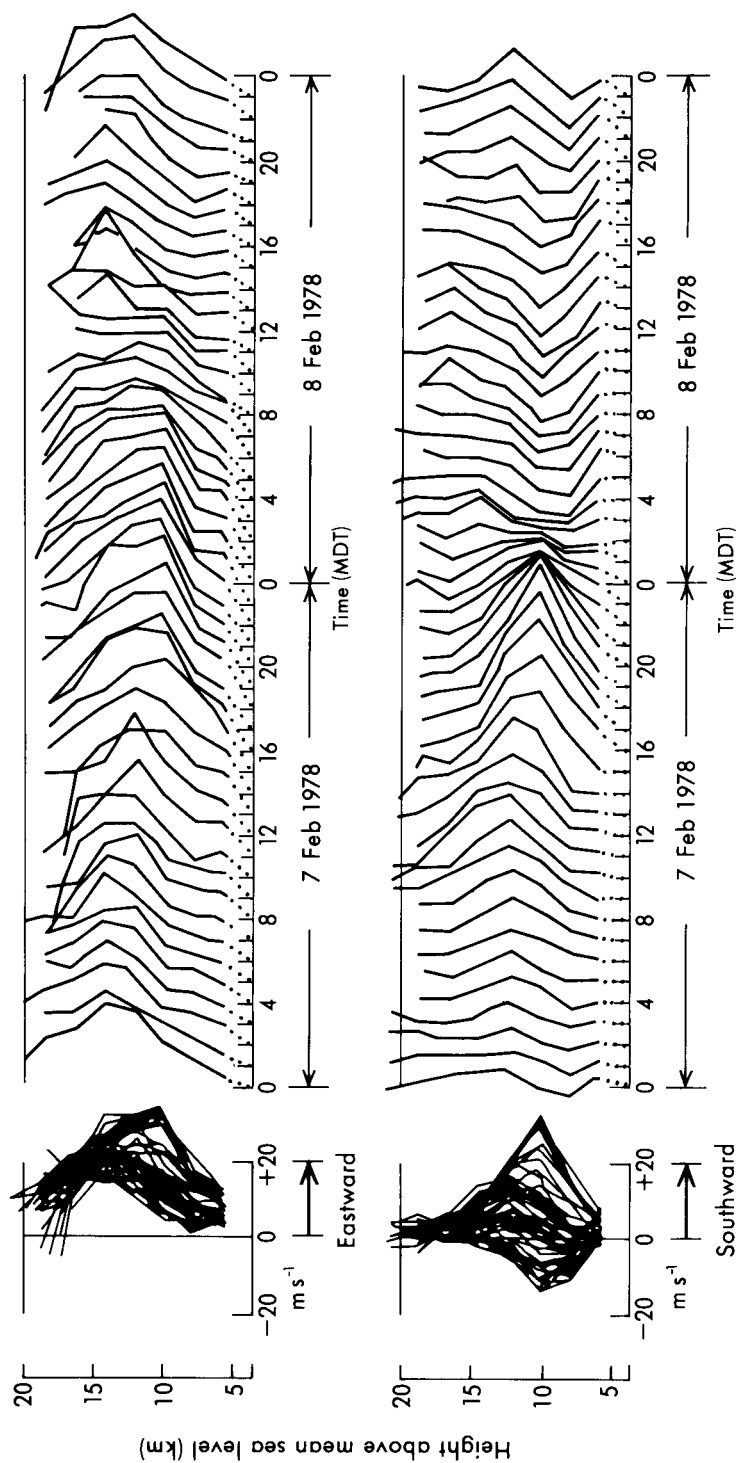


Figure 1. A series of wind profiles from the Profiler radar at one-hour intervals over a two-day period. Height is shown vertically and the eastward and southward components of the wind are shown separately. Horizontal displacement of the solid lines indicates the wind speed at a particular height.

displacement of the solid lines indicates the wind speed at a particular height. The wind was generally obtained up to a height of 17 to 18 kilometres. Wind changes over periods short compared with the interval between 12-hourly radiosondes are very apparent on this occasion.

Fig. 2 shows a time sequence of Denver Profiler measurements in comparison with radiosonde measurements (Little 1982). These results were obtained using the brightness temperatures from the six radiometers together with surface measurements (surface pressure at Denver averages 840mb); no use was made of radar data in this case. Measurements of 700, 500 and 300 mb geopotentials are shown over a four-day period. It was cloudy during the latter half of this period and it was raining lightly on the last day, but this did not appear to affect the accuracy of the results. The comparison draws attention to the value of the fact that, whereas radiosondes are generally launched at fixed intervals of time the Profiler output is essentially continuous. At 700 mb there is very good agreement, detailed comparisons show that the Profiler measures the 700 mb geopotential with a r.m.s. (root-mean-square) difference relative to the radiosonde, of less than 5 geopotential metres (gpm). On the fourth day the Profiler measured an increase in the 700 mb geopotential of 50 gpm in just two hours. Thus one immediately learns of changes in geopotentials and also the time rate of change of the geopotential. This information helps to locate mesoscale features, like fronts, precisely. At 500 mb the Profiler has a r.m.s. difference, relative to the radiosonde, of about 15 gpm and large and real changes are followed by the Profiler (the radiosonde measurements of geopotentials are rounded to the nearest 10 gpm). At greater heights the Profiler becomes progressively less accurate, the difference in measurements of the 300 mb geopotential by the two methods being about 32 gpm (without the benefit of radar data). However the Profiler output is following the general decrease in 300 mb geopotential shown by the sonde measurements as well as showing some structure on a short time-scale. Comparison of Profiler measurements with radiosonde measurements is complicated because radiosondes are carried by the wind and thus the two systems do not sample the same volume of the atmosphere. In addition radiosondes themselves are subject to errors. In an experiment where pairs of radiosondes were launched on single balloons it was found that the paired measurements gave r.m.s. differences of geopotentials of 19 gpm at 500 mb and 27 gpm at 300 mb (Hoehne, 1980). This would suggest that the Profiler measures geopotentials up to 400 mb with an accuracy comparable with the radiosondes used in the USA.

Fig. 3 shows the Profiler r.m.s. retrieval error as a function of height (Westwater *et al.* 1983). The retrieval error was again evaluated by comparison with radiosonde ascents. The solid line gives the r.m.s. 'error' when using radiometer measurements alone, i.e. without radar data, the dashed line shows the improvement obtained when using the radar-measured tropopause height together with the radiometer measurements. Knowledge of the tropopause height improves retrievals at levels between 500 and 100 mb, the improvement being as large as 2°C at the tropopause itself.

5. Conclusions

The Profiler has the following characteristics:

- (a) It has no moving parts.
- (b) It is cheap to operate, and easy to maintain.
- (c) Its output is continuous.
- (d) It operates unmanned.
- (e) It provides almost all-weather operation. Wind measurements are possible in all conditions; temperature and humidity profiles begin to deteriorate at rainfall rates greater than about 3mm/h (C. G. Little private communication).
- (f) It provides profiles of wind and temperature routinely to tropopause heights.
- (g) It is able to measure separately the integrated water vapour and liquid water.

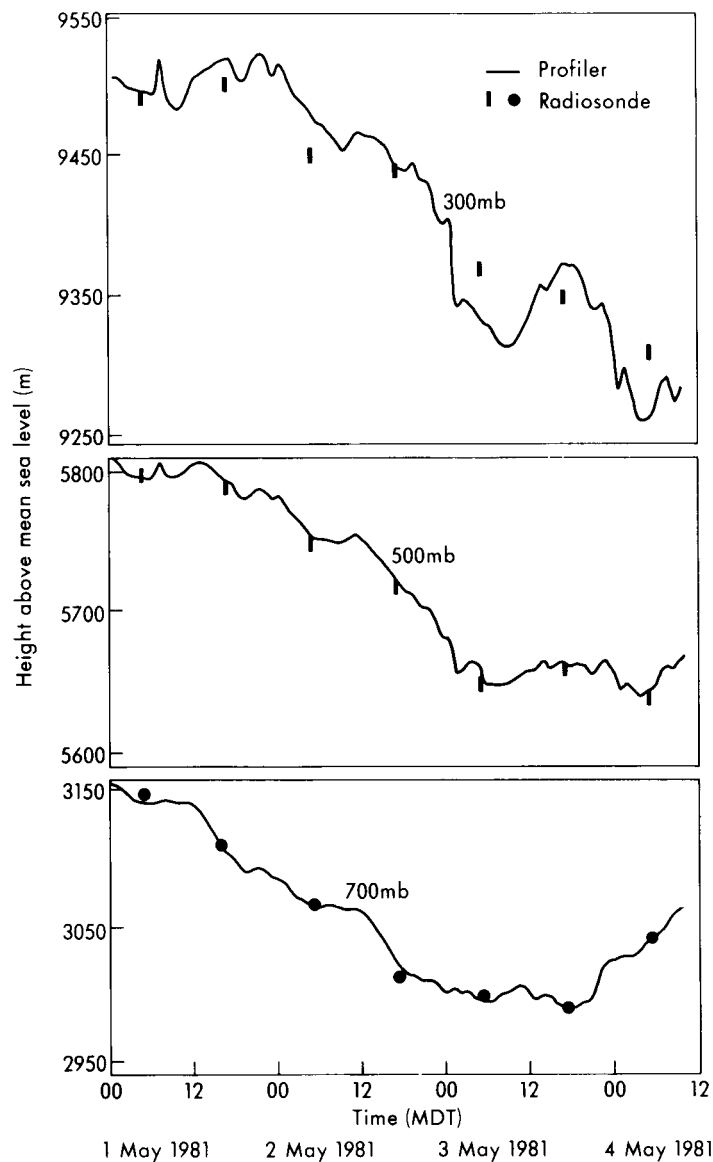


Figure 2. A time sequence of Denver Profiler measurements (without the benefit of radar data) in comparison with radiosonde ascents. The surface pressure at the Profiler site averages 840 mb. The figure shows measurements of 700, 500 and 300 mb geopotentials* over a four-day period. The radiosonde measurements are at 12-hour intervals and are shown as dots or rectangles, the Profiler measurements are shown as continuous lines. Times are shown as Mean Denver Time.

*It will be noted that the y-axis is labelled as 'height above mean sea level (m)'. The reference from which this diagram is taken fails to distinguish between 'geopotential', 'geopotential altitude' (as defined in e.g. the WMO 'International Meteorological Tables'), and 'geometrical altitude' i.e. height above msl, the first quantity being a specific energy and the last two lengths. Probably the numerical differences involved are negligible. Similar remarks apply to Fig. 3.

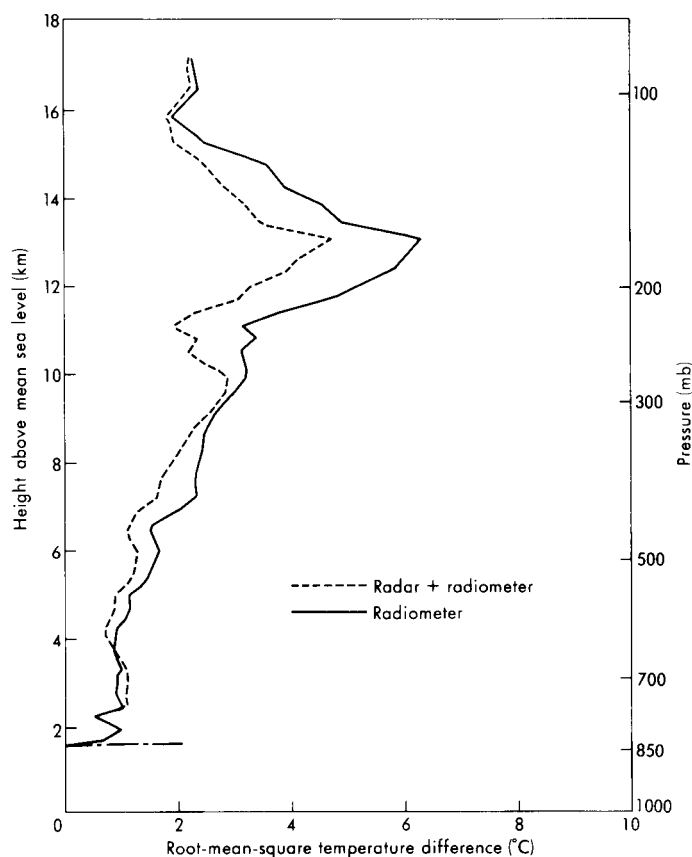


Figure 3. The root-mean-square retrieval accuracy of a Profiler system obtained by comparison of the Profiler output with 21 radiosonde ascents over an 18-day period. Comparative curves are shown with and without the benefit of knowledge of the tropopause height as measured by the radar. The fine structure apparent in the curves is a consequence of the limited sample available.

