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The preparation of data for the Meteorological Office operational 15-level forecast model

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Summary

Observational data consist of measured or derived variables at different levels in the atmosphere, and must be converted to the variables required by the model before they can be used in the operational analysis. The preparation of some types of data is very simple, but for others it is much more complicated, and this paper discusses some of the problems involved.

1. Introduction

Coded observational data are received at Bracknell continuously via the Global Telecommunication System (GTS) and are routed by the Telecommunications Branch to the central IBM computer where they are decoded and stored in the Synoptic Data Bank (SDB). The observations are of different variables at various levels in the atmosphere, and must be converted to the appropriate model variables and formed into an ordered data set before they can be used in the analysis. It is also necessary to incorporate the intervention submitted by forecasters in the Central Forecasting Office (CFO) who monitor the data and model products. Erroneous data can be rejected or corrected, and 'bogus' or artificial data inserted in areas where model fields are poor. The preparation of certain types of data is quite straightforward, requiring only a simple change of variable using a standard formula; however, for other types, the conversions could be carried out in a variety of ways involving different approximations and assumptions. It is clearly very important that the methods chosen should provide the analysis with the best possible information, giving a faithful representation of the original data as well as satisfying all the model requirements. This paper outlines the methods used for each type of data, describing in depth some of the more difficult problems encountered, but first, a brief description is given of the operational analysis scheme in which the data are used.

Notation

p	pressure (mb)
p_s	pressure at station level (surface)
p_*	pressure at model surface
T	temperature (K)
t	temperature (° C)
t_d	dew-point temperature (° C)
ω	precipitable water content (mm)
U	relative humidity
q	humidity mixing ratio (g/g)
m	humidity mixing ratio (g/kg)
z	geopotential
u,v	eastward and northward wind components
θ	potential temperature
γ	lapse rate ($= -dT/dz$)
g	9.80665
R	universal gas constant (=287.05 J kg^{-1} K^{-1})
k	$= 1-(c_v/c_p) = 0.2857143$
	c_p = specific heat of gas at constant pressure
	c_v = specific heat of gas at constant volume

2. Operational analysis

The analysis is global with a latitude–longitude grid in the horizontal (with meridional resolution 1½° and zonal resolution 1⅞°) and 15 levels in the vertical (from the surface up to about 25 mb). In the vertical, the terrain-following sigma coordinate system is used, where at any level j,

$$\sigma_j = \frac{p_j}{p_*},$$

p_j being the pressure at level j, and p_* the pressure at the model surface (generally a smoothed version of the real orography). The analysis is performed every six hours using data valid for up to three hours either side of the analysis time. The analysis is a three-dimensional univariate optimal interpolation scheme, which effectively means that prior interpolation of data to special analysis levels is unnecessary, and each variable is analysed independently. The variables required by the analysis are the independent variables of the forecast model, which are θ (potential temperature), q (humidity mixing ratio), u and v (eastward and northward wind components) and p_*. (Full details of the data assimilation scheme can be found in Lyne, Little, Dumelow and Bell 1983.)

3. Data

3.1 *Surface data (surface land stations, surface ships, drifting buoys)*

Typically, surface observations provide values of surface temperature, dew-point, wind and mean sea level (msl) pressure. Exceptions to this are drifting buoys, which report msl pressure and sea surface temperature only, and high-level stations (above 500 m), where reduction of surface pressure to msl pressure is unreliable. The latter report either station level pressure, or the geopotential of a standard pressure level (see World Meteorological Organization 1982).

Surface temperature data are not used in the analysis, as local anomalies are considered to render them unrepresentative of the atmosphere on the scale of the model grid. For the same reason, surface wind and humidity data are not used over the land, although they are used over the sea after conversion to u and v components, and humidity mixing ratio respectively. The reported pressure must be converted to model surface pressure (p_*). Where the geopotential of the model orography (z_*) is equal to the geopotential of the reported pressure (e.g. over the sea) no work is required as p_* is equal to the reported pressure. However, for most land stations, some extrapolation is required, and assumptions must be made about the temperature structure in the layer between the level of the reported pressure and the model surface in order to calculate p_*. Actual surface temperatures are again considered atypical, especially for thick layers, and therefore no attempt is made to estimate the true vertical temperature structure at the station. The best that can be done is to use model values, and ensure that the method adopted is consistent with the conversion of model p_* values to msl pressure for output.

The calculation is done using the hydrostatic equation integrated assuming a constant lapse rate within the layer. This is derived as follows.

Integrating the hydrostatic equation over any layer bounded by pressures p_1 and p_2 with geopotential heights z_1 and z_2 gives:

$$\int_{p_1}^{p_2} \frac{1}{p}\,\mathrm{d}p = -\frac{g}{R}\int_{z_1}^{z_2} \frac{1}{T}\mathrm{d}z,$$

where $g = 9.80665$ and $R = 287.05$ J kg^{-1} K^{-1}.

Assuming $T(z) = T_0 - \gamma(z-z_0)$, where T_0 is a reference temperature at a known height z_0 and γ is the lapse rate (assumed constant), the hydrostatic equation can be integrated to give:

$$\log_e \frac{p_2}{p_1} = \frac{g}{\gamma R} \log_e \left\{ \frac{T_0-\gamma(z_2-z_0)}{T_0-\gamma(z_1-z_0)} \right\}$$

This can be rewritten as:

$$\frac{p_2}{p_1} = \left\{\frac{T_0-\gamma(z_2-z_0)}{T_0-\gamma(z_1-z_0)}\right\}^{\frac{g}{\gamma R}} = \left\{\frac{T(z_2)}{T(z_1)}\right\}^{\frac{g}{\gamma R}}$$

This equation is used to obtain a reference temperature T_s at the model surface z_* from the temperature at the 5th sigma level of the model, using $\gamma = 6.5$ K km^{-1} which is the value for the ICAO (International Civil Aviation Organization) standard atmosphere up to 11 km. The model temperature at level 5 is used as this is the lowest level outside the model boundary layer.

$$T_s = T_5 \left(\frac{1}{\sigma_5}\right)^{\frac{\gamma R}{g}}$$

Then p_* is obtained from the reported pressure and geopotential:

$$p_* = p_r \left(\frac{T_s}{T_s - \gamma(z_r - z_*)}\right)^{\frac{g}{\gamma R}}$$

This equation is applied whether a pressure, p_r, or the geopotential of a standard pressure level, z_r, is reported. This is illustrated in Fig. 1 which shows schematically three stations, S_1, S_2 and S_3, reporting mean sea level pressure, station level pressure, and the 850 mb geopotential, respectively. The pressure (p_*) at the model surface (z_*) must be calculated in each case from the available pressure (p_r) and geopotential (z_r).

Over many land areas the density of reporting surface stations is too high to be handled by the model. Therefore, during the data extraction program, reference is made to a station list which identifies those stations which are to be passed on to the analysis; stations not appearing in the list are rejected. A similar problem exists with drifting buoys, which report every hour; the difficulty here is one of temporal rather than spatial density. The report closest to the analysis time is selected for each buoy, and the others are rejected.

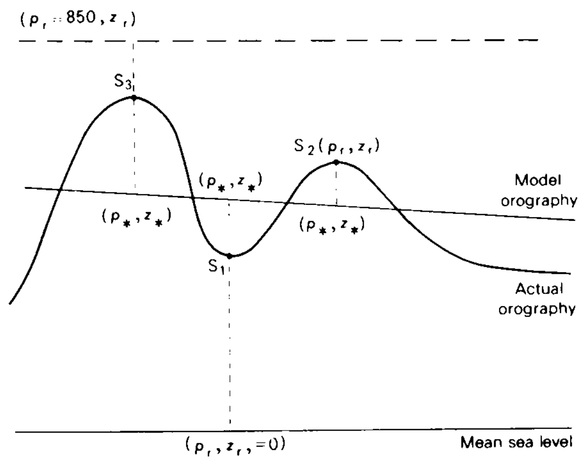

Figure 1. Schematic representation of the derivation of p_* from surface stations with different reporting practices.

3.2 *Upper-air data (radiosondes)*

Radiosonde TEMP messages contain values of geopotential, temperature, dew-point and wind for the standard pressure levels, together with temperatures, dew-points and/or winds at significant levels of the ascent, including the surface. The PILOT messages contain wind data only, at standard and significant pressure levels or at a set of given heights.

The messages generally contain too many levels of data to be handled by the analysis program, and more vertical detail than can be resolved by the model. It is therefore necessary to condense the ascent to a representative set of data at a smaller number of levels. The most convenient levels to choose are model sigma levels, as this reduces the amount of interpolation during the analysis. The simplest method of deriving sigma-level data is to interpolate linearly in $\log_e p$ between neighbouring reported levels. According to the WMO definition of significant levels (World Meteorological Organization 1974), this will give a temperature within 1 °C of the observed value at that level. This was the method originally used. For an ascent with reported levels i, data at sigma levels j, such as illustrated in Fig. 2, can be calculated using the following equation:

$$X_j = X_{i+1} + \left\{ \frac{X_{i+2} - X_{i+1}}{\log_e (p_{i+2}/p_{i+1})} \right\} \log_e (p_j/p_{i+1}),$$

where X is any variable which is being interpolated and $p_{i+2}<p_j<p_{i+1}$. There are 15 sigma levels, distributed so that they are more dense in places where greater resolution is required (i.e. in the boundary layer and near the tropopause). Therefore, the simple method described above of picking 'spot' values from the ascents would generally give a reasonable representation. However, there is a possibility that for some ascents the sigma levels might lie at extreme points, and unrepresentative values be passed to the analysis. Indeed, it was found that using this method, 100 mb height analyses were several decametres too low for ascents where the tropopause was close to a sigma level. For this reason a different method was introduced. This essentially divides the ascent into layers centred on sigma levels and uses all reported values within the layer to produce a mean temperature at the sigma level. This method gives a more accurate representation of heights in the model.

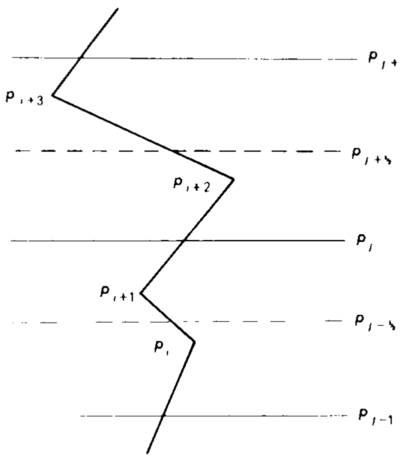

Figure 2. Arrangement of σ-levels, and half-levels $j+\frac{1}{2}$, relative to reported levels i from an ascent.

The half-sigma levels are arranged so that the sigma levels are at the centre of each layer, i.e.:

$$p_j = \sqrt{(p_{j-\frac{1}{2}} \cdot p_{j+\frac{1}{2}})}$$

Referring again to Fig. 2, temperatures at half-sigma levels are derived using simple interpolation:

$$T_{j-\frac{1}{2}} = T_i + \{ (T_{i+1}-T_i)/\log_e(p_{i+1}/p_i) \} \log_e(p_{j-\frac{1}{2}}/p_i).$$

Then a weighted mean for the layer is formed:

$$T_j = \{ (T_{j-\frac{1}{2}}+T_{i+1}) \log_e(p_{i+1}/p_{j-\frac{1}{2}}) + (T_{i+1}+T_{i+2}) \log_e(p_{i+2}/p_{i+1}) +$$

$$+ (T_{i+2}+T_{j+\frac{1}{2}}) \log_e(p_{j+\frac{1}{2}}/p_{i+2}) \} / 2\log_e(p_{j+\frac{1}{2}}/p_{j-\frac{1}{2}}).$$

This 'layer mean' method is also used to derive sigma-level values of dew-point temperature and wind components.