- (h) It monitors the height of the tropopause and significant inversions.
- (i) Its resolution is around 100 mb at low levels but becomes worse with increasing height. However the heights of significant features such as the tropopause and inversions are measured with much better resolution.
- (j) It is able to give an indication of the stability of layers.
- (k) It can also give an indication of the strength of turbulence at a particular height.

Profiler systems will not be able to replace conventional radiosondes entirely, as the vertical resolution of the Profiler is poor in comparison and they are unable to obtain accurate temperature measurements above the tropopause. D. C. Hogg (private communication) has estimated that the cost of a Profiler system in the USA is equivalent to only about four years operation of a conventional radiosonde site; thus it is not unreasonable to consider the possibility of building a network of Profilers to provide observations for very-short-period forecasts. Profiler systems, with their good time resolution and their best accuracy at low levels, can be regarded as complementary to satellite sounding systems, which have good spatial coverage and have their best accuracy at higher levels.

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Long-range transport of air pollution

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Summary

A general review is given of the known facts on the long-range transport of air pollution and its influence on 'acid rain' and of the present state of theoretical and practical investigation of the various problems involved. These include the nature of emissions, the amount of local deposition, the estimation of trajectories and lifetimes of airborne pollutants and their chemistry, relative amounts of dry and wet deposition, and background concentration. An account is given of computer modelling and observational studies being carried out by the Meteorological Office and of possible future developments.

1. Introduction

Oden (1968) was the first to relate reductions in freshwater fish populations in southern Scandinavia to the airborne transport and deposition of air pollutants originating perhaps hundreds or thousands of kilometres away. Similar fears have since been expressed in other parts of Europe (e.g. Scotland: Harriman and Morrison 1980), in the Appalachian mountains of the USA and in large areas of Canada (Harvey 1980). In fact there are many other sensitive areas of the world which might be at risk at equally large distances from major sources of pollution.

At the 1982 Stockholm Conference, Professor Ulrich described an alarming degree of forest 'dieback' in Germany and cautiously postulated that this might be due to root damage, followed by rot penetration, originating from the toxic action of inorganic aluminium released within the soil from its natural bound state under the influence of 'acid rain'. At present, hard evidence in support of this hypothesis is not available and other possible causes do exist. Nevertheless, it does remain a possibility and, if true, a deeply worrying threat to the European and American environment.

Since the original suggestion that ecological damage was being caused by man-made airborne pollutants, two major international collaborative experiments have taken place in Europe. The first (1971–76) involved most of the western European countries and was carried out under the auspices of the Organization for European Co-operation and Development, OECD (OECD 1977). The second (1977–) brought in many of the east European countries, including the USSR, in recognition of the truly international character of the problem, and was mounted jointly under the auspices of the Economic Commission for Europe, the United Nations Environment Programme and WMO (Eliassen and Saltbones 1982). This second experiment is called EMEP (the European Monitoring and Evaluation Programme) and is operated by three Centres responsible to a Steering Committee formed of delegated members from the participating countries. One of the Centres, the Chemical Co-ordinating Centre in Lillestrøm, Norway, under Dr Ottar, is responsible for overseeing and collating appropriate air and precipitation measurements on a daily basis at a large number of sites across Europe, remote from local sources, and inferring total deposition fields. The other two Centres — the Meteorological Synthesizing Centres — one in Oslo under Dr A. Eliassen, the other in Moscow under Dr A. Pressman, are involved in developing and running mathematical models which use estimated emission fields based on statistical data supplied by the governments of the countries involved, and meteorological observations of low-level winds, rainfall and mixing depths to simulate the atmospheric transport and loss processes that should link the emissions to the observed depositions (Fig. 1 outlines the various processes that occur). Similar monitoring and modelling programs have been under way in Canada and the USA since about 1977.

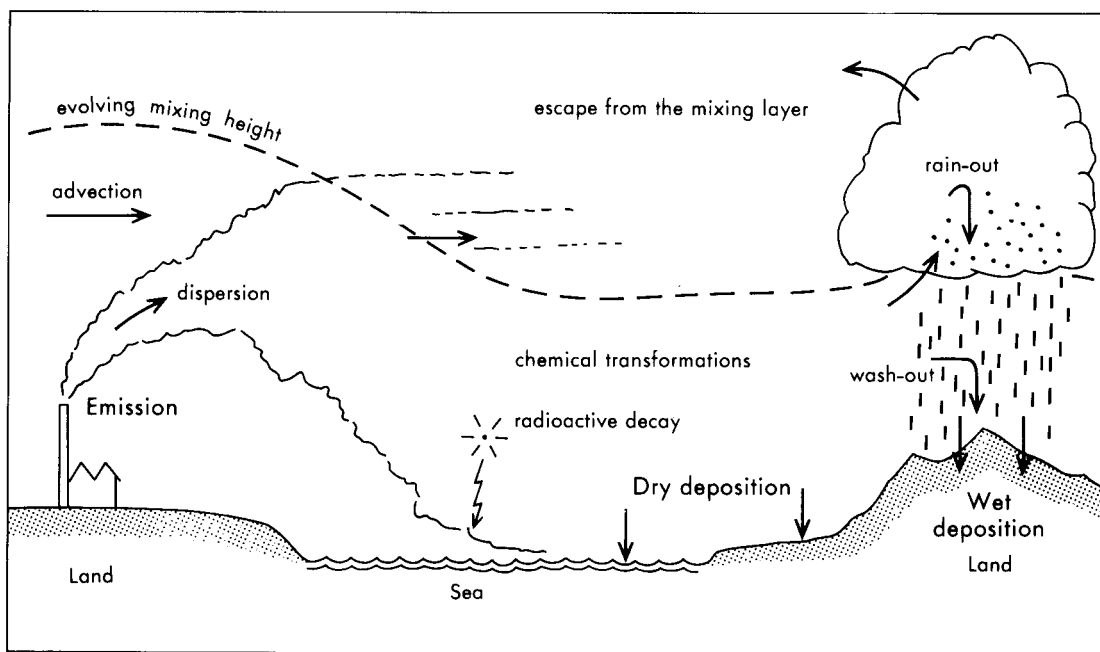


Figure 1. Processes involved in the deposition of atmospheric pollutants.

In addition to this work aircraft sampling flights (sometimes using specially released tracers) have been mounted in the UK since 1971, (see Smith and Jeffrey 1975), in Norway and in the USA to answer very specific questions concerning the physical and chemical behaviour of the pollutants involved in the acid rain problem.

2. Some basic problems

(a) Emissions

Long-term average emissions of sulphur dioxide are reasonably well known in northern and western Europe, in Canada and in the USA. Elsewhere emissions are not well documented. On shorter time-scales, the position on emissions is less satisfactory as data become increasingly uncertain everywhere.

For other acid-rain components, emissions are considerably less certain although estimates have been made for some components such as the oxides of nitrogen.

(b) Local depositions

Some fraction of the emission will be deposited locally, depending on the height distribution of the sources, local topography and atmospheric climatology. Typically, about 10% of the sulphur dioxide emitted within a 150×150 km square is deposited within the area itself. Similarly an analysis of measured depositions implies that about 30–40% of the UK's emissions of sulphur dioxide are deposited within the UK.

(c) *Trajectories*

Trajectories can be obtained using the winds and temperatures given by data-analysis methods used in operational numerical weather forecasting models. The accuracy of such trajectories is, at best, modestly good in simple synoptic situations and over relatively uniform terrain with adequate meteorological station coverage. This is confirmed by results from the North Sea plume-sampling flights that will be referred to later. In more complex situations, more important errors are sometimes evident with serious consequences for the prediction of single pollution events. Nevertheless, these errors are not thought to be of major significance for the estimation of long-term (e.g. annual) deposition fields.

(d) *Lifetimes of airborne pollutants*

All the evidence supports the belief that common industrial pollutants like sulphur dioxide (or SO_4^{2-}) have mean atmospheric lifetimes of the order of a few days and can travel in that time several thousands of kilometres. The lifetimes of reactive gases are affected by the rate of chemical conversion and by 'dry deposition' rates to the underlying surface. Resulting aerosol particles (like sulphate) normally have only small dry deposition rates and their lifetimes are usually determined by the frequency of interception by rain belts. The lifetime of any individual 'quantum' of pollution in the air is therefore highly variable.

(e) *Air chemistry*

Both dry deposition and the uptake of pollution into precipitation depend on the composition of the pollution itself, including the relative proportions of primary and secondary pollutants (e.g. SO_2 and its oxidized form, SO_4). The chemical changes inherent in these proportions often depend on a great number of complex processes within the air which in practice may require basic information totally beyond our capacity to achieve with any kind of precision. It may be postulated that in so far as long-term deposition fields are concerned such knowledge is unnecessary. The total sulphur depositions in Norway, for example, are determined principally by the total amount of sulphur in the air and the long-term rainfall patterns. Oxidation and removal rates are often very rapid in precipitating cloud. Statistical variations in rainfall distribution and intensity on the one hand and in the pollution mixture on the other are virtually self-cancelling except in short-lived single events.

(f) *Dry and wet deposition estimates*

Dry depositions are not measured directly but are inferred from air concentrations assuming so-called velocities of deposition. These are known from field experiments for certain common air pollutants, such as sulphur dioxide, and over such surfaces as short grass. Aircraft sampling studies have also assessed the deposition velocity of SO_2 over the sea and over typical mixed agricultural countryside. Values for other surfaces are largely unknown but where they are sufficiently extensive a balance tends to be achieved between the true velocity and the air concentration which yields a deposition rate which is insensitive to the precise nature of the surface.

The influence of local sources, altitude of the monitoring station and local topography all tend to affect measured air concentrations and hinder validation of model results.

Wet depositions can also be strongly influenced by monitoring-site characteristics and by the presence of mountains which modify airflow, enhance rainfall and change the collection efficiencies of pollutants by precipitation within the boundary layer.

Modelling of wet deposition may also be in error owing to spatial and temporal smoothing of rainfall data from widely separated meteorological observing stations when these data are projected on to the trajectory (Smith 1981a). This source of error is inherent in depositions over all time-scales but is

especially important in single-event depositions when peak values experienced at a point may be of vital importance. Standard meteorological data are incapable of yielding the information necessary for assessing large episodic depositions from large convective storms, for example.

(g) Background concentrations

Measurements confirm that air entering Europe having spent considerable time over the Atlantic contains sulphate not apparently originating in sea-water. Concentrations are low but are sufficient in many western areas, remote from large SO₂ sources, to constitute a significant fraction of the annual total of sulphur wet deposition. In Norway, for example, some 25% is thought to be of this kind. It is reasonable to suppose that much of this sulphur originates from the USA and Canada and has undergone really long-range transport, and has been isolated from prolonged surface deposition by rather low-level marine inversions.

3. Modelling and experimentation

(a) Long-term and short-term depositions

The links between acid rain and ecological damage are imperfectly understood and are often circumstantial and conjectural. Nevertheless, the observed damage is so extensive and potentially long lasting that even conjectures have to be considered seriously. Thus accepting for the while that such links do in fact exist, we are faced with the job of assessing the true nature of the transport and deposition problem. Unfortunately, such an assessment is at present only partial. For example, the relative importance of the following is still not clear:

(1) Long-term depositions (LTD) and average concentrations of the various acid components in the precipitation. These factors may degrade the natural buffering capacity of soils at rates which depend on soil character.

(2) Short-term episodic depositions (STED) containing high concentrations of acidity which, when LTD have degraded the soil beyond some critical limit, may directly effect living organic members of the ecosystem or indirectly do damage through the release of toxic material (such as aluminium) previously safely 'locked' within the natural soil state.

(b) The nature of models

Many models have been developed which attempt to include the emission, advection, diffusion, chemical change, loss from the boundary layer and deposition processes which affect industrial air pollutants. Which model is best for a potential user depends on his intended use, an assessment of the model's validity and the availability of appropriate meteorological data and computer facilities.

Models can be subdivided in a variety of ways which can only be touched on very briefly here. Three of them are as follows:

(1) Models that use statistics of winds, mixing heights and precipitation. Resulting deposition fields may have validity but only in the very long term. They are simple and very economical to run. They can also be surprisingly successful when compared with 'observed' fields.

(2) Models that use day-by-day meteorological data but through the use of much parametrization still have only rather long-term validity. The EMEP models are of this type.

(3) Complex models that are essentially extended mesoscale models taking account of topography and the three-dimensional equations of motion. They require considerable non-standard meteorological data and a highly sophisticated computer facility. The Ontario Ministry of the Environment in Canada is attempting to develop a model of this type. It is difficult to believe such a

model should be run except to study discrete events of exceptional scientific interest or public concern.