For PILOT messages with winds at given heights, equivalent pressure levels must be derived. This is done assuming an ICAO standard atmosphere, using the same equations as for converting AIREP flight levels to pressures (see 3.4). This method is sufficiently accurate, considering the errors involved in determining the heights at the station.

Although reported values of standard-level geopotential are not used directly in the model, they are used to collect statistics on the differences between observed and analysed 100 mb geopotentials. These are used to identify systematic differences between sondes and to derive appropriate corrections, which are given in terms of 100 mb geopotential. These corrections must be incorporated into sigma-level data as an equivalent temperature correction. The temperature correction (ΔT_p) is assumed to vary linearly in $\log_e p$ from zero at the surface up to a constant value (ΔT_T) at the tropopause, i.e.

$$\Delta T_p = \Delta T_T \frac{\log_e \frac{p}{p_s}}{\log_e \frac{p_T}{p_s}} \qquad p > p_T$$

$$\Delta T_p = \Delta T_T \qquad p < p_T$$

where p_s, p_T are the surface and tropopause pressures respectively. Using the integrated hydrostatic equation the 100 mb geopotential correction Δz_{100} can be expressed in terms of the temperature correction at the tropopause as follows:

$$\Delta z_{100} = \frac{R}{g} \frac{\Delta T_T}{2} \log_e \frac{p_s}{p_T} + \frac{R}{g} \Delta T_T \log_e \frac{p_T}{100}$$

This can be inverted to give:

$$\Delta T_T = \frac{g}{R} \frac{\Delta z_{100}}{\log_e \left\{ \frac{\sqrt{(p_s p_T)}}{100} \right\}}$$

Substituting this into the above equations for ΔT_p gives an expression for the temperature correction at any level p, in terms of the 100 mb geopotential correction, the surface pressure and the tropopause pressure. ICAO standard values are used for the surface and tropopause pressures to simplify the calculation. Corrections to the dew-point temperatures are applied in the same way.

Before being passed to the analysis, all sigma-level temperatures are converted to potential temperatures, using $\theta = T(1000/p)^k$, where $k = 0.2857143$. Dew-point temperature is converted to humidity mixing ratio, which is equal to:

$$q = \frac{0.62197e}{p - e}$$

where e is the vapour pressure. From the definition of dew-point temperature t_d (the temperature at which air becomes saturated).

$$e = e_s(t_d)$$

where e_s is the saturated vapour pressure. Now values of e_s are determined by the Goff-Gratch equations (see World Meteorological Organization 1966), which have been calculated and listed in the

Smithsonian Tables. An approximation to the Goff–Gratch equations (Murray 1967) is currently used (with t_d in degrees Celsius):

$$e_s(t_d) = \exp\left(1.80951 + \frac{17.27\, t_d}{237.3 + t_d}\right)$$

Thus humidity mixing ratio can be obtained from values of dew-point, temperature and pressure.

3.3 *Satellite data*

Temperature soundings (from the polar orbiting satellites)

The SATEM messages received via the GTS contain thickness values between a given reference level and the standard levels and, for soundings taken in clear conditions, values of precipitable water content (PWC) for standard layers up to 300 mb. The PWC data are not suitable for use as humidity data directly in the model, but are used at source in the conversion of temperatures to thicknesses. Therefore they should be used again when performing the reverse calculation to convert the thickness back to temperatures for the analysis.

The variables initially obtained from the satellite radiances are temperature and humidity mixing ratio. The conversion to thickness and PWC is done using the following equations (from information provided by NOAA in a personal communication):

$$T_{vi} = T_i + \frac{m_i}{6},$$

where T_{vi} is the virtual temperature (K) at level i, T_i is the temperature (K) at level i, and m_i is the humidity mixing ratio (gm/kg) at level i.

Then,

$$z_{i+1} - z_i = -\frac{R}{2g}\,(T_{vi} + T_{vi+1})\,\log_e \frac{p_{i+1}}{p_i},$$

where z_i is height (m) at level i and p_i is pressure (mb) at level i.

Thicknesses are summed to give values over layers between the reference level and standard levels up to 10 mb.

Also,

$$\omega_i^{i+1} = \frac{1}{10}\,\frac{1}{2g}\,(m_i + m_{i+1})(p_i - p_{i+1}),$$

where ω_i^{i+1} is PWC (mm) of layer $(i, i+1)$, and $p_i > p_{i+1}$.

Values of ω are then summed to obtain data for layers between the reference level and 700 mb, 500 mb and 300 mb.

To recover the original temperature profile as accurately as possible, these equations must be inverted. First, virtual temperatures at mid-points of standard levels are obtained from the thicknesses:

$$T_v(p') = \frac{g}{R}\left(\frac{z_2 - z_1}{\log_e \dfrac{p_1}{p_2}}\right)$$

where $p_1 > p_2$, $p' = \sqrt{(p_1 p_2)}$

To correct these to true temperatures, humidity mixing ratios must be recovered from the PWC data. The latter must first be split into values for each standard layer, assuming that ω varies linearly with $\log_e p$. For example:

$$\omega^{850}_{1000} = \left(\frac{\log_e \frac{850}{1000}}{\log_e \frac{700}{1000}} \right) \omega^{700}_{1000}$$

Then values of humidity mixing ratio can be found, e.g.

$$m(922) = 10g \left(\frac{\omega^{850}_{1000}}{1000-850} \right)$$

True temperatures are then obtained using:

$$T(p') = T_v(p') - \frac{1}{6} m(p')$$

If PWC data are missing, a relative humidity is assumed in order to calculate a temperature correction. Since this occurs when conditions are cloudy, a high relative humidity is appropriate, and a value of 80% is used. Humidity mixing ratio is related to relative humidity (U) in the following way:

$$U = \frac{m(T)}{m_s(T)} \times 100,$$

where $m_s(T)$ is the saturated humidity mixing ratio at temperature T.

Using the virtual temperature t_v obtained from the thickness data, and the pressures at mid-points of standard levels, values of m_s can be found using the approximate equation:

$$m_s(t_v) = \frac{621.97 e_s(t_v)}{p}$$

where $e_s(t_v)$ is the saturated vapour pressure, and is given by the following approximation to the full Goff-Gratch equations, with t_v in degrees Celsius:

$$e_s(t_v) = \exp\left(1.80951 + \frac{17.27 t_v}{237.3 + t_v}\right)$$

Using these equations, humidity mixing ratio can be found and the temperature correction made as before.

This method gives acceptable results, although it is only approximate. The procedure used at source to convert actual temperatures to virtual temperatures when humidity data are absent is very complex and could not be inverted operationally.

The Satellite Meteorology Branch processes satellite soundings locally to provide data at higher resolution and more quickly than normal. This processing system is known as HERMES (High Resolution Evaluation of Radiances from Meteorological Satellites). Temperatures and dew-points at standard levels are available, as well as thickness and PWC data. The standard-level temperatures will be used directly when the HERMES data are introduced operationally. The density of data should be acceptable for the fine-mesh model, but would be too high for the coarse-mesh analysis. For this reason, a method of averaging the data has been derived. This involves using the line and element numbers in the original soundings (which locate the data relative to each other) to set up a grid of values (see Fig. 3). The mean of all available data within a given area is then calculated, the size of an area depending on the resolution required. The mean value is simply the sum of all values divided by the number of data points used, and is located at the point obtained by averaging the latitudes and longitudes of the data points used.

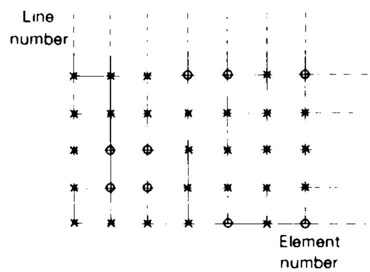

Figure 3. Configuration of HERMES data before averaging.
× data present o data absent

At present the temperatures from all SATEM data are interpolated to sigma levels before being converted to potential temperatures and passed to the analysis. This was originally introduced to give the SATEM data more weight in the model. In addition, SATEMs with reference levels above 1000 mb are rejected, as they were found initially to cause analysis problems over high topography (especially over Greenland). Owing to several changes in the analysis program, it might now be possible to remove the interpolation to sigma levels, and reintroduce SATEMs with reference levels above 1000 mb.

Cloud-track winds (from the geostationary satellites)

SATOB reports contain winds at pressure levels with associated temperatures (the pressure levels being derived at source from the measured temperatures). The winds are simply passed to the analysis at the assigned pressure levels; temperatures are not used, as they are not independent of the pressures.

3.4 *Aircraft data (AIREPs and ASDARS)*

Aircraft reports contain values of wind and temperature together with the flight level, position and time of report. AIREP observations are made by the aircraft every 5° or 10° of longitude along its flight path, and also at certain specified aircraft reporting positions. ASDAR observations are obtained automatically by satellite interrogation of the aircraft at approximately seven-minute intervals while it is in range. Although they provide the same type of data, ASDAR reports occur in strings of close observations whilst AIREPS are more widely spaced. The position, flight level, time and aircraft identifier are checked on all reports; if they are all identical for any two messages, the observed temperatures and winds are examined, and any duplicate or conflicting data are rejected.

The winds and temperatures (after conversion to potential temperatures) can be used directly in the model at the pressure level equivalent to the reported flight level. The conversion of flight level to pressure is carried out using equations based on the ICAO standard atmosphere, as follows (see World Meteorological Organization 1966):

For flight levels h up to 11000 m, a constant lapse rate $\gamma = 6.5$ K km $^{-1}$, surface pressure $p_0 = 1013.2$ mb and surface temperature $T_0 = 288$ K are assumed. Then

$$p = p_0 \left(1 - \frac{\gamma h}{T_0}\right)^{\frac{\gamma R}{g}}$$

For flight levels between 11 000 m and 20 000 m an isothermal atmosphere with temperature $T_1 = 216.5$ K, and pressure $p_1 = 226$ mb at height $h_1 = 11\ 000$ m is assumed. Then

$$p = \exp\left(\log_e(p_1) - \frac{g(h-h_1)}{RT_1}\right)$$

For flight levels above 20 000 m, a lapse rate $\beta = -1$ K km and pressure $p_2 = 55$ mb at height $h_2 = 20\ 000$ m is assumed. Then:

$$p = p_2 \left\{1 - \frac{\beta}{T_1} (h - h_2)\right\}^{\frac{\beta R}{g}}$$

3.5 *Artificial data*

Bogus data

Forecasters in CFO routinely analyse charts of mean sea level pressure, and geopotential at 500 mb, 250 mb and 100 mb over the globe. These are considered to be the best representation available of the atmosphere at the main synoptic hours, and if the corresponding model fields are in major disagreement the forecasters may reject or correct existing data, or insert artificial (bogus) data to correct the model. For example, a feature may be evident from data not available to the model, such as satellite pictures. Mean sea level pressure and standard-level geopotentials are therefore the most natural quantities for the forecasters to insert, although these must then be converted to p_* and potential temperatures for use in the model. The complete set of quantities which may currently be inserted for any latitude and longitude is:

mean sea level pressure and surface wind,
humidity at the surface, 850 mb and 500 mb, and
geopotential and wind at 850 mb, 500 mb†, 250 mb, 100 mb and 50 mb.