An alternative way of subdividing models is in terms of their mathematical nature: whether they are Lagrangian models or Eulerian models. Both have positive advantages and disadvantages which we shall not attempt to describe here. Other subdivisions can be made in terms of vertical resolution and the way vertical dispersion is modelled.

(c) *A very simple statistical model*

A model of type (1) above has been developed within the Meteorological Office. It is extremely simple and efficient to run on a computer, producing deposition fields in a minute fraction of the time required by the EMEP models. The model when applied to Europe assumes a single wind-rose (based on certain UK wind direction frequency statistics) applicable all over Europe and assumes airborne pollution travels in straight lines. Dry deposition occurs at a constant rate. Wet deposition can be represented with various degrees of simplicity; the simplest being to assume that the probability of rain is independent of wind direction and is constant along the track. Under these assumptions the predicted and observed fields are correlated: for dry deposition the correlation coefficient $r = 0.87$ and for wet deposition $r = 0.77$. If, on the other hand, the sporadic nature of rain is recognized using Smith's (1981b) simple probability approach, the probability of rain is allowed to depend on wind direction as observations suggest and, if grid values of dry and wet deposition are modified according to the actual annual rainfall, then the dry-deposition correlation rises to 0.90 and the wet-deposition correlation to 0.83. Amongst the most valuable aspects of the model are its ability to provide inter-country budgets of sulphur pollution (see Table I) and its versatility, so the sensitivity of the results to changes in the parameters or to other ideas can be quickly and economically tested.

(d) *Episodes (STED)*

As already noted, the development of models capable of dealing with single-event depositions, especially of episodic proportions, is a formidable problem. Perhaps the simplest approach at this time is to examine the EMEP data for occasions of high episodic concentrations of sulphate in precipitation

Table I. *A budget of annual total depositions (grams of sulphur per square metre per year) given by the EMEP Meteorological Synthesising Centre-West's Lagrangian trajectory model when applied to 1978-79.*

The budget gives the estimated contributions to the average deposition in one country arising from other countries. Only a selection of countries is given and these are ranked in order of deposition magnitude. It is interesting to note that Czechoslovakia receives over 12 times as much sulphur deposition as Norway. Note that the figures quoted for the USSR refer only to the area of that nation within the analysis area of the model — very roughly that part within Europe.

Receiving country	Area (10 ³ km ²)	Emitting country												Total
		Czech.	GDR	Belg.	FRG	Poland	Neth.	UK	France	USSR	Norway	Others	Undec.	
Czech.	128	4.5	1.8	0.1	1.0	0.9	0.1	0.3	0.4	0.1	0	2.1	0.8	12.2
GDR	108	0.6	5.5	0.1	0.9	0.3	0.1	0.2	0.2	0	0	0.4	0.3	8.6
Belgium	30.5	0	0.1	2.6	0.9	0	0.2	0.7	1.1	0	0	0.3	0.4	6.3
FRG	250	0.2	0.6	0.2	2.7	0.1	0.1	0.3	0.5	0	0	0.4	0.4	5.6
Poland	313	0.5	0.8	0	0.1	2.2	0	0.1	0.1	0.1	0	0.8	0.3	5.1
Neth.	41	0.1	0.2	0.5	1.3	0	1.2	0.8	0.4	0	0	0.3	0.3	5.1
UK	244	0	0.1	0	0.1	0	0	3.3	0.1	0	0	0.1	0.4	4.2
France	544	0	0	0.1	0.2	0	0	0.2	1.4	0	0	0.3	0.4	2.7
USSR	3363	0.1	0.1	0	0.1	0.1	0	0	0	1.3	0	0.3	0.4	2.5
Norway	324	0.03	0.08	0.01	0.07	0.04	0.01	0.15	0.04	0.03	0.07	0.14	0.27	0.94

and to consider the meteorological situations which gave rise to them, and to assess in broad terms where the pollution originated. This has been done for a group of stations in the 'sensitive' area of southern Scandinavia. Frequently these episodes occur when a blocking high over central Europe begins to weaken and fronts start to penetrate across Scandinavia drawing air from the industrial areas to the south, which over the previous days has become highly polluted. Fig. 2 shows a sector analysis for episodes and all depositions within the area for the years 1977–80. An episode is here defined as a concentration in rain exceeding 4 mg of sulphur per litre, with the condition that at least 1 mm of rain should have fallen. The sectors were chosen to cover the main industrial countries, i.e. UK, Netherlands, Federal Republic of Germany, German Democratic Republic, Poland and the USSR. The episode 'bar' simply gives the percentage number of occasions when the air originated from within the sector. The all depositions 'bar' is not quite the same in this figure: it represents the fraction of sulphur originating from each sector to the *total* deposition.

The episode values may be contaminated by dry deposition on the collecting funnel during the previous dry spell. Although in principle the funnel should be washed daily, a correlation appears to exist between the apparent wet deposition and $\Sigma \text{SO}_2/R$ (where ΣSO_2 is the sum of the sulphur dioxide concentrations over the preceding dry days and R is the rainfall). However, the correlation may be

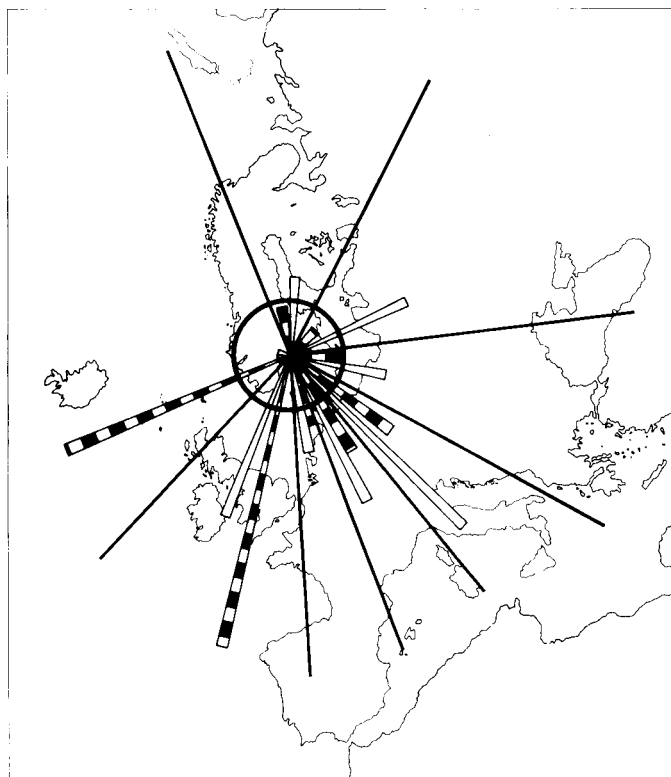


Figure 2. Sector analysis for southern Scandinavia 1977–80. White bars represent frequency of wet deposition. Striped bars represent all depositions. See text for explanation.

entirely spurious since an equally good correlation exists between the concentration in the collected rainwater and the current sulphate-in-air concentration, and the latter may be reasonably correlated with ΣSO_2 .

4. Meteorological Office/Central Electricity Research Laboratories (CERL) flights

A collaborative program between the Meteorological Office and the Central Electricity Research Laboratories (CERL) is currently in operation to study the plume from Eggborough Power Station in South Yorkshire. The Meteorological Research Flight Hercules aircraft has been instrumented to measure winds and other relevant meteorological data and to monitor pollutants during flight. Special sorties are made whenever the meteorological situation seems satisfactory and the aircraft is available. Fifteen flights have so far been made and analysis of the data is proceeding. To assist in the interpretation (particularly necessary since the plume is not isolated from other source plumes) tracers are injected into the stack effluent: sulphur hexafluoride is injected continuously during flights and sometimes PB2, a freon, is injected intermittently to act as time markers for Lagrangian studies. The following questions are being tackled: (a) oxidation rates of SO_2 to sulphate, (b) loss rates to the surface and out of the upper boundary to the troposphere above, (c) the history of sulphur drawn into precipitating clouds, (d) the accuracy of forecast trajectories, and (e) the origin intensity and influence of atmospheric mesoscale motions on plume behaviour.

5. The future

The Meteorological Office has an important role to play in the future of this study, although ultimately the exact nature of the role must depend on the consensus view of ecologists, and others, on whether or not industrial pollutants *are* causing grave damage to the environment at long range. If that becomes their viewpoint then it is likely that certain actions will be taken that will not involve the Office. For example, it is likely that desulphurization of flue gases will become more common, and that greater emphasis will be placed on energy generation from non-polluting processes (e.g., nuclear power etc).

Nevertheless, some alleviating actions may well involve the Office in research and daily operation. Three examples are as follows:

(a) *The reduction of the emission of other components in the pollutant mix.* If meteorologists and atmospheric chemists can demonstrate that another more easily and cheaply controlled pollutant holds a key role in the atmospheric sulphur cycle and its elimination could very significantly reduce depositions within Europe, then this might provide a very useful strategy. The Office would be involved in modelling the chemical interactions within the framework of atmospheric transport to see if such control would or would not be effective.

(b) *The reduction of depositions within Europe by increasing effective source heights.* A comprehensive study is required of the effectiveness of increasing the height to which hot plumes can rise under the action of their own buoyancy or motion with a view to maximizing the insulation of the pollution from ground-deposition processes. Over the last few decades the UK has followed a policy of building high stacks for large emitters with the view of controlling nearby ground-level concentrations and this policy has been eminently successful. However, the UK has sometimes been accused of thereby increasing the amount travelling out of the country and increasing its deposition in sensitive areas. A rather simple analysis I carried out some years ago indicated that in 1969 (the last year for which data on current stack heights were available) if all the high stacks were deliberately reduced to medium-height stacks (about 80 m high) the resulting average nearby surface concentrations would increase by *at least* 35% whereas the long-range transport would decrease by only some 10%. In fact, some of this 10% from high stacks

actually gets well above the mixing layer and may not be available for deposition within Europe. A more detailed analysis based on today's chimney height figures and occasional aircraft sampling flights might be advantageous in meeting the accusations of the critics of the high-stack policy and might point to the effectiveness, or otherwise, of pursuing this policy even further.

(c) *Emission control.* It is possible that power stations could have additional supplies of low-sulphur fuel that could be used whenever meteorological forecasts predicted travel of the effluents to specified sensitive areas. At other times cheaper and more readily available fuels, containing more sulphur, would be consumed. A pilot study of this possibility was made in 1974 when the quality of three-day weather forecasts was significantly less than it is today. Considering the sum of the time of travel of a typical plume from, for example, the UK to Norway, the time required to enact a fuel switch and the time to produce a trajectory forecast following the collection of weather observations, we find that three-day forecasts would probably be required. If success were identified as a trajectory error of less than 250 km at a range of 1000 km (corresponding to the distance between the UK Midlands and central southern Norway) then the 1974 study indicated that only about a 45% success rate could be achieved. This was deemed unsatisfactory at that time. Perhaps a new study should now be carried out to see if the situation has significantly improved. For the present and the immediate future, it is imperative that the Meteorological Office and CERL collaborative flights should continue with a determination to answer the questions posed earlier in this paper. The modelling work should also be exploited to its full potential, particularly if many of the air-chemistry processes can be grossly simplified for LTD purposes, and incorporated into the simple model described earlier. The physical, chemical and meteorological character of episodes also needs to be investigated in greater depth with a view to understanding the significance of these relatively uncommon events to the whole problem of acid-rain damage.

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Noctilucent clouds over western Europe during 1982

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Table I summarizes the observations of noctilucent cloud (NLC) over Western Europe during 1982, as reported to the Department of Meteorology, University of Edinburgh.

The times given in the second column of the Table do not necessarily indicate the duration of the display, though appearance and disappearance times are referred to in the Notes where known. In the third column brief notes of the displays enlarge on the facts listed in the other columns — NLC forms discernible, tropospheric cloud conditions, photographs and sketches available. Co-ordinates of the observing stations and selected details of elevation and azimuth appear in the remaining columns.

Routine hourly observations were made at 12 Meteorological Stations in the United Kingdom and at Reykjavik in Iceland when darkness permitted. Observers at these stations provide information of sky conditions during all hours of darkness; the significance of 'negative' nights, i.e. when an observer can state with confidence that there is no NLC, is obviously great when trying to assess the total number of appearances of NLC. Each year, however, we note with appreciation that in many instances NLC is recognized when quite large amounts of tropospheric cloud — in fact, up to seven-eighths (oktas) — are present.

As in most previous years a high incidence of tropospheric cloud seriously interfered with observation of the NLC. The interference in 1982 was in fact probably at a record high level, as evidenced by the fact that, on average for the UK observing stations, cloudiness exceeded six oktas on 22 of the 30 'peak NLC' nights from mid-June to mid-July; while on only one of these nights was the average tropospheric cloud at the stations less than four oktas.

Nevertheless, during the season some extensive and bright displays were seen by observers at widely separated stations in the network, and in many instances photographed. In all, 37 occurrences of the clouds are listed; latitudes of observing points varied from 50°N to 65°N, and longitudes from 27°E to 07°W. Mr Parviainen, Finland, recorded in great detail by means of notes, sketches and photographs, the many displays of NLC he observed. It is difficult to do justice in this brief report to his work and to that of the many other contributors.

Time-lapse photography was carried out at the Department of Meteorology, Edinburgh, throughout the season, providing a record of nightly conditions there. Dr Michael Gadsden at Aberdeen ran a photometer, on nights when skies were good enough for photometry, at 20° elevation in the plane containing the directions of the zenith and the sun.

Noctilucent cloud data have been collected, collated and published by the Department of Meteorology, Edinburgh, since 1964, financed by an annual grant, originally from the Royal Society and in later years from the Meteorological Office. The efforts of many observers have contributed to the lists; we offer most grateful thanks for their help over the years. The data are filed in the Department of Meteorology and will continue to be held there, available to any who wish to consult them. Information in future should be sent to the Director of the Auroral Section of the British Astronomical Society (Mr R. J. Livesey, 46 Paidmyre Crescent, Newton Mearns, Glasgow G77 5AO).

Note

A summary for the whole period of the survey will appear in a later edition of *The Meteorological Magazine*.

Table 1. Displays of noctilucent clouds over western Europe during 1982

Date — night of	Times UT	Notes	Station position (to nearest 0.5 degree)	Time UT	Max. elev.	Limiting azimuths degrees
1982						
23/24 May	2400	Patches of NLC visible between tropospheric cloud, W and E of N. Easterly patch bright with band formation. Almost complete cloud cover before and after this observation from Kinloss.	57.5°N 03.5°W	2400		345-015
9/10 June	2200	Small patch NLC visible between tropospheric cloud (6/8). Cloudy conditions later.	56.5°N 07°W	2200		
13/14	2400-0200	Aldergrove and Tíree reported clear conditions and no NLC at 2300. At 2400 NLC seen clearly to N; display extended NW to E by 0100, in zenith as viewed from Tíree. Newcastle reported band and wave formation. Faint patches still visible Tíree at 0200.	56.5°N 07°W 55°N 01.5°W 54.5°N 06°W	0100 0200 0050 0145	90 — 10 14	090 045 340-040 335-075
14/15	0100	Clear conditions and no NLC visible 2300, 2400 and 0200. At 0100 billow formation NLC visible above tropospheric cloud.	56.5°N 07°W	0100	8	350-010
15/16	0100	Faint patch of NLC visible from Tíree after tropospheric cloud clearance. No NLC visible at 0200 in clear conditions. (Almost complete cloud cover down E side of N Britain.)	56.5°N 07°W	0100		
20/21	0100	Possible NLC visible at Boulmer in tropospheric cloud breaks.	55.5°N 01.5°W	0100		330-050
21/22	2010	Weak display visible at Rønne — through binoculars only.	55°N 14.5°E	2010	25	340
22/23	2200	Photograph taken by Mr Beeston in N London clearly shows NLC bands. No other report — N Britain cloud covered.	51.5°N 0°	2200	10	360
25/26	2315-2340	Report from Udny (Aberdeenshire) of NLC at very low elevation. (Report of red glow seen at Fiane — 59°N 09°E — high in S sky at 2038 thought unlikely to be NLC.)	57°N 02°W	2330	2	360
29/30	2330-0100	Faint bands of NLC visible on Edinburgh film.	56°N 03°W	2400		020
30/1	2200-2230	Very bright patch of NLC seen and photographed by Mr Andersen at Wildbjerg; its extensive spread was seen through tropospheric cloud. Faintly visible area of NLC in NE direction. Display also seen by Mr Ebers at Hitzacker (W. Germany), and Mr Bouma of Groningen who photographed the clouds at 2206 when brightly visible above tropospheric cloud bank.	56°N 09°E 53°N 11°E 53°N 06.5°E	2210 — 2206	15 — 15	360 — 360
1/2 July	2400-0145	The three reporting stations viewed the NLC through tropospheric cloud breaks — both Kinloss and Edinburgh (film) recording high elevation.	57.5°N 03.5°W 56°N 03°W 54.5°N 06°W	0100 2400, 0100 2400	26 20 7	010-040 — 020-030
2/3	2105-2350	Display seen by Mr Olesen from aircraft over Czechoslovakia and E. Germany, en route Rome/Copenhagen. Observed in Finland first as faint irregular bands to high elevation. At maximum of display (around 2240) bands and billows spread into SW and SE sectors. At 2300 N-S oriented bands seen E-SE. Observations ceased 2350 with NLC fading into the dawn.	60°N 22.5°E 50°N 10.5°E	2200 2230 2300 2130	40 120 140	315-360 225, 135 135 ?—045
3/4	2350-0115	Reported by Kinloss as possible NLC. From Udny NLC seen at very low elevation. Faintly visible on film at Edinburgh through tropospheric cloud breaks.	57.5°N 03.5°W 57°N 02°W 56°N 03°W	2400 2350 0100	— ½ —	315-360 350-355
4/5	2115-0215	Bright display visible in Finland (Mjösund) almost to S horizon; in Denmark (Alrø) — very bright in tropospheric cloud breaks; and in E Britain to high N elevation. The widespread display seen in Finland was patterned by band and billow formation over the whole extent. Bands, billows and delicate structure were seen at Edinburgh to 50° elevation. At Aberdeen photographs were taken every 15 minutes from 2345 to 0215.	60°N 22.5°E 57.5°N 03.5°W 57°N 02°W 56°N 03°W 56°N 03.5°W 55.5°N 01.5°W 55°N 14.5°E 55°N 01.5°W 54.5°N 01.5°W	2210 2230 2250 2310 0130 0200 2310 2250 2310 2327 2310 0025 0200 2215 2300 0130	140 160 165 140 9 13 40 25 30 50 30 30 30 30 7 3	225-110 135 135 250-110 360-020 350-040 345 340-060 320-050 340 360 340-010 340-020 340-045 360 010
6/7	2145-2240+	Medium bright display visible Mjösund, with faint forms beyond zenith, brightest in NNW. Bands and wave forms. Maximum of display 2225. Observations suspended because of fog conditions.	60°N 22.5°E	2200 2215 2225 2235	80+ 90 90+ 90	315-045 300-090 300-090 270-030

Date — night of	Times UT	Notes	Station position (to nearest 0.5 degree)	Time UT	Max. elev. degrees	Limiting azimuths
7/8	2045–2310 0001–0100	Bright display seen Mjösund with long bands in N–SW direction; spreading through NW and NE sectors past zenith; fog and moonlight possibly obscuring fainter areas. At Rønne the display was very bright and to high elevation. Photographs taken Aberdeen 0033 & 0053.	60°N 22.5°E	2105 2135 2145 2200 2245 57°N 02°W 0001 55°N 14.5°E 2105	40 90 100 110 120 — 55	315 270–090 270–090 290–090 — 045 340–135
8/9	2048–2350	With almost complete cloud cover in Mjösund it was impossible to assess the extent of the display. Only NW was clear; but occasional breaks in tropospheric cloud in NE and E disclosed no NLC. The very bright display was observed for 3 hours at Alrø, where Mr Olesen took a series of colour and black and white photographs.	60°N 22.5°E 56°N 10°E	2220 2250 2120	8 15 45	315 315 290–045
9/10	2300–2320	Weak display observed at Alrø.	56°N 10°E	2312	5	020–045
10/11	2050–0208	In Finland seen as medium bright small scale display mainly in E sky. Described as very bright from Kirkwall and Tiree. 23 fine prints taken at Malin Head record the details of the display, which was still bright and extensive in last photograph (0208).	60°N 22.5°E 59°N 03°W 56.5°N 07°W 55.5°N 07.5°W	2050 2100 2150 2210 0115 2300 2400 0100 0200 2400–0208	90 90 90 90 — 10 13 14 14 12	045–090 270,090 250 350–090 030–090 315 310–340 330–030 330–040 330–070 315–045
11/12	2200–2330 0300–0330	NLC bands and billows visible Tiree, Wick and Kirkwall, in NW sector. Later sighting from Wick of veil in NE. No NLC visible 2400 in clear conditions Tiree and Wick.	59°N 03°W 58.5°N 03°W 56.5°N 07°W	2300 2200 2300 0300 2205 2230 2300	— 15 15 20 6 7 6	290 315 300 045 320–360 345 305–330
13/14	2150–2215	Faint small scale display of weak bands in N seen Mjösund. Possible sighting at the same time queried by Boulmer. Aberdeen reported auroral display 2320 to 0150, and queried possible NLC at 0150.	60°N 22.5°E 57°N 02°W 55.5°N 01.5°W	2150 2200 2215 0150 2200	10 12 15 — 15	360 360 360 — 300–020
16/17	2230–2315 2400–0209	Wispy bands reported Kinloss and Dyce, faintly visible on film from Edinburgh, and to low elevation but bright from Boulmer. In Denmark display weakly visible showing band and veil structure.	57.5°N 03.5°W 57°N 02°W 56°N 03°W 56°N 10°E 55.5°N 01.5°W	2400 0038–0209 2230 2255 2400 0100	11 10 10 12 5 5	350–030 360–020 360 360 350–020 010–020
18/19	2140–0200	Picturesque, small display seen Mjösund, still visible after 2330 when observations ceased. Band and billow formation. Faintly visible on Edinburgh film.	60°N 22.5°E 56°N 03°W	2140 2200 2230 2300 2330 2230	— 18 30 30 30 30	315–045 340–020 340–045 360–045 315–045 360
19/20	2230 0200–0220	NLC bands, medium brightness, visible Northumberland. Faintly visible earlier on Edinburgh film.	56°N 03°W 55.5°N 01.5°W 55°N 01.5°W	2230 0200 0200	— 15 7	— 355–005 335–005
21/22	2100–0230	Display seen from very varied locations, medium brightness in Britain and very bright in Finland. Many brighter bands against veil background. In Denmark display bright, showing band and billow structure with red coloration near horizon. Photographs taken at Alrø and Wildbjerg.	60°N 22.5°E 57.5°N 03.5°W 56.5°N 07°W 56°N 03°W	2100 2125 2205 2330 0100 2230 2305 2325 0030 0050 56°N 09°E 2210 56°N 10°E 2110	8 15 10 9 6 9 6 6 5 3 — 15	360 360–045 360–045 350–025 330–010 010–040 360–030 345–020 355–015 355–015 — 340–045
22/23	0300	Diffuse band of NLC visible Tiree. Clear conditions and no NLC 2200–0200.	56.5°N 07°W	0300	14	030–038

Date — night of	Times UT	Notes	Station position (to nearest 0.5 degree)	Time UT	Max. elev.	Limiting azimuths degrees
24/25	2220–0230	'Best display since 1978' according to Mr Parviainen, though maximum (2330) occurred when sky brightening. At 0030 the display covered whole sky except low NE where obscured by rising sun. Mr Hapgood, travelling in roughly the same latitude, recorded the appearance of the NLC in the NE, developing towards the zenith until dawn, with marked wave structure after 0200. Mr Parviainen provided 20 photographs of the display taken at Mjösund, and Mr Hapgood sent details of the 20 he took some 300km to the west, at Gävle, in Sweden.	61°N 17°E 60°N 22.5°E	2245 2400 0100 2220 2235 2315 2335 0005 0020 0030	– 10 20 30 90 90+ 140 180	360 045 045 360,045 315–045 360–090 270–090 250–090 135–225
25/26	2100–0100	Another 'great display' as seen Mjösund to maximum elevation 22°, with very bright area on eastern tip (045°). Sumburgh and Wick reported the NLC area at high elevation when observed at 0100.	60°N 22.5°E 60°N 01.5°W 58.5°N 03°W	2100 2125 2145 2230 0050 0100	20 20 20 22 35 30	360 315–360 315–020 300–045 350–040 360
26/27	2030	Diffuse NLC visible through widespread breaks in tropospheric cloud at Fiane.	59°N 09°E	2030		
27/28	2100–2150	Very faint small scale display, soon obscured by tropospheric cloud.	60°N 22.5°E	2100 2120 2140 2150	10 15 10 15	360 315,360 360 360
28/29	2150–2225	Very faint NLC showing no development during observing time.	60°N 22.5°E	2150	10	360
29/30	2245–2335	Clear sky at 2200. Quiet display of short duration; band and billow formation in NW sky, becoming faint at 2335.	60°N 22.5°E	2245 2305 2315	40 16 30	315–360 360 315
30/31	0200–0400	At Håstrup, Denmark, short lived appearance of medium brightness NLC. NLC not visible in clear conditions at Tisee until 0300, when two narrow bands in NNW moved slowly into NNE.	55.5°N 10°E 56.5°N 07°W	0200 0300 0400	20 12 14	340–045 340–360 020–030
3/4 Aug	2145–2315+	Relatively bright display on a very cold night in N Finland. When observations began, NLC already bright in N sky; greatest extension 315–090 at 2230; maximum brightness 2250.	65°N 27°E	2155 2205 2245 2305	40 20 22 18	345–070 315–090 360–070 360–045
14/15	2100	Silvery bands reported from Benbecula, with N–S origination to maximum elevation 7°.	57.5°N 07°W	2100	7	315
17/18	2040–2115	Possible short sighting of NLC at high elevation.	59°N 09°E	2100	90	