Wind and humidity values are simply converted to the appropriate model variables and passed to the analysis at the pressure level specified. Mean sea level pressure values are converted to p_* using the same method as for other surface data (see 3.1); if the geopotential of another level is also entered at the same location, a new 1000 mb geopotential is calculated using the equation:

$$z_{1000} = \frac{R}{g} T_s \log_e \frac{(p_{msl})}{1000},$$

where T_s is the same derived model surface temperature as is used to calculate p_*.

Model values of standard-level geopotential are then used to calculate the increments implied by the bogus data at the intervention levels, as follows:

$$\Delta z = z(\text{bogus}) - z(\text{model}).$$

After calculating the increments for each intervention level, the thickness change implied over each 'intervention layer' is then used to adjust all the temperatures within the layer. The temperature profile is derived at mid-points of standard levels from the model standard-level geopotentials, using the integrated hydrostatic equation. The temperatures thus obtained (from thickness values) are, of course, virtual temperatures and the mid-point pressures are defined by $p' = \sqrt{(p_1 p_2)}$.

These virtual temperatures are then converted to actual temperatures using the model standard-level relative humidities. The method is similar to that used for satellite data without PWC values (see 3.3). Relative humidities are first interpolated linearly in $\log_e p$ to mid-points of standard levels:

$$U(p') = U(p_1) + \left\{ \frac{U(p_2) - U(p_1)}{\log_e(p_2/p_1)} \right\} \log_e(p'/p_1).$$

Then humidity mixing ratios (q) at mid-points of standard levels are obtained by using the virtual temperatures in:

$$q = q_s(T_v) \times \frac{U}{100},$$

where $q_s(T_v) = 0.62197 e_s(T_v)/p$ and $e_s(T_v)$ is the saturated vapour pressure. The virtual temperatures are then converted to actual temperatures using:

$$T = \frac{T_v}{1+0.61q},$$

where T and T_v are in kelvins and q is in g/g.

A full vertical profile of temperatures is thus passed to the analysis for every location at which a bogus geopotential is inserted.

Over the Southern Hemisphere satellite (thickness) data predominate over other types, so charts of 1000–500 mb thickness are analysed instead of 500 mb geopotential. Therefore, bogus data entered at 500 mb are assumed to be thickness and thermal winds. These values are then converted to 500 mb geopotential and wind using either model values of 1000 mb geopotential and wind, or 1000 mb geopotential calculated from the bogus msl pressure, and bogus surface wind, if available.

PAOB data

PAOBS are artificial data generated by Australian forecasters to force their numerical model to fit their manual analyses. Data are specified on a coarse 10° latitude/longitude grid for the whole of the Southern Hemisphere, and also on a finer scale to define important features over the Australian area. They serve a similar purpose to the bogus data inserted into our own analyses, but are generated routinely on a much wider scale as regular input to their numerical model. This is because conventional

†or thickness and thermal wind in the Southern Hemisphere (see end of this section).

data are sparse in the Southern Hemisphere, and heavy reliance is placed on satellite pictures to determine the state of the atmosphere.

The PAOB data received via the GTS are values of msl pressure and 1000–500 mb thickness. They are processed in a similar way to bogus data, but a temperature profile is generated only up to 500 mb, as no data are available for levels above that. PAOBS are received at Bracknell rather late (at approximately $T+10$ hours), and are given a very low weight in the analysis. Those in the area 140° W to 20° E, 30° S to 70° S are permanently rejected as the conventional data available are considered to be superior.

4. Concluding remarks

Data preparation is an essential part of any operational forecasting system, and the formulation of some of the methods used with the Meteorological Office 15-level model have been described here. It is a subject which receives little attention in the scientific literature, not because it lacks importance, but because the problems involved and solutions to them tend to be specific to the model in which the data are to be used, and not generally of relevance to others. However, the objective is always the same, and that is to convert the data into a form which satisfies all the model requirements and also represents the original observations as accurately as possible. In an operational environment, where forecast products are required as soon as possible, there is also a constraint that the pre-processing should be done as quickly as possible. Computational efficiency is an important consideration, and a satisfactory balance must always be found between the cost incurred and the accuracy attained when choosing methods of pre-processing data. Fig. 4 is a flow chart showing all the steps involved in preparing the data for the model.

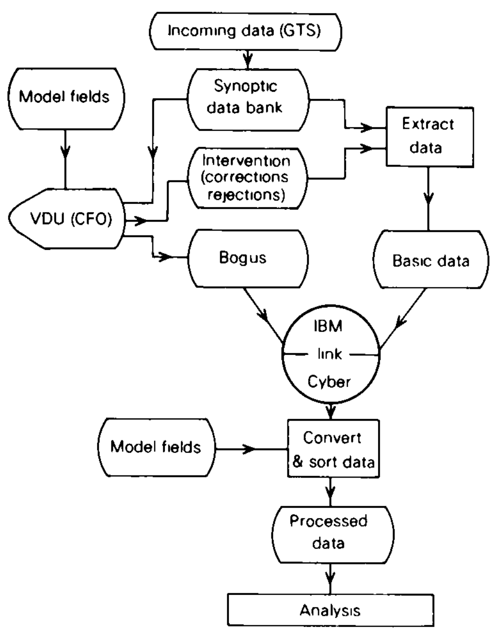

Figure 4. Flow chart showing the different stages of data preparation.

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Forecasting visibility over southern England in polluted easterly airstreams

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Summary

An analysis of visibilities in easterly airstreams over southern England is presented. The effect of relative humidity is illustrated and graphs enabling visibility to be forecast from surface wind speed and relative humidity are produced for a typically polluted airstream.

1. Introduction

Clean, unsaturated air is virtually transparent. Rayleigh scattering by the molecules themselves is negligible and would still allow a theoretical visibility of several hundred kilometres. However, the air is never clean. Natural airborne particles occur, caused for example by volcanoes, dust-storms, forest fires and the release of salt particles into the atmosphere by the oceans. Over industrialized regions man-made pollution particles are more common than natural particles, and the visibility estimated by any one observation is a snapshot value of a parameter that has a large spatial and temporal spread. There are also problems in the estimation itself. Meteorological visibility is defined as the greatest horizontal distance that a dark object can be seen and recognized with daytime illumination. A suitable reference object should subtend an angle of 0.5 to 5.0 degrees at the observer, but over much of southern England few suitable objects can be seen at distances greater than 10 km. This is particularly true when one remembers that the visibility in the worst direction is reported, and an isolated mast perhaps 15 km away may be the only reference. Thus, even allowing for the high standards of observing in the United Kingdom, daytime estimates will vary somewhat. Night-time visibility should be comparable with daytime but is usually estimated by brightness of lights or their extinction. The further subjects of visual ranges into sun, and slant visibilities are not considered here. The best that meteorologists can offer to users is a forecast of meteorological visibility. It is up to film studios, photographers, pilots and various military users to interpret this forecast in terms of their own requirement. For many purposes including filming or photography the effective limit will be one half of the meteorological visibility. The aim of this study was to assist in the production of a forecast of afternoon visibility (say 1400 GMT) at 0600 and evening visibility (say 2200 GMT) at 1400.

2. Selection of gradient directions

It has been clearly shown by Bonvoisin and McHugh (1983) that easterly surface winds bring the highest frequency of visibilities in the 1-10 km range over southern England. At Gatwick, for example, the greatest frequency of visibilities below 8 km is with surface winds between 060° and 090°.

This is true even in summer when easterlies with their short sea track bring low relative humidity (RH). Thus the major pollutant sources must logically be in the continent. The traditional view of the Ruhr area of West Germany as the industrial heartland of Europe is no longer altogether valid. Aircraft pilots report that Rotterdam is a major source of smoke along with towns in Belgium and north-eastern France. Much of the pollution obviously comes from still further east. Wildenrath and Gütersloh statistics also show a bias towards poor visibilities with easterly airstreams. East Germany, Poland and Czechoslovakia are also sources as shown, for example, by Eliassen and Saltbones (1983). A straight easterly gradient will bring air across successive industrial areas towards southern England. Trajectories are notoriously difficult to establish but the study presented here was done on the basis that at least 24 hours of easterly flow were necessary to bring polluted air to the 'target' stations in southern England. The position of the five stations used in the study is shown in Fig. 1. Four are in rural locations and, since

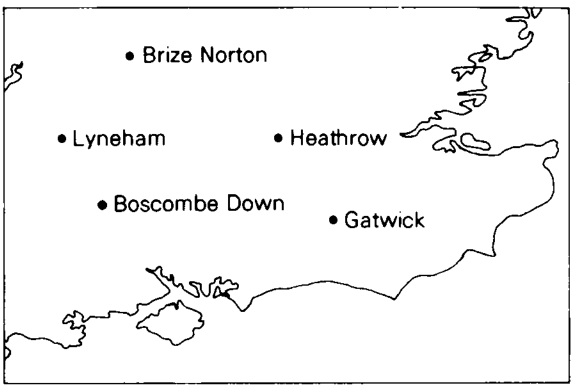

Figure 1. The stations used in the investigation.

the Clean Air Act of 1956 and the subsequent improvement of visibilities over London, Heathrow may be considered as suburban.

The decision to use gradient winds for the selection of dates rather than surface winds was based on a consideration of the likely vertical motion of particles over a 24-hour period. Only with light winds and no convection would surface winds be more relevant. With topography of 500 ft plus and the normal turbulence associated with surface winds greater than 6 knots, gradient direction will be a fair guide to the direction of travel.

The 1200 GMT charts for the years 1979–82 were classified for gradient direction (to the nearest 10 degrees) over central southern England. Out of a total of 1461 days, 137 were classified as 'variable'. These were occasions when no direction could be identified from the chart, and were situations either with very light winds or when a depression was centred over the area.

Gradients of 080° to 130° were considered most likely to be polluted and it was decided that two consecutive days within this 'easterly' arc would normally draw the air from a continental source. An intervening day of 'variable' winds did not necessitate a fresh start. Once the 'easterly' was established then any succeeding days of 'easterly' or 'variable' gradients also qualified. Thus in the example below those days marked with an asterisk would qualify:

150° 130° *110° 180° 100° Variable *120° *Variable *080° 060°

This selection procedure gave 54 days in the 4-year period, although it was later noted that many near-misses with gradients 140°–170° also had poor visibility. The selection was thus somewhat crude and took no account of the upwind shape of the isobars. A practising forecaster could easily better the selection at 0600 GMT on the day of forecast by considering the likely trajectory from a sequence of synoptic charts. The arc included in the study had boundaries of 075° and 135°, corresponding approximately to surface winds 060° to 120°. However the inclusion of 'variable' days and possible changes in gradient after 1200 GMT on the selected dates means that surface winds during the afternoon and evening could vary quite considerably. On both 'variable' and easterly days some United Kingdom pollution would be added to that already present. The map (Fig. 2) shows the relationship of the main source area to the target area. The southern boundary is marked by the Alps and the northern boundary attempts to exclude clean air which has crossed the Baltic and Scandinavia. Although gradient wind directions were used in the selection of dates, the subsequent analysis dealt with surface wind speeds as these were readily available from the synoptic data.