Photographs

22/23	June	2200	London
29/30		2330–0100	Edinburgh Met. Dept
30/1		2206	Groningen
		2225	Wildbjerg
1/2	July	2400–0145	Edinburgh Met. Dept
2/3		2200–2300	Mjösund
3/4		0001–0115	Edinburgh Met. Dept
4/5		2210–2300	Mjösund
		2310–2325	Edinburgh (Cammie)
		2315–0145	Edinburgh Met. Dept
		2345–0215	Aberdeen
		2330	Edinburgh (Joppa)
6/7		2200–2230	Mjösund
7/8		2130–2300	Mjösund
		0033, 0053	Aberdeen

8/9		2048-2330	Alrø
10/11		2120-2200	Mjösund
		2355-0208	Malin Head
13/14		2200	Mjösund
16/17		2230-2300	Edinburgh Met. Dept
18/19		2230-2300	Mjösund
		2230-0200	Edinburgh Met. Dept
19/20		2230	Edinburgh Met. Dept
21/22		2125-2215	Mjösund
		2152-2205	Alrø
		2200-0230	Edinburgh Met. Dept
		2210	Wildbjerg
24/25		2300-0030	Mjösund
		2326-0022	Gävle
		0230	Edinburgh Met. Dept
25/26		2330-2400	Mjösund
27/28		2130	Mjösund
29/30		2330	Mjösund
3/4	August	2145-2315	N. Finland

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Meteorology and crop-spraying

By N. Thompson

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Summary

Adverse weather can seriously degrade the effectiveness and safety of crop-spraying and, in particular, may lead to damaging spray drift. This paper provides a brief review of meteorological factors of importance in crop-spraying, and gives quantitative descriptions of spray drift and the related off-target uptake and deposition of pesticides in both vapour and drop forms.

1. Introduction

Crop-spraying has advanced within the last two decades from a relatively minor activity on most arable farms to one of the most frequent and important of the various field operations in British agriculture. Two of the major reasons for this are: first, the recognition of the economic benefits of using sprays to reduce agricultural losses caused by pests and diseases and, second, changes in farming practices which demand much greater use of herbicides than hitherto; examples of the latter are the substitution of minimum cultivation techniques for ploughing, and the increase in acreage of winter cereals.

Many of the pesticides* are phytotoxic (damaging) to neighbouring crops which are not targets for the spray. Also, some (e.g. growth regulators and herbicides) are effective or safe only when applied at a

*Pesticide is the collective term for sprays used against insect pests, plant pathogens and weeds; it is now also applied to hormone-based plant growth regulators.

particular growth stage of the plants being protected or controlled. Meteorological factors therefore play an important part in a number of aspects of spraying; they determine, for example, whether spraying at the appropriate time can be carried out successfully or whether there is a significant risk of pesticide drifting on to, and damaging, sensitive off-target crops, either through drifting spray drops at the time of application or from pesticide which volatilizes at some time after application.

A number of studies (e.g. Adams 1980, Spackman and Barrie 1981) have confirmed that in some years the periods for spraying that are best in biological terms often do not coincide with optimal meteorological conditions. Then, for example, farmers may be forced to spray on occasions when the soil is so wet that damage is caused to the soil structure by the spraying vehicle, with consequent penalties in terms of crop yield. Alternatively, spraying may take place in conditions where excessive drift occurs, with the possibility of damage to sensitive plants growing outside the target area. The magnitude of drift is linked very closely to meteorological factors, and the remainder of this paper describes how recent work within the Meteorological Office (Thompson 1983, Thompson and Ley 1982) has led to progress in quantifying the spray drift hazard.

2. Some factors contributing to damaging spray drift

(a) *Vapour drift*

Most phytotoxic pesticides have low volatility, and at the time when they are often widely applied (in spring) temperatures are usually low enough for only insignificant quantities of pesticide to volatilize after application. However, some very effective pesticides which contain esters are much more volatile, and for them up to about 40% of the amount applied has been found to volatilize within a few hours of application in warm conditions with temperatures around 25 °C (Maybank *et al.* 1978). Vapour pressure, and hence rate of evaporation, of many pesticides decreases by a factor of around 4 for each 10 °C decrease of temperature (e.g. Burkhard and Guth 1981), so in Britain it might be expected that around 10% of the pesticide applied with these formulations would volatilize on the warmer spring days.

Another important aspect of vapour drift is that the wind direction may change between the time of application of the pesticide and the period in which damaging drift occurs. In order to avoid direct drift damage (i.e. by drops), the operator would not spray in the vicinity of sensitive off-target plants while the wind was blowing directly towards them; however, he would be unlikely to abandon an attempt to spray because of a forecast of a potentially damaging wind shift *after* completion of the task.

Thus, the combination of wind shift and high temperatures in the period after application, and the use of pesticides with high vapour pressure, are usually responsible for damaging vapour drift.

(b) *Drop drift*

At present most crop-spraying involves the use of a hydraulic system in which the pesticide, diluted around 100 times with water, is ejected through spray jets mounted on a boom about 0.5 m above the plants. The hydraulic pressure is typically 250 kPa, which forces the liquid from the jets at around 20 m s⁻¹ in a thin fan-like sheet. The sheet breaks up into drops with a wide size-spectrum, entraining air in the process so that the drops decelerate more slowly than if they had been ejected singly from the sprayer. In the absence of wind there is clearly no drift; conversely, an increase of wind produces an increase of drift, for two main reasons. Firstly, a stronger wind will disrupt the spray sheet and its entrained air more quickly, so that drop trajectories become controlled solely by atmospheric turbulence and drop fall-speeds at a height above the surface (called the effective release height) which is greater than in light winds, leading to a potentially larger source of drifting drops. Secondly, in stronger winds a larger proportion of the emitted drops have fall speeds which are small compared to the

turbulent updraughts and downdraughts in the atmosphere, and so behave more like neutrally-buoyant particles which can drift long distances before impacting on the surface.

Therefore, the most damaging drop drift usually occurs when spraying takes place in windy conditions, with the general direction of airflow from the target area towards the sensitive non-target plants.

3. Quantifying spray drift

(a) Vapour drift

The factors of importance here are (i) the source strength (amount of pesticide volatilizing), (ii) dilution, by atmospheric turbulence, of the vapour as it moves downwind, (iii) relation between rate of uptake of pesticide by plants and the vapour concentration in the air around the plants and (iv) the relationship between phytotoxicity and dose for the pesticide and plant species in question: the first three are strongly controlled by meteorological factors, and the last may also involve a dependence on weather, through temperature or an earlier weather-induced stress (e.g. through frost or soil moisture shortage).

There are considerable difficulties in estimating the rate of volatilization of a pesticide applied in known amounts to a target area. Thus, the pesticide may be distributed initially, in poorly-defined proportions, between foliage and the underlying soil. Volatilization from the soil will be influenced by adsorption, soil moisture and temperature. Loss of pesticide to the atmosphere from foliage will be determined by leaf temperature, wind speed, rate of absorption into the leaf tissue, form of the dilutant and physical nature of the deposit (e.g. its surface area). Both foliage and soil surface temperature may depart significantly from screen temperature, especially if the soil is dry. For these reasons it is not usually possible to provide a reliable estimate of rate of volatilization of the applied chemical; however, on the basis of earlier comments, a quantity of the order of a few percentage of that applied is likely to evaporate on the day of application when the more volatile formulations are used.

The treatment of the dilution of the vapour as it moves downwind is more straightforward. Areas sprayed in arable farming are usually several hectares in size, and so without much loss of generality the effects of lateral dispersion on dilution can be ignored. It is convenient to idealize the source as a series of long, adjacent cross-wind strips of unit alongwind length and then, following Pasquill (1974), the near-surface concentration of vapour, C , produced by a single source strip emitting Q units $s^{-1}m^{-2}$, at a distance x downwind is approximately

$$C(x) = \left(\frac{2}{\pi}\right)^{1/2} \frac{Q}{\bar{u} \sigma_z(x)} \quad \dots \quad (1)$$

This assumes that the distribution of vapour concentration in the vertical, about an axis at ground level, is Gaussian with standard deviation $\sigma_z(x)$, and that the mean speed of movement downwind is \bar{u} . The vapour concentration when contributions from all the source strips are included is then

$$C(x) = \left(\frac{2}{\pi}\right)^{1/2} \frac{Q}{\bar{u}} \int_x^{x+X} \frac{dx}{\sigma_z(x)} \quad \dots \quad (2)$$

with X the alongwind length of the sprayed area. $\sigma_z(x)$ is a function of atmospheric turbulence as well as x , and so varies with wind speed, atmospheric stability and aerodynamic roughness of the underlying

surface. Pasquill (1961) presented graphs showing how $\sigma_z(x)$ is related to distance and stability. The graphical data are described more conveniently in the present context by power-law relations which for fairly unstable (Pasquill's class B), near-neutral (class D) and fairly stable (class F) cases are approximately:

$$\left. \begin{aligned} \sigma_z(x) \text{ (B)} &= 0.12 x^{0.89} \\ \sigma_z(x) \text{ (D)} &= 0.10 x^{0.81} \\ \sigma_z(x) \text{ (F)} &= 0.055 x^{0.52} \end{aligned} \right\} \dots \dots \dots (3)$$

Substitution of equation (3) in equation (2) allows the calculation of vapour concentration at different distances from source areas of specified size.

The rate of uptake of vapour by plants depends on numerous factors apart from vapour concentrations adjacent to the plants. However, an estimate of this rate for most field crops may be obtained from the assumption that the vapour enters the plants through the leaf stomata*, and is then completely absorbed into the plant tissue; postulation of this mechanism for uptake of sulphur dioxide for example (Fowler and Unsworth 1979) leads to calculated rates of uptake in close agreement with measured values. A simple resistance analogue provides a method for developing the necessary theory in the case when the plants form a dense canopy completely covering the ground. Then the vapour concentration difference between that just above surface ($C(z)$) and that at the absorption sites in the leaves ($C(0)$) produces a flux density of vapour (F) which is controlled by two resistances in series:

$$F = (C(z) - C(0))/(r_a + r_c). \dots \dots \dots (4)$$

Here r_a is the average resistance to the transfer of vapour from the reference height z to the surface of the plant foliage; it may be estimated from wind speed, surface roughness, stability and molecular diffusion coefficient of the vapour (Monteith 1973 and Chamberlain 1974), and for short crops in near-neutral conditions has a value around 200 s m^{-1} when the 10 m wind is 2 m s^{-1} . r_c is the average resistance, per unit ground area, for the transfer of vapour from the leaf surface through the stomata. It has not been measured directly for pesticides, but can be deduced from the typical observed value of around 40 s m^{-1} for water vapour transfer through this pathway. This is done by applying a correction factor resulting from the smaller molecular diffusion coefficient of pesticides; most have molecular masses of around 300, compared to 18 for water vapour, and so r_c has a value around $40 (300/18)^{1/2}$ or about 150 s m^{-1} . Substituting these values for r_a and r_c in equation (4), and putting $C(0) = 0$ in view of the assumed perfect sink for the vapour within the leaf tissue, leads to a vapour flux density

$$\begin{aligned} F &= u_g C(z) \\ &\approx 3 \times 10^{-3} C(z) (\text{units } \text{m}^{-2} \text{ s}^{-1}). \dots \dots \dots (5) \end{aligned}$$

Here u_g is the *deposition velocity*, which in this case takes a value equivalent to the whole vapour cloud sinking towards the surface at 3 mm s^{-1} . The treatment may be modified slightly to apply to isolated individual plants, for which the rate of uptake is found to be several times larger than for the same plants when grouped to form a dense ground cover.

*Stomata are small pores in the leaf surface which permit the exchange of water vapour and carbon dioxide between plant and atmosphere.

The vapour concentrations calculated from equation (2) and (3) may be used with equation (5) to provide daytime estimates of likely rates of pesticide vapour uptake by plant canopies downwind from sprayed areas of typical size (Table I); no values are given in the Table for night-time because stomata are then usually closed. It is seen that in conditions typical of a warm, fairly sunny day the rate of uptake of vapour is calculated to exceed 1% of the source strength out to distances of at least 200 m. The larger uptake in near neutral conditions has to be set against the lower source strength then expected because of the lower temperatures found in these conditions.

Table I. *Estimated rate of uptake of pesticide vapour by a short, dense plant canopy: the vapour is assumed to be emitted from a broad field, 200 m long in the alongwind direction, at a rate of 1 unit $m^{-2}s^{-1}$ and to move downwind at 2 $m s^{-1}$.*

Downwind distance from field edge (m)	Rate of uptake (units $m^{-2} s^{-1}$)	
	Moderately unstable	Near-neutral
5	0.055	0.087
10	0.046	0.076
20	0.038	0.065
50	0.027	0.046
100	0.020	0.034
200	0.013	0.023
500	0.007	0.013
1000	0.004	0.008

The results indicate that for a case where 10% of the pesticide deposited on a target subsequently volatilizes, the uptake within about 200 m of the target can exceed 0.1% of the target dose. This figure may be considered in the light of the results from a number of experimental studies (e.g. Way 1964) in which sensitive plants have been sprayed by damaging pesticides to provide an indication of the magnitude of the dose required to cause some injury. Data given in Table II indicate that a number of horticultural crops can be damaged by very low doses. For the conditions under which Table I was constructed it is seen that when 10% of the applied pesticide volatilizes, then for lettuce affected by the herbicide 2,4-D for example, damage might be expected out to around 100 m from the field; if 20% of this herbicide volatilized, the distance of hazard would increase around threefold. These results are not

Table II. *Minimum damaging doses of herbicide (as percentage of normally applied dose) for various crops.*

Herbicide	Minimum damaging dose	
	0.1 – 0.4%	0.4 – 1%
MCPA	Outdoor lettuce, tomato	turnip
2,4-D	Outdoor lettuce	tomato, turnip, swede, cabbage, cucumber
Mecoprop	Outdoor lettuce, turnip, tomato	

inconsistent with some reported cases of herbicide drift damage. Thus there is some prospect that, provided sound methods are established for estimating the magnitude of the vapour source strength, and the necessary relationships between dose and damage are known for different plant species, meteorological treatments may be used to establish the weather conditions under which spraying can take place near sensitive plants without a subsequent risk of damage from vapour drift.

(b) *Drop drift*

A typical conventional hydraulic sprayer produces a drop-size spectrum with a volume median diameter around $250\ \mu\text{m}$, but the spectrum is broad so that as much as 10% of the spray volume may be carried by drops less than $100\ \mu\text{m}$ in diameter. Many factors additional to drop size affect drift; the most important are probably

(i) height distribution of each drop-size fraction when the drops have decelerated from their initial high ejection speeds to speeds where their subsequent trajectories are determined solely by fall speed and atmospheric flows,

(ii) wind speed and atmospheric turbulence,

(iii) rate of evaporation of the drops, and

(iv) the collection efficiency of the underlying surface for each drop size involved.

There are many interactions between these various factors, of which one of the most important is between (i) and (ii); it is well established that the number of drops which become potential drift (fail to be deposited immediately after release) increases with increasing wind speed in the case of conventional sprayers (e.g. Courshee 1959).

A qualitative picture of the drop-size range which is liable to drift may be obtained by comparing drop fall speeds (Table III) with typical vertical turbulent velocities in the atmosphere. Spraying usually takes place in daytime conditions with mean 10 m wind speeds less than about $5\ \text{m s}^{-1}$, when root-mean-square (r.m.s.) vertical velocities are typically less than about $0.5\ \text{m s}^{-1}$. Drops with fall speeds around or significantly larger than these turbulent velocities will have their trajectories largely determined by mean wind and gravity; drops for which the r.m.s. velocities significantly exceed their fall speed will behave more like neutrally buoyant particles, and be likely to drift. On this basis, drift will usually be negligible for drops larger than about $150\ \mu\text{m}$, unless spraying takes place with wind speeds greater than $5\ \text{m s}^{-1}$ or with a release height substantially greater than about the 0.5 m usually employed.

Table III. *Fall speeds of water drops in still air.*

Drop diameter	Fall speed
μm	m s^{-1}
20	0.01
30	0.03
50	0.07
100	0.25
150	0.48
200	0.71
250	0.93
300	1.15
400	1.60

There have been numerous experimental studies of crop-spray drift, but because of the large number of variables involved, and their mutual interactions, it has not been possible to derive from the results general expressions quantifying drift in terms of the variables. An inherently more satisfactory method of estimating the magnitude of spray drift is to construct mathematical models based on the underlying physics that may be applied after validating them against the results of limited numbers of field experiments. Until recently such models usually invoked a diffusing, sedimenting plume, with surface deposits determined from the geometry of intersection of the plume and the surface (e.g. Bache and Sayer 1975). However, these models are not able to represent satisfactorily all the processes involved,

and more recently 'random-walk' methods have been used to provide a more comprehensive description of drop drift (Thompson and Ley 1982, 1983).

Before describing results from the latter class of models, it must be pointed out that at present there appears to be no satisfactory method for describing simply the dynamics of drops in the period immediately following emission from hydraulic sprayers; it is necessary therefore to assume, rather than calculate, effective release heights of the drops whose trajectories are being modelled.

The random-walk model assumes that the trajectories of individual drops, away from the immediate influence of the spraying system, can be represented by a connected series of discrete displacements determined partly by a correlation between successive drop velocities and partly by a random selection from a Gaussian distribution of turbulent air velocities. Considering the vertical component of drop motion (the treatment is extended readily to three dimensions) and ignoring initially the drop-fall speed, we find the appropriate description is provided by the equation

$$w_{i+1} = \alpha w_i + \eta_{i+1} \sigma_w (1 - \alpha^2)^{1/2}, \quad \dots \quad (6)$$

where w is the vertical velocity of the drop, i is the number of the time step, η is a random variable with zero mean and standard deviation of unity, and σ_w is the r.m.s. vertical velocity. α is related to the Lagrangian time-scale (τ_L) of turbulence and the length of time step (Δt) used; provided that $\Delta t < \tau_L$ and, with several lesser assumptions, it may be shown that (e.g. Hall 1975)

$$\alpha = \exp(-\Delta t / \tau_L). \quad \dots \quad (7)$$

Introducing the fall speed (v_s) of the drop, and noting that the z axis is orientated upwards, leads to

$$w_{i+1} = \alpha (w_i + v_{si}) + \eta_{i+1} \sigma_w (1 - \alpha^2)^{1/2} - v_{si+1}. \quad \dots \quad (8)$$

The treatment is valid only for drops with a settling speed small enough for them to respond adequately to the velocity fluctuations in the surrounding air, but this is not a restrictive condition in the present context since, according to Smith (1959), this will be the case for $v_s < 2 \text{ m s}^{-1}$ (corresponding to water-based drops less than about $450 \text{ } \mu\text{m}$ in diameter).

Since the drops are usually water-based, their fall speeds change with time unless the air is saturated. The drops contain about 1% pesticide, whose evaporation may usually be neglected, and so decrease to about one fifth of their original diameter when all the water is lost. It is convenient to assume that mass transfer takes place from the drops as if they are pure water until only pesticide remains and it appears that this simplifying assumption adequately represents the evaporation of water-based sprays in many cases (Wanner 1980). On this basis the temperature of the drops is close to the wet-bulb temperature of the air (Ranz and Marshall 1948); following these last authors, the rate of change of drop diameter with time is approximately

$$\frac{d}{dt} d_\mu = -0.36 (\Delta p / d_\mu) \{ 2 + 0.124 (v_s d_\mu)^{1/2} \}, \quad \dots \quad (9)$$

where d_μ is the drop diameter in μm , and Δp (Pa) is the saturation deficit at the wet-bulb temperature ($\Delta p \approx 67 \times \text{wet-bulb depression}$).

Evaluation of the boundary layer variables contained in equation (8), and in the equivalent expression for alongwind motion, is carried out using similarity theory and flux-profile relations for non-adiabatic conditions (Ley 1982, Ley and Thomson 1983, Dyer 1974, Panofsky *et al.* 1977).

Application of the equations to the estimation of drop deposition on the underlying surface, and of numbers remaining airborne, at different distances from the source requires, in both cases, some assumptions about how the drops are trapped when they meet the underlying surface. It is found that the results are relatively insensitive to the height at which the drops are assumed to be deposited within the plant canopy, but are affected by the efficiency of collection. It is satisfactory therefore to assume that the trapping surface for the drops is at the top of the plant canopy; the possibility of less than complete capture of the drops when they first cross this surface (Lawson and Uk 1979) is accounted for by introducing partial absorption in the model, with the absorption coefficient ranging from one for large drops (diameter $> 100\ \mu\text{m}$) to values close to zero for very small drops. The model may then be used to calculate drift of drops and surface deposit densities for any distance from the source, although in crop-spraying applications it is convenient to limit this distance to a few hundred metres. It is necessary to follow the trajectories of a large number of individual drops (up to 10^4) in order to reduce statistical variability of the calculated deposits at longer distances to a level where reliable smooth curves of deposit density against distance can be drawn.

Quantitative estimates may then be obtained indicating the effects on drift of changing any of the meteorological or source variables, but for brevity only the effects on drift of varying effective release height, wind speed and rate of evaporation will be described here. Fig. 1 shows estimates of surface deposit densities at various distances from a long cross-wind line source of strength 10^4 drops per metre, for two drop sizes and a range of wind speeds and effective release heights. Except very close to the source, the effect of an increase in release height is seen to be an increase in drift deposits at all distances. In very light winds most of the $100\ \mu\text{m}$ drops fall out close to the source, but when winds are moderate or fresh the deposit densities are roughly proportional to effective release height. A smaller, but still marked, dependence of deposit density on release height is seen also for $50\ \mu\text{m}$ drops. The large increase of drift deposit with increasing wind speed which is evident for the $100\ \mu\text{m}$ drops is not observed for the $50\ \mu\text{m}$ size, because the smaller drops, with fall speeds only one quarter of those for $100\ \mu\text{m}$ drops, behave more like neutrally buoyant particles, even at wind speeds as low as $2\ \text{m s}^{-1}$. As discussed earlier, an important consequence of an increase in wind speed is an increase of the effective release height of the drops, which in turn widens the size spectrum of those drops liable to drift. Thus, directly or indirectly, wind speed is seen to exert a very large influence on drift; this is in accord with the experience of spray operators who believe that spray drift of phytotoxic chemicals becomes unacceptably large in many cases when $10\ \text{m s}^{-1}$ winds increase above about $5\ \text{m s}^{-1}$.

Drop evaporation also has a significant influence on drop drift, but a difficulty here is that the collection efficiency of the surface on which the drops are deposited decreases as the drops shrink in size, but in a way which is at present not quantified. The physical nature of the underlying surface will be important here (Lawson and Uk 1979), and the wind speed as well; however, in the absence of an accepted relation it will be assumed that collection efficiency (β) decreases linearly from 1.0 for $100\ \mu\text{m}$ drops to 0.1 after complete evaporation of water, with the corresponding range from 0.5 to 0.05 for drops which are initially $50\ \mu\text{m}$ in size. The results using these assumptions are compared in Fig. 2 with those for non-evaporating drops, and for drops with the absorption coefficient remaining constant in size as the drops shrink in size; the results are given for a wind speed of $5\ \text{m s}^{-1}$, effective release height of $0.5\ \text{m}$ and (for cases with evaporation) a relative humidity of 50% at 20°C . It is seen that, beyond a few hundred metres, the deposit densities of evaporating drops are substantially larger than for non-evaporating drops, and are also nearly independent of the lower boundary assumption. This unexpected latter result must however be viewed in conjunction with the numbers of drops airborne in the different cases (Table IV). Partial absorption leads to a larger number of the drops remaining airborne, particularly at longer distances. However, the estimated increase in the airborne fraction from this cause would be completely inadequate to compensate for the small absorption coefficient (about 0.1) if those drops, when reflected, became distributed in the vertical in the same way as those still