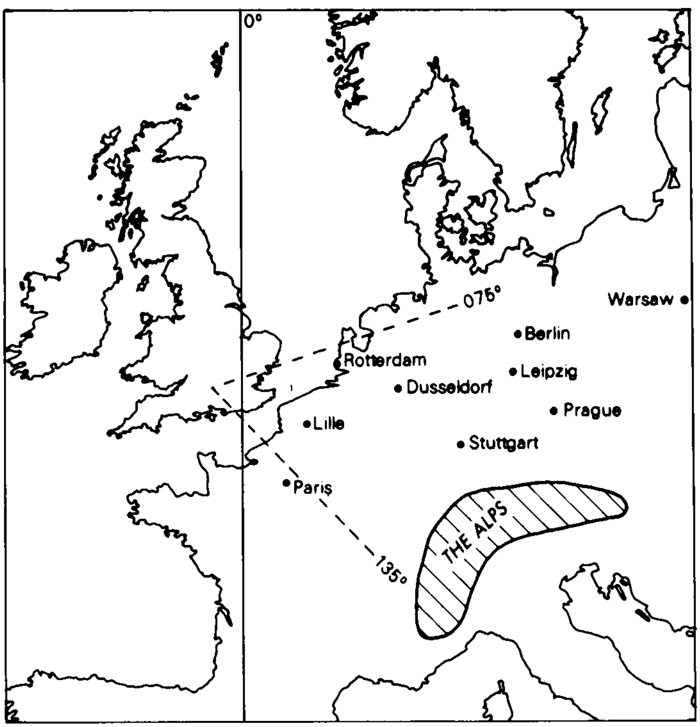

Figure 2. The position of the British Isles in relation to some of the possible sources of continental pollution.

3. Afternoon visibilities on days of persisting easterlies

The visibilities for Brize Norton (03649), Lyneham (03740), Boscombe Down (03746), Heathrow (03772) and Gatwick (03776) were analysed at 1200, 1400 and 1600 GMT on each day of persisting 'easterlies'. They were recorded against relative humidity for three classes of surface wind speed, namely

1-6, 7-11 and over 12 knots. Stronger winds are associated with better visibility, partly because of the greater depth through which the pollution particles are mixed, but also because the air has spent less time over the pollution-producing zone in situations with widespread and persistent strong gradients. Occasions with precipitation falling at the time of observation, precipitation within sight or with blowing snow were discarded (present weather 14, 15, 16, 38, 39, 50–99) as were the very small number of calms. The resulting information for the 7-11 knot wind class is given below (Table I). Note that the items of data are not independent, with 3 values from each of 5 stations giving a possible 15 visibility estimations on any one day.

Table I. *Afternoon visibility (1200, 1400, 1600 GMT) against relative humidity for the 7-11 knot wind class in easterly airstreams*

Relative humidity (%)	Visibility (km) 0–0.7	0.8–1.7	1.8–3.6	3.7–4.9	5–7	8–15	16–30	35–60
	Number of occasions							
88–100	4	5	3	7	12	6	5	0
73–87	0	0	7	18	52	63	29	0
58–72	0	0	6	8	26	88	71	8
43–57	0	0	9	3	10	41	81	6
28–42	0	0	0	3	4	24	47	13
13–27	0	0	0	0	0	0	8	2

4. Graph of afternoon visibility against relative humidity

It was decided to draw graphs for each wind class using the median values of visibility for each relative humidity class. Certain assumptions had now to be made. When condensation occurs at 100% RH, it is common experience that a visibility of approximately 0.1 km usually results and the curves were drawn through this point for light and moderate winds, but it was felt unrealistic to extend the strong wind curve above 87%. The drier end of the range provided another problem. The data show that visibility continues to improve with decreasing relative humidity, and in the case of strong winds down to about 40%. This contradicts the widely held view amongst forecasters that hygroscopic nuclei only have a significant effect above 80% or 90%. Evidence from individual days suggested that visibility does vary with RH in the 30–80% range. One late spring example is given in Table II.

Table II. *Variations in visibility on 14 May 1982 at Boscombe Down*

Times GMT	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Surface wind speed (kn)	10	8	8	7	8	8	10	15	16	7	8	9	14	10	11	10	12	9
Relative humidity (%)	76	76	70	65	57	53	39	35	34	53	50	49	58	71	75	83	92	96
Visibility (km)	7	7	7	7	8	8	12	15	12	10	11	11	6	7	5	4	3	2

Theoretical work by Hänel (1971) has shown that nuclei are swollen when humidities exceed 30% and for this reason it was decided to draw the curves to an asymptote of this value, as shown in Fig. 3.

5. Graph of evening visibility against relative humidity

The visibility at 2100, 2200 and 2300 GMT was recorded for the same selected days and three further curves were produced (Fig. 4). The evenings provided considerably more high humidity values but these curves must be considered as coming from a different data set from the afternoon visibilities because the

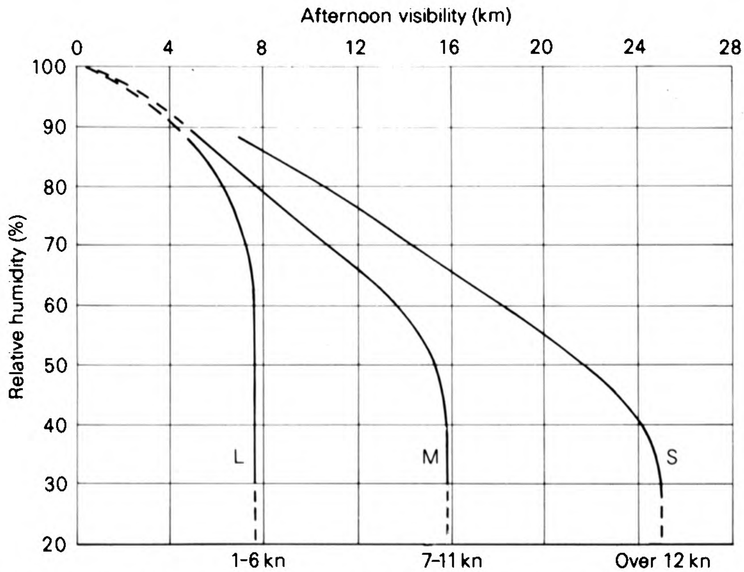

Figure 3. Afternoon visibility against relative humidity for three classes of wind speed in 'easterly' synoptic situations. Median values are represented by L, M and S for light, moderate and strong winds respectively. The curves should be regarded as provisional for relative humidities above 87% and below 30%.

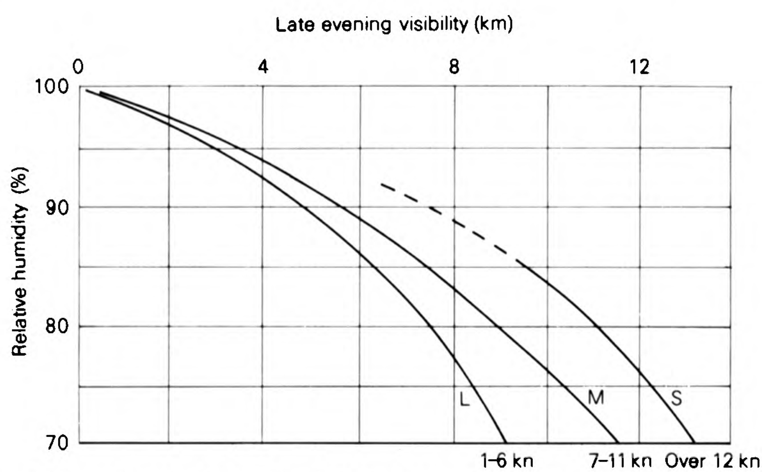

Figure 4. Late evening visibility against relative humidity for three classes of wind speed in 'easterly' synoptic situations. Median values are represented by L, M and S for light, moderate and strong winds respectively. The curve for strong winds should be regarded as provisional for relative humidities above 87% where data were sparse.

surface wind speed will often have halved between 1400 and 2200 GMT as the lower levels of the atmosphere stabilized. The 'over 12 knot' afternoon class should approximate to the evening '7–11 knot' class. The relationship between afternoon and evening visibility could of course be destroyed in a period of 1 to 3 hours if there is a local source of pollution just upwind. There were insufficient data for these curves to be extended below 70%. Both the afternoon and the evening graphs support the view that stagnant conditions and poor visibility go hand-in-hand.

6. Seasonal variations

Although Bonvoisin and McHugh's statistical analysis had shown that winter was markedly the worst season for visibility, this was without reference to moisture content. For the combined 43–72% relative humidity classes in the present study, the values of afternoon visibility were as given in Table III.

Table III. *Seasonal comparison of median values of visibility for humidities in the range 43–72% (wind class 7–11 knots) for easterly airstreams.*

Winter (Dec.–Feb.)	Spring (Mar.–May)	Summer (June–Aug.)	Autumn (Sept.–Nov.)
	kilometres		
12.6	12.2	14.2	15.2

Thus spring emerges as the worst season from this limited selection of dates. The apparent contradiction with Bonvoisin and McHugh is caused by the lower frequency of dry air in winter. So whilst real visibilities are worse in the damp days of winter, the levels of pollution may well be just as great in spring with its high frequency of prolonged blocked situations. Certainly power station and home heating output will be high in winter and early spring, and a marked inversion will often be present in both winter and spring easterlies to form a 'lid' through which pollutants are unable to escape. When little cloud is present (as is often the case in spring with a short sea track) aircraft pilots frequently report a haze top between 2000 feet and 8000 feet.

7. Effects of convection

The popular belief amongst forecasters is that a sudden improvement of visibility occurs when convection develops. This is of course true for most southerly, westerly and northerly airstreams, for with these gradient directions the air aloft is clean and only pollution produced locally in the British Isles is trapped below the early-morning inversion. With the onset of convection the nuclei are spread upwards, and with unstable westerlies and northerlies through such a depth that even with the limited visibility points of southern England an estimated value of 30 or 40 km will be reported. With easterly airstreams the evolution is somewhat different. Local pollution is often trapped below one inversion at say 1000 ft, with continental particles below another inversion at perhaps 5000 ft. In this case the destruction of the low-level inversion by surface-based convection will produce a marked improvement for perhaps 15–30 minutes but soon there will be a partial reversal of the trend as mixing is completed throughout the lowest 5000 ft. Dilution of the pollutant is therefore less effective in easterlies, and such improvement as does take place is partially accounted for by the fall in relative humidity. The surface wind will also usually have increased. A schematic diagram illustrates the point (Fig. 5).

A study of inversion heights in Crawley (03774) radiosonde reports for 1200 GMT reinforced the view that correcting for convection depth is of remarkably little help in forecasting visibilities in easterlies. However, strong surface winds suggest a higher inversion so the depth of mixing is already taken into account by the wind speed categories in Figs. 3 and 4.

8. Sinks for pollution

Much has been written about sources, but what of sinks? The increase in haziness over recent decades has been noted by astronomers at mountain observatories but obviously it is not a one-way traffic. Some dry deposition must occur but the fall speeds of particles of radius 0.2 to 1.0×1.0^{6} m are small in relation to the normal vertical motions in the atmosphere generated by turbulence or convection. Scorer (1978) has pointed out that deposition can occur where horizontal airflow impinges upon hedges or woodland and this might have a significant effect on visibility in rural locations. Nevertheless, during prolonged easterly or anticyclonic spells a progressive deterioration in visibility usually occurs. Practising forecasters appreciate the considerable benefit of rain in improving the visibility, and occasions were noted during the present study when pollution appeared to be washed out of the atmosphere. Drizzle, on the other hand, may not be as effective as rain because the nuclei possibly avoid collision with small precipitation droplets. Smith (1983) has described lifetimes of particles as 'of the order of a few days' and 'determined by the frequency of interception by rain belts'. Fig. 6 shows the synoptic situation on a day of very poor visibilities over eastern England and Fig. 7 shows the situation as westerlies were re-established, with cleaner air of maritime origin already affecting the British Isles and extending eastwards across Germany. When considering visibilities in polluted airstreams in western Europe, replacement of the air by clean westerlies is the usual mechanism for improvement. As one travels eastwards across Europe wash-out becomes increasingly important because the westerlies themselves are less clean.