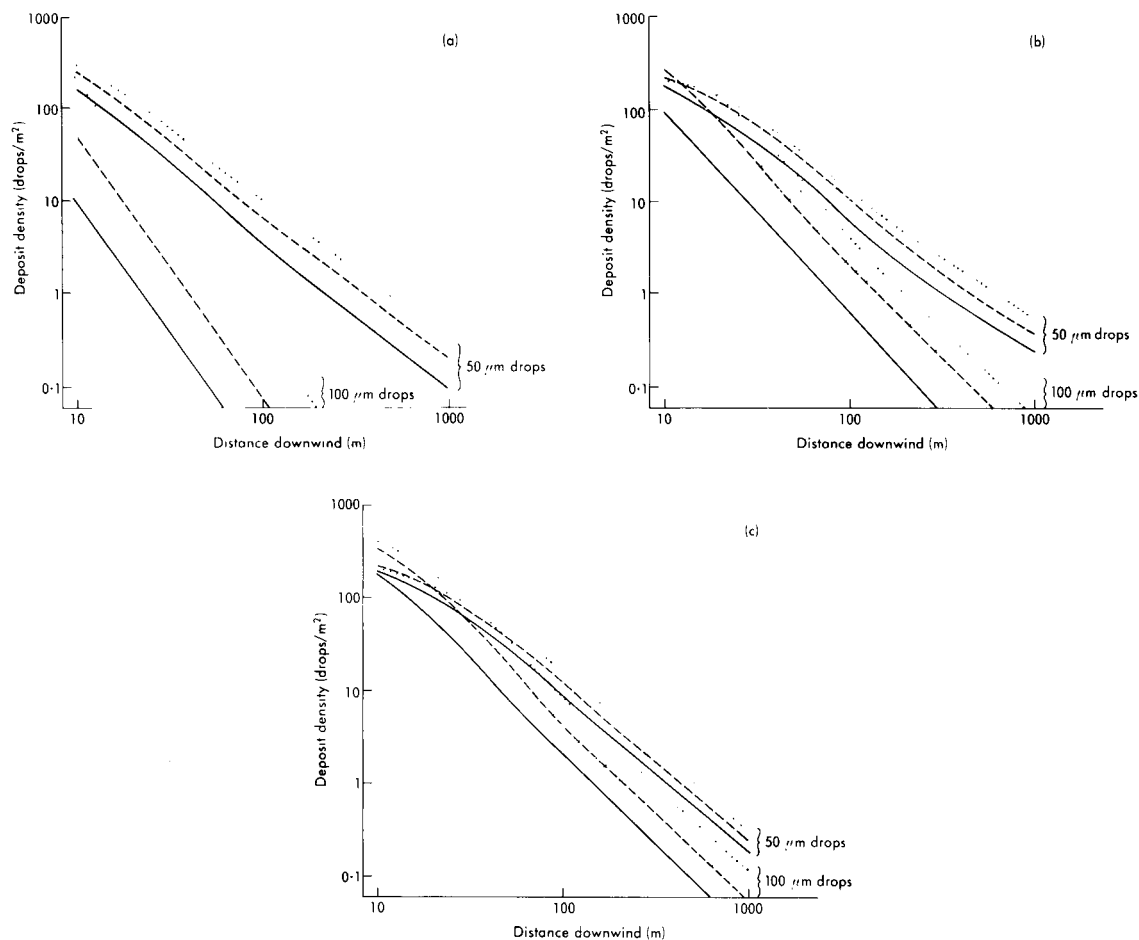


Figure 1. Estimates of surface deposit densities at various distances from a long cross-wind line source of strength 10^4 drops per metre, for two drop sizes ($50\text{ }\mu\text{m}$ and $100\text{ }\mu\text{m}$), three effective release heights (0.2 m —, 0.5 m ---, and 1.0 m) and a range of wind speeds (a) 2 m s^{-1} (b) 5 m s^{-1} and (c) 10 m s^{-1} .

Table IV. Percentage of drops remaining airborne at different distances from source: an effective release height of 0.5 m , and a wind speed of 5 m s^{-1} , are assumed.

Drop size (μm)	Assumed conditions	Percentages airborne			
		at 10 m	50 m	100 m	500 m
50	a	63	28	20	12
	b	69	44	37	27
	c	81	72	67	58
100	a	24	3.8	2.0	0.5
	b	30	10	8	5
	c	29	12	11	8

- a = non-evaporating drops with constant β (collective efficiency)
 b = evaporating drops with constant β
 c = evaporating drops, with β decreasing with decreasing drop size

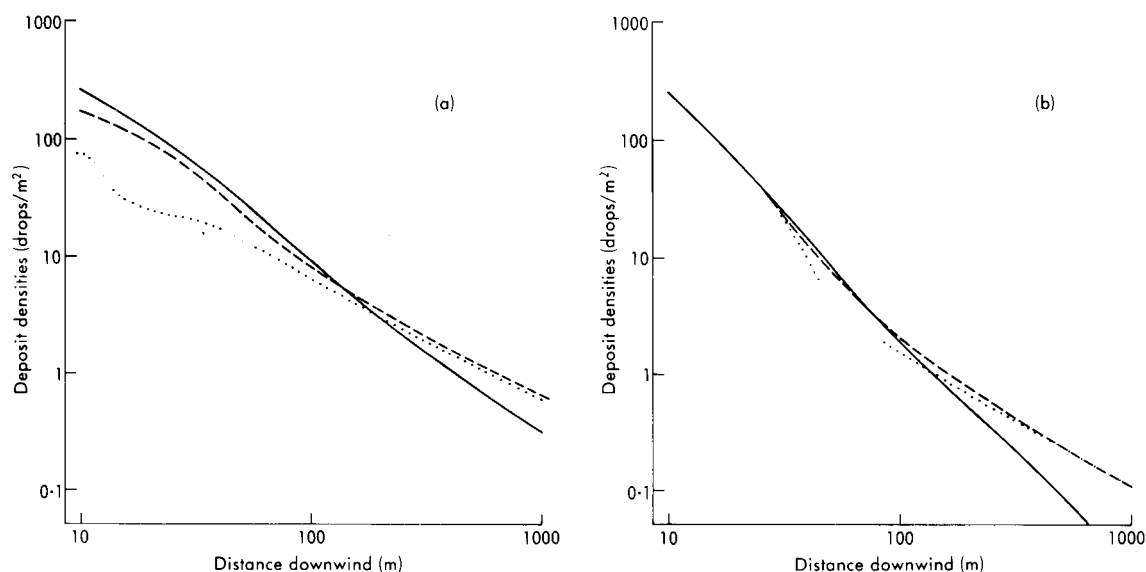


Figure 2. A comparison between surface deposit densities, in unstable conditions, of non-evaporating drops ———, evaporating drops (collection efficiency, $\beta = 1$) ---- and β decreasing with decreasing drop size ····, for drops that are initially (a) 50 μm and (b) 100 μm .

unreflected. On the other hand, reflected drops are likely to remain close to the surface for some time, and perhaps undergo further partial reflection, because of the small scale of atmospheric turbulence at these low heights. Reflected drops produce, therefore, a substantial increase in drop numbers near the surface, and in the context of deposit densities this appears largely to compensate for the low absorption coefficient; some measured distributions of drop numbers with height given by Lawson and Uk (1979) provide support for this idea. Nearer the source the proportion of reflected drops is much smaller and a reduced absorption coefficient therefore leads to a substantial reduction in surface deposit.

4. Concluding remarks

It is clear that meteorological factors have a considerable influence on the safety and success of crop-spraying on any particular occasion. It has been shown in this paper how knowledge of the relations between the structure of atmospheric turbulence near the surface on the one hand and simple meteorological parameters such as wind speed on the other allows the development of quantitative treatments of spray drift in both vapour and drop form with the help of simple models of turbulent flow. At present the full potential of such studies cannot be realized because of uncertainty in the precise nature of the sources of vapour or drops, a difficulty which is unlikely to be resolved easily; in spite of this the meteorological treatments are clearly able to give useful information on how drift varies with changes in meteorological variables. As more information becomes available on the characteristics of pesticide sources producing the drifting material the goal of estimating drift and drift hazard over the whole range of meteorological conditions normally experienced in crop-spraying should become attainable.

Although little has been said in this paper about the problem of spraying in wetter periods with only small soil moisture deficits, here too the application of meteorologically-based models provides useful

information on the number and duration of those periods in which spray vehicles are likely to be able to move over the land without damaging its soil structure. The approach required involves simulation of the variations of soil moisture with time at different depths in the soil by use of models of evaporation from the soil surface, and of water flow in soil, in conjunction with standard meteorological observations. The methods applied here are clearly very different from those used in estimating spray drift, indicating the great scope for application of physical principles, and those of atmospheric physics in particular, in problem-solving in agricultural meteorology.

5. Acknowledgments

I am grateful to Miss A. J. Ley for making available her random-walk model which was used to obtain a number of the results that have been described. I am indebted also to I. A. Barrie and R. D'Costa for their contributions to work on which this paper has been based.

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Concorde forecasts and the new 15-level model

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Summary

A global 15-level numerical model recently replaced the 10-level model at Bracknell and its behaviour in relation to the preparation of 100 mb flight forecast charts for Concorde aircraft has been monitored. Results so far are favourable, although a few dynamical problems have emerged.

1. Introduction

The 10-level model used at Bracknell for the past decade was not suited to produce forecasts of 100 mb temperature to be used in the preparation of flight forecast charts for Concorde. Temperatures were consistently too high in troughs and too low in ridges and the analysis did not even fit the reported temperatures from radiosonde stations (Atkins 1982). However, at the beginning of September 1982, the 10-level model was replaced operationally by the new 15-level model. This followed a period of trials lasting over six months during which time both models were run and the results assessed in various ways.

The development of the new model has been described by Gilchrist and White (1982) showing that the 10-level geopotential analysis has been replaced by an analysis of wind, temperature and surface pressure fields, moulded by a six-hour period of assimilation. Also, since the new model extends up to near 20 mb, instead of 100 mb for the 10-level model, it should be more suitable for producing temperature and wind forecasts at 100 mb. Assessments have been carried out by the author and although they were made on an irregular basis, it has become clear that there has been a marked improvement on the 10-level model although some consistent faults have been noted.

The form of the output from the 15-level model, run on the Cyber 205 computer, is virtually unchanged from the 10-level model and the times of receipt also remain about the same.

2. Analysis of the 100 mb temperature field using data assimilation

A considerable improvement has been noticed on the 100 mb temperature analysis mainly because the 10-level model temperatures were deduced from the thickness of 100 mb layers and the top such layer was 200–100 mb. A typical example of a comparison between the analysis of the two models and the analysed radiosonde reports is shown in Fig. 1. The improvement is seen in an objective verification of the 100 mb temperature analyses in August 1982 using observations over an area including Europe, the Atlantic and parts of America. The root-mean-square errors for the two models were as follows:

10-level model	2.1 °C
15-level model	1.5 °C

3. Behaviour of the 15-level model at 100 mb

The 24-hour forecast 100 mb geopotential contour patterns are mostly good. There is a tendency to forecast low values of geopotential although this does not necessarily affect the shape of the pattern and

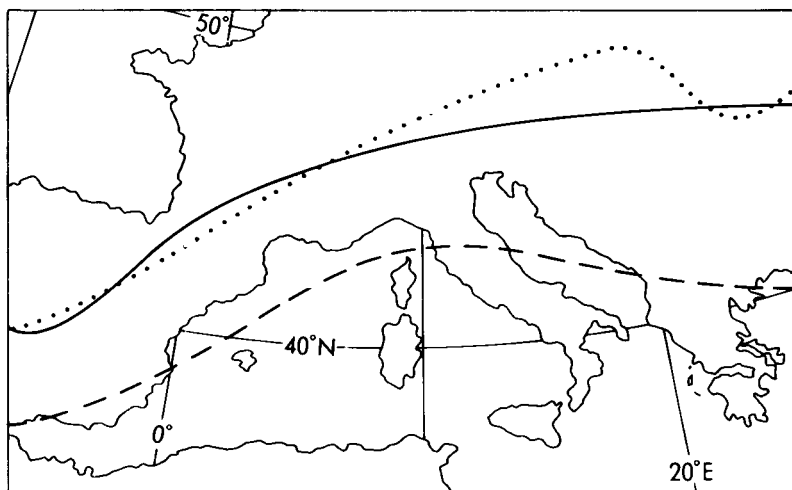


Figure 1. A comparison between the analysis of the 10-level model (dashed line) and the 15-level model (dotted line) of the -56.5 degrees Celsius isotherm (the International Standard Atmosphere) at 100 mb, for 00 GMT 21 July 1982. The full line shows analysed radiosonde temperatures.

hence the wind field. The model is also liable to move troughs and ridges a little too far east but this has only a minor effect on a 24-hour forecast. A more serious problem does occur on a few occasions when the model extends an upper trough excessively with consequent effects on the temperature and wind fields. Fig. 2(a) is an example of the error which can arise in the 24-hour forecast, while Fig. 2(b) shows the corresponding error in the forecasts of temperature (deviations from the International Standard Atmosphere); temperatures are seen to be as much as 5 degrees Celsius too high on the 24-hour forecast. Fig. 2(c) shows that, in addition, the area of maximum winds lying directly over the Concorde route at validity time, was displaced southwards off the route. Nevertheless, the 15-level 100 mb geopotential contour patterns are of an acceptable standard to be used generally in the preparation of the flight forecast charts, as indeed were the fields from the 10-level model.