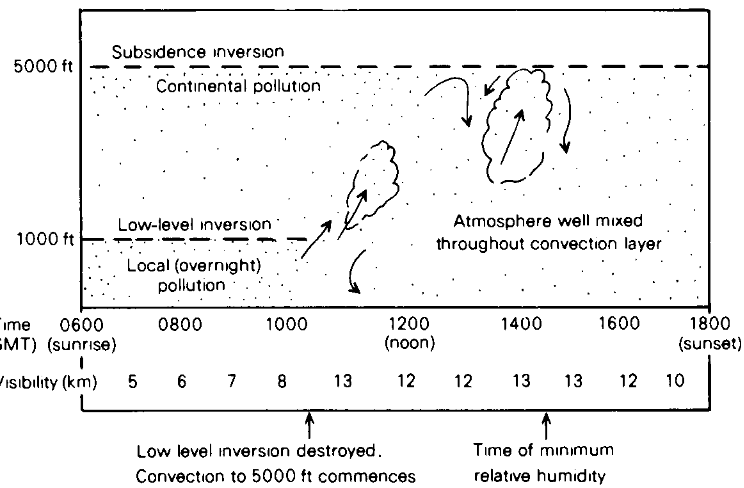

Figure 5. A time cross-section to illustrate typical visibility changes on a day when convection develops in an easterly airstream. In this schematic example two visibility maxima take place. One occurs shortly after the low-level inversion has been destroyed by surface heating and the second occurs around the time of minimum humidity.

9. Practical applications

It is not intended that Figs. 3 and 4 should be used in isolation. A forecast made at 0600 GMT of temperature, dew-point and surface wind speed for 1400 GMT would produce a nominal visibility forecast from the graph. It is far better, however, to look at upwind values of humidity and wind speed to see if they are above or below the median line and then multiply by this 'pollution factor'. For example, if the 1400 GMT visibility were 8 km against a median value of 10 km, then the 2200 GMT forecast should be multiplied by a factor of 0.8, assuming no change of air mass and no special source of local pollution. Yesterday's upwind 1400 GMT observation can be corrected for today's 1400 GMT forecast wind speed and RH.

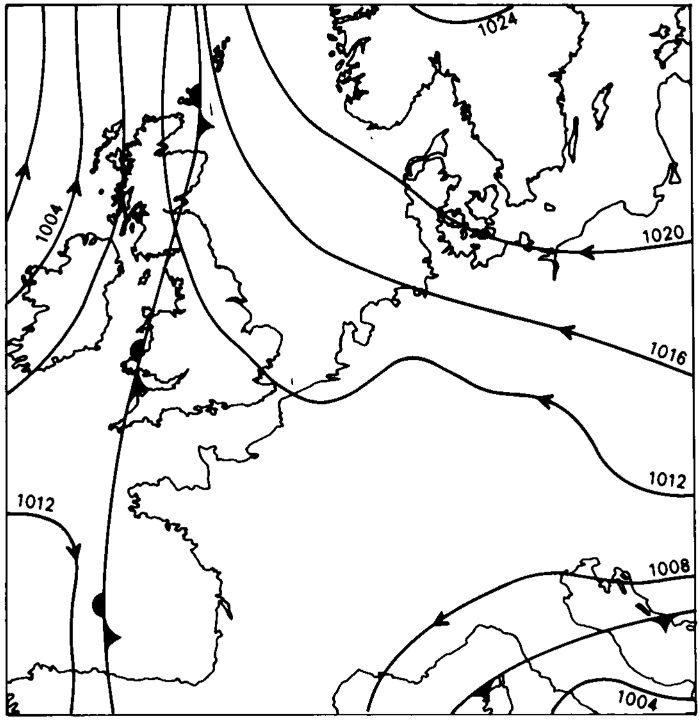

Figure 6. Surface analysis for 1200 GMT on 22 March 1984. Visibilities were poor over Germany, Belgium, Netherlands and the eastern half of England.

The bench forecaster will of course be dealing with temperature and dew-point to produce his forecast humidity and should bear in mind the slight fall of dew-point that usually occurs during the evening, as well as the decrease of surface wind.

On a chart of plotted observations the southern boundary of the polluted arc is far from sharp. There will still be some haze in a 170° gradient. The northern boundary is much more critical and often visible on the working chart. A straight 060° gradient will bring clean air from Scandinavia but a cyclonically curved flow from Germany can approach southern England from 060° loaded with pollutants and a high moisture content to give the worst conditions (see Fig. 8). Some idea of the source regions for this pollution can be gained from Fig. 9 which is taken from the EMEP report by Eliassen and Saltbones (1982). Although this map is of sulphur emissions it gives an indication of the relative degree of industrialization.

In the worst cases, which can occur after a week of light to moderate easterlies, visibilities may get down to half the values indicated by the median line. If winds then increase there will be a time-lag before values reach the 'over 12 knots' category. However, strengthening easterlies often bring only a temporary visibility improvement during a prolonged blocked situation and one still has to wait for an Atlantic front to restore truly clean air.

10. Results from a test of the method

Spot values of visibility at Brize Norton were examined for 'easterly days' in 1983. The dates were chosen by the same method as the original data. Values were recorded for 1400 and 2200 GMT and the

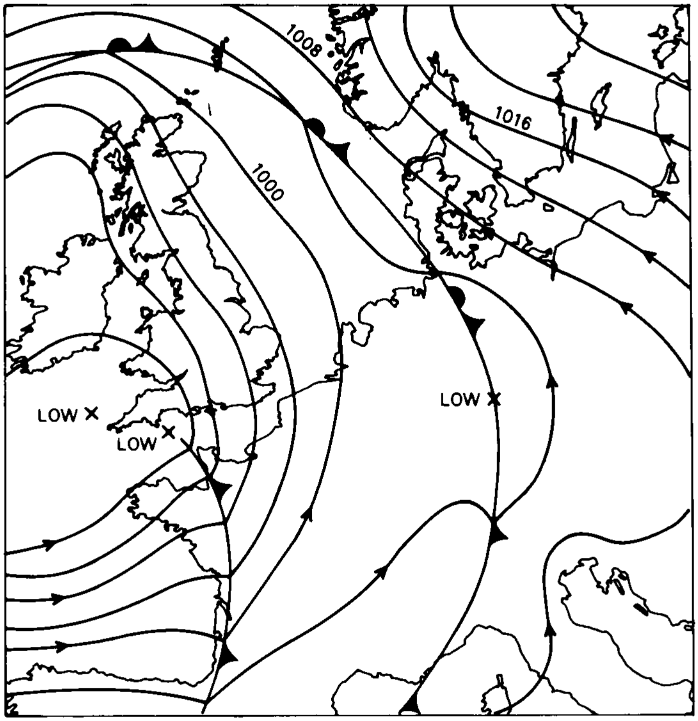

Figure 7. Surface analysis for 1200 GMT on 25 March 1984. The two eastward-moving fronts brought clean air into Europe from the Atlantic.

first 15 results are shown in Table IV. The 'uncorrected forecasts' are those obtained from the graphs, with the admittedly artificial use of the observed values of relative humidity and surface wind speed. 'Actual values' of visibility in the table are those recorded at Brize Norton. The 'corrected forecast' for

Table IV. *Test of method using the correction factor to give a modified forecast for 2200 GMT. Visibilities are in kilometres.*

1400 GMT		2200 GMT		
Uncorrected Forecast	Actual	Uncorrected Forecast	Corrected Forecast	Actual
14.2	20.0	8.9	12.5	18.0
10.7	10.0	10.2	9.5	8.0
12.1	10.0	8.4	6.9	8.0
11.8	15.0	6.2	7.9	8.0
10.5	8.0	7.7	5.9	10.0
7.2	4.0	4.4	2.4	2.0
7.0	4.5	4.0	6.6	4.5
15.3	25.0	14.0	22.9	25.0
20.0	35.0	11.4	20.0	20.0
15.3	10.0	7.5	4.9	4.0
12.5	4.5	7.7	2.8	3.5
15.3	10.0	7.0	4.6	8.0
19.4	25.0	9.0	11.6	8.0
6.7	25.0	4.9	18.3	14.0
13.0	20.0	2.8	4.3	7.0

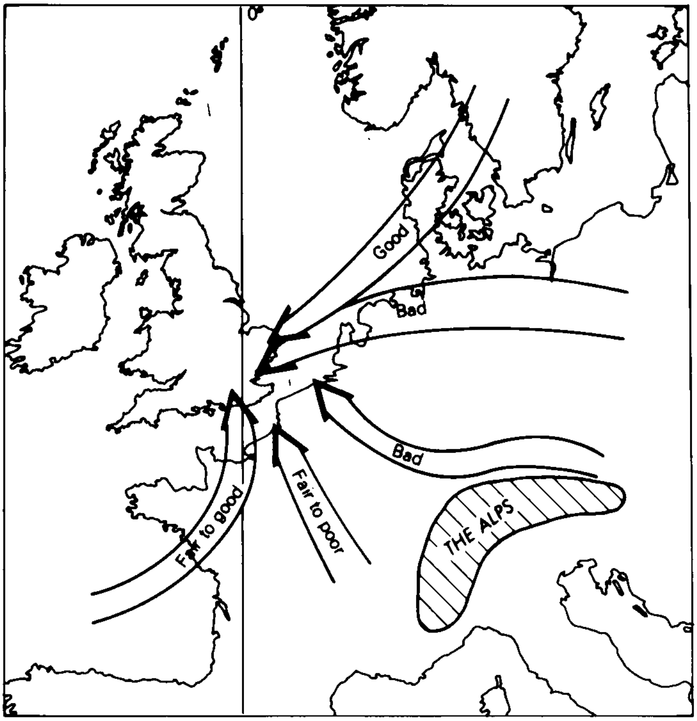

Figure 8. Visibility with various continental airstreams.

2200 GMT is obtained by multiplying the uncorrected graph reading by a 'pollution factor'. This factor corrects for the difference between the particular day of interest and the typical value represented by the median line on the graph. It is the ratio of 1400 GMT actual to the 1400 GMT uncorrected forecast. In practice the forecaster will normally use an upwind observation to obtain the appropriate 'pollution factor'.

A total of 25 days were tested in this way and on 19 occasions the correction based on the 1400 GMT actual was in the 'right' direction.

The artificial use of actual wind speed and humidity will be offset in reality by the ability of the outstation forecaster to look at upwind values of visibility rather than his own station's 1400 GMT values.

Conclusion

No forecasting method for visibility can ever produce accurate answers all the time. A stubble fire at the end of the runway or a fresh burst of activity at a nearby factory will see to that. Equally, though, the forecaster should have some help in establishing a preliminary estimate and the writer hopes that the graphs produced here for easterly airstreams will give him something to set his thought processes in train. The modification of upwind visibilities in terms of changes in relative humidity and surface wind speed plus a small subjective correction for convection depth constitutes a possible way forward.