4. The 15-level model forecasts of 100 mb temperature fields

Seventy-five assessments were made of the 24-hour forecast isotherms and these showed conclusively that there has been a marked improvement on the 10-level model forecasts. The forecasts were marked as poor when the error was assessed to be at least 4 degrees Celsius over at least 400 nautical miles of the flight route. Of the 75 forecasts checked, only 7 were marked as poor and 5 of these were related to excessive troughing. However, the success rate of the new model means that the computer forecasts of the 100 mb temperature can be used with a high degree of confidence in the preparation of the flight forecast chart. Little confidence was held in the 10-level model which necessitated the effort to find a method to obtain an acceptable forecast (Atkins 1982). A typical comparison between the 10- and 15-level model forecasts and the analysis for the same validity time is seen in Fig. 3. Objective verification against observations of the 100 mb temperature forecasts from T+24 hours to T+48 hours, for August 1982, when both models were running in parallel, is shown in Table I. The verification area includes Europe, the Atlantic and parts of America. These figures confirm the subjective assessments that the new 15-level model 100 mb temperature forecasts are better than the 10-level model.

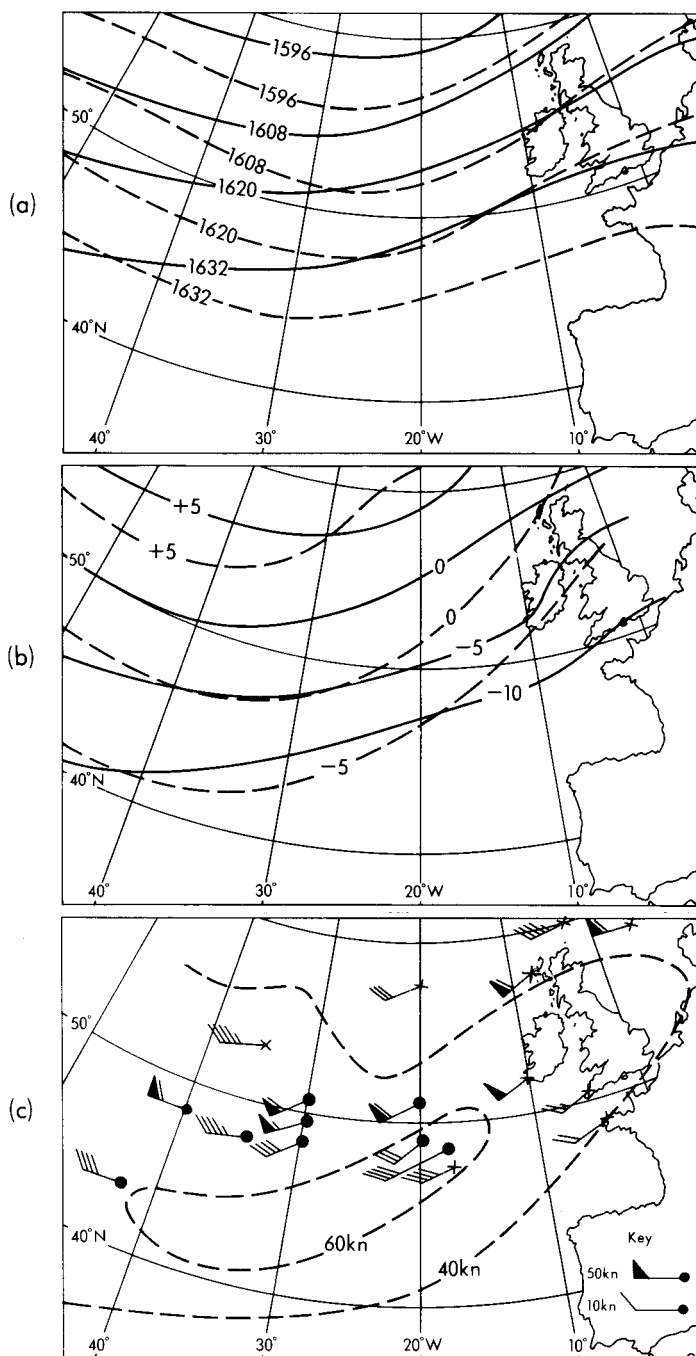


Figure 2. Comparisons between 100 mb charts for 00 GMT 20 October 1982. (a) The analysed geopotential contour chart (full lines) and the 15-level 24-hour forecast (dashed lines). Values in decageopotential metres. (b) The analysed isotherms (full lines) and the 15-level 24-hour forecast (dashed lines). Values in degrees Celsius as a departure from the International Standard Atmosphere. (c) The 15-level 24-hour forecast isotachs (dashed lines) and actual reports. Radiosonde stations for the same validity time are marked X, Concorde reports with a flight level near 100 mb, 3 to 6 hours earlier, are indicated by ●.

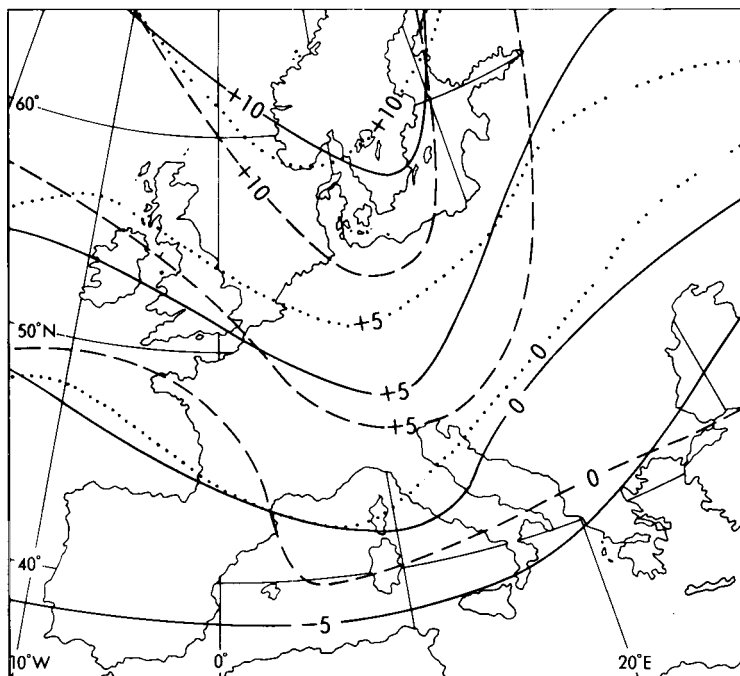


Figure 3. A comparison between the analysed 100 mb isotherms for 12 GMT 21 August 1982 (full lines) and the 24-hour forecast 10-level model (dashed lines) and the 15-level model (dotted lines) of the same validity time. Values in degrees Celsius as a departure from the International Standard Atmosphere.

Table I. *The root-mean-square error 100 mb temperature (degrees Celsius) forecast, verification against observations for August 1982. The mean error is given in brackets.*

	T+24	T+36	T+48
10-level model	2.2 (-0.5)	2.4 (-0.6)	2.6 (-1.0)
15-level model	1.8 (0.2)	2.4 (0.2)	2.1 (0.1)

5. The 15-level model forecast of 100 mb wind fields

Apart from the fault of excessive troughing mentioned above, the 100 mb wind fields are generally good, with areas of maximum wind strength well generated. However, anticyclonic winds in particular can be a little too strong, by about 10 kn, but it is possible for the forecaster to modify the numerical product. An example is given in Fig. 4 when the 80 kn isotach was deleted from the 15-level 24-hour forecast before issue. As can be seen from the verifying observations this proved to be a correct decision.

6. Concluding remarks

(a) The 100 mb temperature analysis has been improved with the introduction of the 15-level model and the chart analyst can accept the computer product with reasonable confidence even in data-sparse areas.

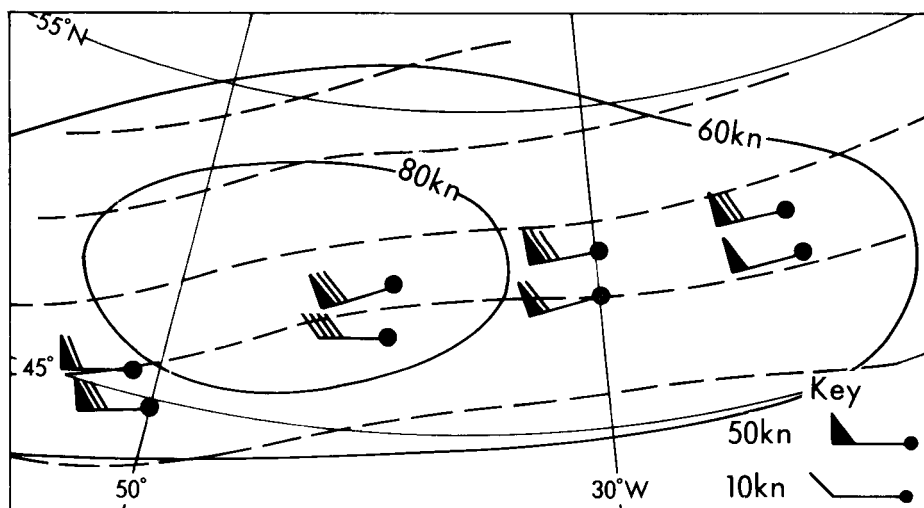


Figure 4. The 15-level 24-hour forecast of 100 mb isotachs for 00 GMT 10 December 1982 (full lines) and all the Concorde actual reports with 4 hours of that time with flight level near 100 mb. The 24-hour forecast 100 mb contour flow is indicated by the dashed lines and is similar to the subjective analysis for the same time. In the event, the 'anticyclonic' 80 kn isotach was deleted before issue.

(b) The 15-level model has produced a marked improvement on the 24-hour 100 mb temperature forecast. Temperatures may be up to 5 degrees Celsius too warm due to excessive troughing but, if this is taken into account, the standard of forecasts should be high.

(c) Subjective modification of the 15-level forecast isotachs can be beneficial.

(d) The 15-level model is still in its early stages and changes are continually being made to improve it. When the problem of excessive troughing has been overcome it might be possible to computerize the flight forecast chart so that a 12-hour forecast with data time 00 GMT could be used for the early morning forecast, perhaps issued a little later. At present the data time goes back 16 hours.

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|-----------------------------------|------|---|
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Notes and news

Dr G.O.P. Obasi (Nigeria) appointed Secretary-General of WMO

The Ninth World Meteorological Congress, meeting in Geneva in May of this year, appointed Dr Godwin Olu Patrick Obasi (Nigeria) as Secretary-General of the World Meteorological Organization (WMO) for a period of four years commencing 1 January 1984.

Dr Obasi was born in Nigeria in 1933 and joined the Nigerian Meteorological Department in 1956. Subsequently he studied at McGill University, Montreal graduating in Mathematics and Physics and then at the Massachusetts Institute of Technology where he gained a Master's degree with distinction, a doctorate in meteorology and the Carl Rossby award for the best doctoral degree thesis. In 1963 he returned to the Nigerian Meteorological Service.

In 1967 he went to Kenya as Senior Lecturer at Nairobi University under the WMO/UN Development Programme, subsequently becoming Professor and Dean of the Faculty of Science. Returning to Nigeria in 1976, he was appointed Adviser to the Federal Government in Meteorological Research and Training and Head of the Nigerian Institute for Meteorological Research and Training and in 1978 he joined the WMO Secretariat in Geneva as Director, Education and Training Department. He has served as member or chairman of several important national and international scientific committees and working groups including being Chairman (1976–78) of the Nigerian National Committee for the West African Monsoon Experiment and Chairman (1965–67) of the Working Group on Tropical Meteorology of the WMO Commission on Atmospheric Sciences.

He is married and has six children.

He succeeds the present Secretary-General, Dr Aksel C. Wiin-Nielsen who has held the post since 1 January 1980.

Obituary

We regret to record the death on 29 March 1983 of Mr J.L.F. Irwin (Assistant Scientific Officer) of the Operational Instrumentation Branch (Met O 16). Mr Irwin joined the Office in 1971 and had worked from then on in the Radiosonde Calibration Plant. He was a keen morris dancer and was a member of the Yately Morris Men. He was also a musician with the Mayflower Morris Group.

THE METEOROLOGICAL MAGAZINE

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NOTICES

It is requested that all books for review and communications for the Editor be addressed the Director-General, Meteorological Office, London Road, Bracknell RG12 2SZ and marked 'For Meteorological Magazine'.

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Printed in England by Robendene Ltd, Amersham, Bucks,
and published by
HER MAJESTY'S STATIONERY OFFICE

£2 monthly

Annual subscription £26.50 including postage

Dd 717701 C15 8/83

ISBN 0 11 726937 9
ISSN 0026-1149