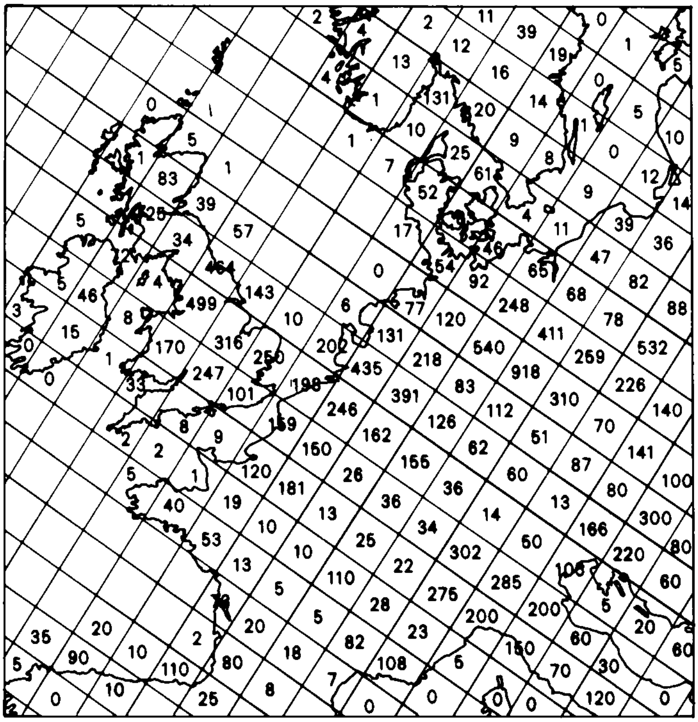

Figure 9. European Monitoring and Evaluation Programme (EMEP) emission data for 1978 in part of the 150 km× 150 km grid network. Units are thousands of tonnes sulphur equivalent per year.

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How the meteorological reconnaissance flights began

By E. B. Kraus

Summary

An account is given, based on personal reminiscence, of how meteorological reconnaissance flights started during the Second World War. Some experiences of the pilots and observers are described.

This is a very personal account of the beginning of the meteorological reconnaissance flights.

In 1939, I was a graduate student of Jack Bjerknes in Bergen, Norway. I also held a Czech private pilot's licence and both British and Czech soaring (C) licences. I had done some soaring on Dunstable Downs during the summer of 1938 and had met, during that visit to England, Professor Lindeman (later Lord Cherwell) and E. Gold (then Deputy Director of the Meteorological Office). I mention these names, because they played a role in the subsequent Meteorological Reconnaissance Flight story.

After the outbreak of the war I volunteered for service in France and finally got there in March 1940. When France collapsed in June 1940, I made my way to England via Algiers and Gibraltar. Things were a bit confused at that time. I arrived in England without any papers and in some trouble after a spat with a senior Czech officer during the passage from Gibraltar to Liverpool. As a result I found myself — with several thousand others — in Pentonville prison while the authorities pondered who we were and what to do with us.

When nothing happened for two weeks or so, I contacted Gold who sent Flt. Lt. Portass, the former Meteorological Liaison officer in France, to Pentonville to identify me. Things developed quickly after that. I was released and asked to join the Czech army in England as a private. At the same time I was offered via Portass a commission as a meteorological officer in the RAF Volunteer Reserve. My experience during the passage from Gibraltar had made me chary of the Czech military. Like other armies-in-exile they were desperately short of enlisted men (officers are much more mobile in defeat). Pilot Officer sounded grander than private 2nd class; it also seemed to offer a chance of flying again. The decision to join the RAF was clinched after a talk with Col. Kalla who was the military attaché at the Czech embassy. He told me not to be a fool and to use my opportunity. (Kalla was executed in Prague after the communist take-over.)

By that time, the Battle of Britain had started. Like all new officers in the RAF I was given 40 guineas to buy myself two uniforms and other paraphernalia. I then reported to Adastral House. The interviewing officer told me that I was posted to familiar grounds in Dunstable and — by the way — here was some secret material which had to be carried by an officer, so would I please take it along. Until then, even after my release from Pentonville, I had to report to the local police once a week as a suspect foreigner. The confidence of this unknown briefing officer had suddenly made me a member of the club. Nothing could have kindled more loyalty to the RAF than this simple and probably unpremeditated casual gesture.

In Dunstable I worked briefly with Douglas* and — I believe — with Durst†. In September or October 1940 I was posted as a Meteorological Officer to No. 4 Group, Bomber Command in York. The Senior Meteorological Officer in York was Richard Veryard‡. We got on particularly well together, but

*C. K. M. Douglas: The Meteorological Office's greatest forecaster. See obituary notice in *Meteorol Mag*, **111**, 1982, 252.

†C. S. Durst: Assistant Director (Special Investigations) 1948–53.

‡R. G. Veryard: Deputy Director (Central Services) 1958–59. President of the Commission for Climatology of WMO 1957–61.

I still wanted to fly. Both Veryard and I felt that meteorological forecasts would be improved if more data were available from oceanic locations. To get these data on a regular basis would require special, long-distance meteorological reconnaissance flights. A letter which rationalized and advocated the institution of such flights was drafted by me and sent — under our joint signature, I believe — to Nelson Johnson who was then Director of the Meteorological Office. This letter is presumably still in the archives. We also discussed the matter with Air Vice Marshal Coningham who was Air Officer Commanding No. 4 Group and who supported the idea through RAF channels.

I do not know whether it was really this initiative which led to the establishment of the meteorological reconnaissance flights. The idea may have been in the air, because I got a very fast response. Within weeks, probably in November 1940, I was summoned to London to see Johnson at the Air Ministry. He referred to Veryard's and my letter and asked me whether I would like to organize and start the flights. The following day in London, I was taken to lunch by Sydney Chapman. We ran accidentally into Lindeman who told me that he had heard about the meteorological flight initiative and that he thought it a good idea. As he was Churchill's adviser, this may have contributed conceivably to the realization of the project.

I was asked to recommend an operational procedure and a data reporting code for Gold's approval. I suggested regular flight tracks over the Atlantic in a north-westerly and south-westerly direction. The North Sea was added to this on Gold's insistence. My suggested plan of operations was to fly out at a low level to a distance to be determined by the range of the aircraft, then make a spiral ascent to the 500-millibar level and then return on a glide path to save fuel and stretch out the aircraft endurance. All this was rather readily accepted, but the proposed code turned out to be much more controversial.

In his time, Gold had devised innumerable codes and standards for the international meteorological community. He considered himself — rightly — an expert in this field. He also was a passionate adherent of the imperial as distinct from the metric system. We fought heatedly over trivia, until I felt that it was unbecoming for a young man to be so dogmatic with this old, experienced gentleman. I then proceeded to accept everything he said, but that too was the wrong policy. Gold loved to argue. From the moment I agreed with him, he turned round and found merit in what he had criticized so bitterly before. In retrospect, I believe Gold to have been probably the brightest and almost certainly the most distinguished scientist in the upper Meteorological Office ranks during the nineteen thirties and forties. It may have been his argumentativeness and his undisguised contempt for anything he considered foolish that kept the directorship of the service out of his grasp.

My first meteorological flight posting was to Aldergrove. When I got there in January 1941, I found three Blenheims and a complement of ground crews at my disposal — but no aircrews. Pilots were at a premium just after the Battle of Britain. For a month or so I moped around in Aldergrove, sending increasingly shrill requests through my direct pipeline to Gold and Johnson for either pilots or for permission to fly myself. In the meantime, I amused myself by flying convoy missions with one of the local Anson squadrons (No. 206) and by borrowing some of their pilots during their spare time for meteorological instrument calibration on the Blenheims.

In due course, I heard from the Air Ministry that there was no time for me to go through pilot school before starting the meteorological flights, but that they would send me to a crash navigators' course instead. As far as I remember, the course was in the Lake District or in Northumberland. It gave me a lifelong interest and facility in reading the lie of the land from the sky; I also learned a lot about celestial navigation but, at the final examination, I failed—in meteorology. One of the questions asked about the weather associated with a lapse rate of 10 °F/1000 feet. The expected answer was that it would be very unstable; instead I pointed out that such a lapse rate is not observed and cannot exist in the free atmosphere. The examiners were not amused and did not pass me, but after some noisy protests to Air Ministry I was told to stick on that badge and for God's sake to stop making such a nuisance of myself. A long time later, after I left the meteorological flights and after several hundred hours of operational flying during which I had worn my flying badge, I received a totally unexpected letter from HQ. No. 17 (Training) Group, which certified me as a qualified air observer — so I did become legitimate in the end.

While I did my navigation course, two pilots had been posted to 1403 Meteorological Flight in Bircham Newton and I went there to join them at the end of February 1941. The senior of the two, FO Douglas Bisgood (Fig. 1) was a regular fighter pilot, who had somehow been patched together again after being terribly wounded in a head-on air collision during the Battle of Britain. After a few training and calibration flights, as well as a flying visit to Aldergrove to keep up the morale of the still pilotless ground crews of No. 1405 flight there, Douglas Bisgood and I (Fig. 2) carried out the first operational meteorological reconnaissance flight on 14 March 1941.

Figure 1. Douglas Bisgood.

Figure 2. Eric B. Kraus.

Bisgood and I flew together almost every day during the following month (Fig. 3). We tested different psychrometers and experimented with the use of bomb-sights to measure our height above a cloud surface. The Blenheims were not ideally suited for the job we had to do. They barely staggered up to the 500 mb level. We developed a procedure which required straight and level flight or even a shallow dive when the aircraft approached its ceiling. When the speed had become large enough during this phase, the pilot pulled up the nose for a little hop to a higher level where the procedure was repeated again. After a few of these steps we usually managed to get up to 500 mb.

Towards the end of March, Bisgood and I were joined by two other pilots: Flt. Lt. Denis Wykeham-Martin who took over as OC 1403 flight and Flt. Lt. Pat Ritchie (Fig. 4). When I flew with Douglas Bisgood I had to remind him sometimes that his job was no longer that of a fighter pilot. In return he used to tease me mercilessly. One day in April, he came back from a meteorological reconnaissance flight — without me — and saw three Junkers 88s returing from a raid over England to Germany. He stalked them through the summer cumulus clouds, attacked the last of the much bigger aircraft with his single, forward-shooting Blenheim popgun and shot it down. On Wykeham-Martin's recommendation, Bisgood got a DFC for this — I believe it was his second DFC. He died less than a year later.

We split up at the end of April. Bisgood was promoted and became the CO of 1403 flight in Bircham Newton, Ritchie took over as CO in Aldergrove and Wykeham-Martin went to St. Eval to start No. 1404 Meteorological Reconnaissance Flight there. I too had been promoted and was left free to commute between the three flights, though I made my permanent base in St. Eval. Later in the summer of that year, Wykeham-Martin was sent to some course or staff college for three months and I took over as acting CO of 1404 flight during his absence.

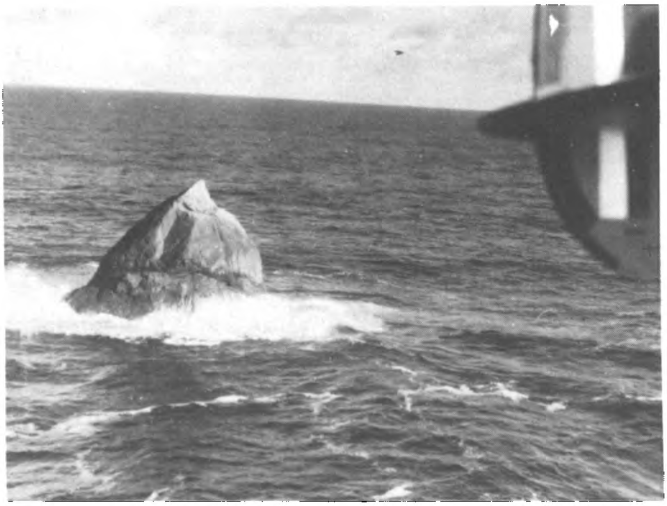

Figure 3. Rockall seen from Blenheim Z7340.

Figure 4. From left to right: Wykeham-Martin, ?, ?, Ritchie, ?

Our flights out of St. Eval over the Bay of Biscay were twice as long as those from Bircham Newton. We saw many U-boats. The fact that our sightings were relatively more frequent than those of the regular anti-U-boat patrols led to a change in official Coastal Command tactics, I believe. Instead of cruising just above the waves the patrols were ordered to fly at the higher level from which the meteorological flight crews had reported most of their first sightings. One day, coming back from the Bay with myself on the controls. I saw a U-boat below. With great excitement I dived down, popgun blazing. It was only when I levelled out above the water that I discovered it had been a poor whale whom I had so mercilessly attacked.

Meteorological flight crews became accustomed to fly in really bad weather when everyone else was grounded. Our unofficial flight badge — umbrella over skull and crossed bones with the motto *Semper in excreta* below — which had been designed by Bisgood and was painted on the side of our Blenheims (Fig. 5) perhaps bears witness to this. The aerodrome at St. Eval was closed officially when the ceiling was down to 400 feet, but we did not like to be diverted and by informal arrangement with the local meteorological officers the indicated ceiling was always at least 400 feet when the meteorological flight came back, whatever the actual cloud-base height. This permitted the returning pilot to make his own decision.

Figure 5. Flight badge of the meteorological flight's Blenheims, designed by Flt. Lt. Bisgood — *not* approved by King George VI.

One of the most experienced pilots in 1404 Flight was Flight Sergeant Portman (Fig. 6). I had recommended him for a commission while I was acting CO. On his first flight as a Pilot Officer, he returned in miserable weather — with the usual indicated ceiling of 400 feet. He broke cloud over what he expected to be the sea, but was in reality the Lizard. The first object he saw was a bush right in front of him. The only thing he could do was to force the aircraft up the slope of a hill which just matched the maximum Blenheim climbing rate. The propellers churned through the heather, a fence was knocked over and an innocent pedestrian only saved himself through violent evasive action. Finally, Portman reached the summit of his hill and then made it safely to St. Eval. His Blenheim, with the leading edge and the landing lights full of gorse which Portman had collected during his climb, is shown in Fig. 6.

Figure 6. Note gorse on Blenheim's leading edge. For left to right: ?, ?, Flt. Sgt. Portman, Flt. Lt. Kraus.

Through most of 1941 I had been able to write my own ticket. I had cut quite a few corners to get the meteorological flights off the ground. In the autumn of 1941, these free-wheeling days came to an end and bureaucracy took over. I was put formally under the command of a Wing Commander Carey at Coastal Command. At the same time, Peter Sheppard was appointed head of a Branch in the Meteorological Office which was to be responsible for meteorological reconnaissance. Carey first kept me in an office next to his at Coastal Command and then ordered me to Iceland to start a reconnaissance flight out of Kaldadharnes. It was the first time I was told by higher authority what to do.

I went by train and ship to Aldergrove and then took one of Ritchie's planes to Iceland. By that time, the Blenheims of 1405 Flight had been replaced by Lockheed Hudsons, which were considered a death-trap in a forced landing on water. I remember that when we landed in Kaldadharnes the wind blew at about the same speed as the landing rate of the Hudson. When Flt. Lt. Eccles put the aircraft down, it rolled to a stop within about ten yards. On the return flight, somewhere between Iceland and Aldergrove, I heard in snatches over the radio about Pearl Harbor and about America's entry into the war. I knew then that the war had entered a new phase.

When I got back to London I had jaundice. I was also tired after some 400 hours of operational flying in eight months. I had to get Carey's permission to get married early in 1942, which was granted rather grudgingly. After a short honeymoon, I was posted as an instructor to a training station in Thornaby. I cannot remember what or whom I taught there — it may have been new meteorological observers. From my log-book I see that I did some flying in Thornaby, participated in two bombing raids and visited Bircham Newton again. In April 1942, I went on four long Meteorological reconnaissance flights out of Wick, Scotland. One of these must have got me over Norway, because I have some photographs of it in my album. Curiously, these days are much less vivid in my mind than the early Meteorological Flight days in Bircham Newton and St. Eval.

After the summer of 1942, when I was posted to Benson, Oxfordshire as the Senior Meteorological Officer with the Photographic Reconnaissance Unit there, I lost contact with the Meteorological reconnaissance flights. Douglas Bisgood, Denis Wykeham-Martin and John Portman were all killed in different places during this year. Ritchie went on after the war to become Master of the Guild of Navigators in Australia and then Managing Director and, I believe, Chairman of Qantas Airways.

Three years after my official departure from the Meteorological Flights, just after the end of the European war, Sqn. Ldr. Saffery and I ferried a long-range photo-reconnaissance Mosquito aircraft from Benson to Calcutta. While we were in India, we were asked to fly to Colombo for a visit to the South East Asia Theatre HQ. I was briefed there about the planned dispatch of several bomber groups from England to China for participation in the war against Japan. In preparation for this effort, I was to explore the Chinese meteorological facilities and also make suggestions for the establishment of a Mosquito meteorological reconnaissance flight over the South China Sea. It was in China — again in the air — between Kunming and Chungking that I heard about the Hiroshima bomb, which made the establishment of a Pacific meteorological flight rather irrelevant.

This article was written in response to a general appeal for such reminiscences; although not originally intended for publication, it will, we think, interest our readers.

Notes and news

MOLARS goes on-line

The Meteorological Office Library Accessions and Retrieval System (MOLARS) contains a bibliography of books, journals and individual articles held by the National Meteorological Library, London Road, Bracknell, Berkshire RG12 2SZ. Since 1972 over 9000 items a year have been catalogued and classified by UDC (Universal Decimal Classification) numbers covering meteorology, climatology and related atmospheric sciences.

On-line access to MOLARS is now available from the European Space Agency Information Retrieval Service (ESA-IRS). Details may be obtained from the United Kingdom agent, DIALTECH (telephone: 01-212 5700). Access to MOLARS from within the Meteorological Office is available on terminals from the main computing complex (COSMOS).

For details of MOLARS, see Harris and McSean (1980).*

Last remaining serving wearer of the 'M' brevet leaves the RAF

Wing Commander B. D. (Brian) Tanner, the last remaining serving wearer of the 'M' brevet, retired from the Royal Air Force last April.

Wg/Cdr. Tanner joined the RAF as a National Serviceman in August 1953 and in March 1957 attended the Aero Met Observers' Course at RAF Aldergrove, and was awarded his now unique 'M' brevet in June 1957. As a Sergeant Meteorological Observer he flew over 1800 hours in Shackleton and Hastings aircraft, deliberately seeking out and flying in the foullest weather to obtain essential weather data. In Septeber 1959 he left the Service but re-entered shortly afterwards and was commissioned in September 1960 into the Air Traffic Control Branch. The Squadron responsible for Meteorological Research, No. 202, was disbanded in 1963 and the majority of the 'M' brevet holders retired soon after. Squardron No. 202 was later re-formed and found further fame in the Search and Rescue role.

As an air traffic controller Wg/Cdr. Tanner has held a wide variety of appointments, including Senior Air Traffic Controller at RAF Leeming and Command Air Traffic Controller at HQ Strike Command; his last was as Officer Commanding Central Air Traffic Control School.

*Harris, E. W. C. and McSean, T.; MOLARS — Automating the National Meteorological Library. *Meteorol Mag*, **109**, 1980, 18-21.

Wing Commander Brian Tanner (left) with Squadron Leader Mike Stokes, Officer Commanding, Meteorological Research Flight. The WC130 of the Meteorological Research Flight is in the background.

Reviews

Our threatened climate: ways of averting the CO_2 problem through rational energy use, edited by Wilfred Bach. 182 mm × 248 mm, pp. xxiv + 368, *illus*. D. Reidel Publishing Company, Dordrecht, Boston, Lancaster, 1984. price Dfl 95.00, US $29.00.

Professor Bach is already the author or editor of several books on topics including energy, pollution, food production and climate. Thus, it is not surprising that this book is not just confined to a narrow survey of CO_2 and climate, but delves into wider economic and social issues as well. The book could equally well have been called 'Our threatened world: ways of averting an energy crisis and related problems through rational energy use'. The book, an updated version of the German original, is intended to present the recent state of scientific knowledge in a manner comprehensible to those outside the scientific community and to decision makers in particular. Apart from some reservations listed below, the author has provided a readable text without in general sacrificing scientific accuracy, and his treatment of the climatic aspects of the problem, on which I am best qualified to comment, is for the most part fair and balanced.

The main text is preceded by an executive summary (why 'executive'?) of the chapters to come. Next there is a short introduction, followed by a chapter on climate and climate change, including the history of the earth's climate, a description of the climate system and how it is affected by changes in the concentration of radiatively active gases, and a survey of numerical models of climate. Chapter 3, on social and political aspects of the problem, discusses population growth, settlement patterns and future energy demands. Chapter 4, on the influence of society on climate, is the heart of the book. It covers not only the carbon cycle, past and future levels of atmospheric CO_2 and their impacts on climate, but also sections of variable quality on the effect of other trace gases, waste heat, and of changes in land use. (The conclusions of the chapter are spelt out in a short question and answer section, just to make sure no-one misses the point!)

Chapter 5, on the impacts of climate changes on society, says much about the impact of climate on society but is necessarily vague and speculative where climate change is mentioned. Consequently, one arrives at Chapter 6 (Strategies for averting a CO_2–climate problem) with little quantitative idea of the problem to be averted. Bach argues that technological fixes to reduce CO_2 emissions are impracticable, hence the only immediate solution is to increase the efficiency of energy use and reduce wastage, allowing time to develop renewable energy sources. The final chapter, on opportunities for the future, develops this theme and suggests how it might be implemented. There are an additional 100 pages which include references, indexes, appendices, a bibliography and a glossary of technical terms.

The style of the presentation is largely descriptive, as befits the intended audience. There is some necessary repetition, as on pages 42 and 104. In places, the author discusses particular examples as if they were generally true, as on page 106 where he does not make it clear that the paragraph on the length of integrations (and initial conditions) refers to a specific study and would be inappropriate, for example, for a model including the oceanic mixed layer. There are also several inaccuracies. For example, the sea temperatures off eastern South America in Figure IV. 13 are overestimated because upwelling is ignored, not just poorly represented in the model; the overlap of CO_2 and H_2O absorption bands does not amplify the CO_2 influence on the radiative flux (page 108) but modifies it, as explained on page 133; and, on page 182, the relationship between sunspot number and climate is at best speculative, and no plausible mechanism such as that suggested in the text has been verified.

Most of the diagrams are clear and well produced, but the text gives an impression of being cramped, and some of the tables are very difficult to read. I noticed few faults, apart from a missing reference (Gornitz *et al.* 1982, on page 188) and one or more missing lines of text on page 174.

Much of the author's argument rests on the premise that the impacts of increased CO_2 are necessarily undesirable and should be avoided. I found the case against CO_2 'not proven', largely because Professor Bach gives inadequate consideration to the possible beneficial effects of increased CO_2, both through direct effects on plant growth and indirectly through changes in climate. However, some of his other arguments for rational energy use are more convincing. To judge for yourself, you will need to read the book.

J. F. B. Mitchell

Carbon dioxide: current views and developments in energy/climate research, edited by W. Bach, A. J. Crane, A. L. Berger and A. Longhetto. 160 mm × 245 mm, pp. xvii + 525, *illus.* D. Reidel Publishing Company, Dordrecht, Boston, Lancaster, 1983. Price Dfl 180, US $72.00.

This book consists of the lectures given at the second course of the International School of Climatology held at Erice from 16 to 26 July 1982. The murky photograph of the participants, a poem on the CO_2 blues (in Italian!) and cartoons (no doubt dreamt up in the evening at the bar) are probably included to remind those who attended what a good time they all had. For other readers, in the foreword it is hoped that the volume will provide a balanced perspective on the CO_2 problem as it currently stands whilst the preface hopes that together the lectures form a coherent text of real educational value. Despite the unfunny cartoons these objectives are largely achieved.

As is customary now for books on CO_2 there are sections on I/the carbon cycle, II/climate effects and III/impacts and strategies with 16 contributions in all. These are mostly of reasonable length and some effort has been made in editing and cross referencing so that themes are developed by different authors without too much repetition.

In part I, Wallen gives an account of the history of monitoring the CO_2 content of the atmosphere from the late 18th century to the present-day measurements made at the Mauna Loa Observatory which show an increase from 315 parts per million by volume (ppmv) in 1958 to 337 ppmv in 1980. The global network of monitoring stations is described with reference to the problems of standardization and the influence of the biosphere on regional and continental stations. Baes then gives a nice introduction to the role of the oceans in taking up the excess CO_2 released into the atmosphere from fossil fuels. The oceanic chemistry is presented clearly and possible changes in the composition of surface waters illustrated by the titration alkalinity/total inorganic carbon diagrams, these are well worth the effort to understand if, like me, you find the numerous possible chemical reactions rather confusing. Attempts to model the carbon cycle are reviewed by Bjorkstrom with particular emphasis on the oceanic uptake which has been modelled using a simple two-box model and more sophisticated models with diffusion and representations of the circulation. Such models have been employed to predict future levels of CO_2 and in the following chapter, Kohlmaier *et al*, discuss the difficult problem of the role of the biosphere in the carbon cycle. The uncertainties in the inventories and fluxes between the various components of an ecosystem are stressed whilst quantifying human impact by changing land use is hampered by lack of data on past changes. They conclude that terrestrial biota may be a net source of atmospheric carbon of from 0 to 5 gigatonnes per 100 years. Also historical changes from forest to agriculture and grasslands in temperate latitudes may have been responsible for some of the observed increase in CO_2 although now such regions may be acting as sinks due to re-growth and are probably balancing the major clearances of tropical rain forest. This is supported by the proxy data on atmospheric CO_2 content from tree rings described here by Lorius and Raynaud. Estimates of the pre-industrial level of 230 to 260 ppmv suggest that late 19th century pioneer agriculture was an important non-fossil fuel source. Ice core studies are also described for longer time-scale variations.

In part II, Kandel describes the basic physics of the greenhouse effect and the likely increase in global mean surface temperature due to increased CO_2 deduced from simple radiative-convective and energy balance models. Some of the arguments on the surface energy balance I found a little difficult to follow and unfortunately the emphasis on global surface temperature changes tends to be a too restrictive view of climate. General circulation models could provide a means of determining possible changes in regional climate such as temperature and changes in the hydrological cycle. The equilibrium response to increased CO_2 is clearly described by Gilchrist with particular reference to experiments performed in the Meteorological Office which are compared and contrasted to those carried out at GFDL. Whilst equilibrium experiments are extremely useful for determining which processes are important it is the transient response that we are likely to experience and Hoffert and Michael consider this in the following chapter, particularly the ocean's role in delaying future warming. This interesting topic is here rather marred by various errors in the equations which although usually obvious are frustrating. In shorter chapters of this section Oerlemans describes models of the reaction of polar ice sheets to CO_2 warming, Flohn speculates on possible major climatic events, and Volz considers the possible impact of aerosols, land-use changes, waste heat release and other trace gases. The last, he concludes, could contribute significantly to the greenhouse effect with the combined effect possibly as large as that of CO_2 alone. Schönwiese deals with statistical techniques that can be used to analyse observed climate variability in the modern instrumental period. Insufficient explanation and detail make this chapter harder to follow than that on the detection of CO_2-induced climate change by Schuurmans.

Part III on impacts and strategies is inevitably more speculative. Kellogg outlines some possible effects of changes in temperature and rainfall on regional scales to natural vegetation, agriculture, fuel demand, water resources, fisheries, health and human comfort and describes possible strategies to deal with such climate-induced changes. It is emphasized that not everyone will be affected in the same way so impact studies need to treat specific regions and specific economic sectors, and for this the likely climate changes need to be known with more confidence.

Laurmann's chapter on the development of quantitative methods of assessing alternative strategies proposed to reduce or avoid the environmental threat was novel and interesting. However, unfamiliarity with economic jargon and several long-winded and pretentious euphemisms made it difficult to read and grasp the ideas. It is a pity that some basic definitions were not provided to help those not schooled in economics. The obscure language is well illustrated on page 451 '... unless [market penetration time lags] are endogenously put into the model as pre-selected parameters'. I think he means they should be variables of the model.

In the final chapter Bach presents a low CO_2-climate risk policy characterized by using energy more efficiently and requiring less fossil fuel energy than forecast in conventional energy projections based on population and GDP extrapolations. By placing the emphasis on the end-use for which energy is required an analysis of alternative ways of meeting the tasks and substituting fuels reveals the large potential for greater efficiency. From a case study of possible cost-effective improvements towards energy efficiency in West Germany, Bach argues that the world demand for energy could be 37% *lower* in 2030 than in 1975 if such a program were adopted globally.

The book is well produced and the print easy to read apart from a few stray superscripts here and there. The diagrams are mostly clear and uncluttered although some in chapter 1 are rather small and the grey shading, e.g. Figure 1 of Schuurmans, hardly visible. Parts of it could usefully be recommended in advanced courses though, as I have indicated, some chapters are harder to read. On the whole I think a balanced view of the many disciplines involved in the 'CO_2 problem' is provided.

C. A. Wilson

Atmospheric chemistry: Report of the Dahlem Workshop on Atmospheric Chemistry, Berlin 1982, May 2–7, edited by E. D. Goldberg. 150 mm × 210 mm, pp. viii + 385, *illus.* Springer-Verlag, Berlin, Heidelberg, New York, 1982. Price US $19.90.

This book, Volume 4 in a series on Physical and Chemical Sciences Research Reports, arises from a Dahlem Konferenz held in Berlin in May 1982. There are thirteen single-authored papers, one multi-authored, and four group reports.

The thirteen authors are all well known and cover between them most aspects of tropospheric chemistry, albeit with some redundancy. Space does not permit a review of all these chapters, but particular highlights for me included that by Morgan on the pH and oxidation capacity of rain, with its insistence on pointing out the non-linear nature of the system. Jørgensen's review of C, N and S gases from oxygen-deficient environments was very clear, as were the last three chapters, by Niki on homogeneous gas phase oxidation, by Crutzen on the global distribution of hydroxyl and by Penkett on non-methane organics in the remote troposphere.

The volume is slightly marred by Slinn's paper, in which the impact of some well-made points is diluted by being interleaved with musings about the philosophy and politics of pollution which ought to have been filtered out somewhere down the line between the conference bar and the editor's desk.

The four review group reports are well considered, and leave one with a clear impression of the impressive progress made in tropospheric chemistry during the last decade, and also of the scale of future effort required to endow the subject with predictive power for input to policy decisions on air pollution control strategies. The book should be more useful to those requiring a contemporary survey of the broad state of the field than to those who need an introduction to the basic principles.

A. F. Tuck

Absorption and emission by atmospheric gases: the physical processes, by Earl J. McCartney. 160 mm × 235 mm, pp. xii + 320, *illus*. John Wiley & Sons, New York, Chichester, Brisbane, Toronto, Singapore, 1983. Price £47.50.

This book is aimed at scientists, development engineers, technicians and students in meteorology, atmospheric physics, aerospace surveillance and air pollution control. Such a diverse audience has necessitated a treatment in which topics are developed from the most elementary stages. This can be seen from the Chapter titles: 1, Introductory Ideas and Useful Facts; 2, Gas Properties, Thermodynamics and Molecular Kinetics; 3, Quantized Energy States and Population; 4, Molecular Internal Energies; 5, Spectra of Energy Transitions; 6, Parameters of Line and Band Absorptions; 7, Absorption and Emissions Data. Any reader who has come to atmospheric transmission via an adequate background in spectroscopy, gas kinetics or atmospheric physics is likely to find it a test of his patience in parts, but those who have entered from other traditions may well find it useful. Useful features of the book are the data-laden Appendices and extensive references to the literature.

The book appears in a series in Pure and Applied Optics, and is a companion volume to McCartney's *Optics of the atmosphere: scattering by molecules and particles*. Ever since the appearance in 1964 of Goody's *Atmospheric radiation. I. Theoretical basis* there has been a need for Volume II, on radiative transfer in the real atmosphere. It is an acknowledgement perhaps of the nature and development of the field that it has never appeared. It is badly needed; perhaps the publishers can be persuaded to add such a book to McCartney's pair.

A. F. Tuck

Books received

The listing of books under this heading does not preclude a review in the Meteorological Magazine at a later date.

Weather and climate of the Antarctic, by W. Schwerdtfeger (Amsterdam and New York, Elsevier Science Publishers, 1984. Dfl 120, US $46.25) is No. 15 in the series Developments in atmospheric science. Its purpose is to present an up-to-date description and, as far as possible, an explanation of the meteorological characteristics of the southern continent. Some problems which need further field work and theoretical investigation are outlined in detail. Questions of weather forecasting are discussed only where it appears that new information or understanding of the atmospheric processes involved make it worthwhile. The difficulties of an adequate interpretation of minor regional climate functions are commented on.

World climate change: The role of international law and institutions, edited by Ved P. Nanda (Boulder, Colorado, Westview Press, 1983. £17.25) provides a comprehensive discussion and analysis of the legal and institutional aspects of world climate change and weather-related problems, recognizing that these are no longer isolated issues countries can grapple with individually. The authors appraise several options for atmospheric management and make specific recommendations to reduce and ameliorate the adverse global effects of climate fluctuations and changes.

Climatic changes on a yearly to millennial basis, edited by N.-A. Mörner and W. Karlén (Dordrecht, Boston, Lancaster, D. Reidel Publishing Company, 1984. Dfl 210, US $79.00) is the Proceedings of the Second Nordic Symposium on Climatic Changes and Related Problems held in Stockholm, May 16–20, 1983. It focuses on the processes and data that are typical for the Nordic countries and the papers printed here can be divided into four main groups: paleoclimatological records; historical records; instrumental records; and theories, models and geophysical explanations.

The climate of Europe: Past, present and future, edited by Hermann Flohn and Roberto Fantechi (Dordrecht, Boston, Lancaster, D. Reidel Publishing Company, 1984. Dfl 130, US $49.00) consists of six chapters, prepared by individual specialists, each of which is followed by a summary and/or set of conclusions. It gives a broad view of the complex background to the problem of climatic change and the different factors involved, reviews changes that have taken place in the world's climate over the past thousand years or more, and analyses in greater detail the recent centuries for which instrumental weather data are available. It also discusses the extent to which man himself may affect the climate by his activities, looks into the past to find analogues to what appear to be the more likely lines of climatic development in the future, describes how European agriculture has reacted to climate change and fluctuations over the past 200 years or so, and considers also the effects on future food production.

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NOTICE

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