

The

DUPLICATE

Meteorological Magazine

January 1989

Real-time analysis of precipitation
Introduction to fronts: Part II
Satellite sounding radiances in NWP
Noctilucent clouds during 1987



DUPLICATE JOURNALS

HMSO

National Meteorological Library
FitzRoy Road, Exeter, Devon. EX1 3PB

Met.O.986 Vol. 118 No. 1398



The Meteorological Magazine

January 1989
Vol. 118 No. 1398

551.501.777:551.507.362.2

Real-time analysis of precipitation using satellites, ground-based radars, conventional observations and numerical model output

C.G. Collier, D.M. Goddard and B.J. Conway
Meteorological Office, Bracknell

Summary

In this paper we review methods of estimating precipitation using satellite data, which is a prime requirement of systems designed to aid the production of very-short-period weather forecasts or nowcasts. An attempt is made to assess and compare the accuracy of the various techniques in order to indicate the performance likely to be achieved by any procedure implemented in real time. The combination of several different types of data is likely to provide improvements in measurement accuracy. By way of illustration a real-time procedure currently being developed for operational use in the Meteorological Office is described. This procedure uses radar and conventional observations with satellite imagery and numerical model output. The need for quality control procedures, preferably based upon objective algorithms, is stressed, as no single source of data is capable of defining the precipitation field over large areas.

1. Introduction

The requirement for precipitation measurements arises in many aspects of both operational and research meteorology, climate monitoring, hydrology, and ecology. Collier, Szejwach and Testud (1988) discuss these requirements noting the differences between the needs of nowcasting (observation of the weather now and forecasts up to a few hours ahead) and those of regional and global numerical weather prediction models. In spite of these differences there is a consistency in space and time which ensures that measurements of precipitation made for nowcasting and short-period forecasting are also useful for larger-scale numerical modelling, although not providing the global coverage which is really needed. Hence, even for applications on these larger scales it may be more profitable to consider how best to measure precipitation for periods of less than one day rather than for longer time-scales.

In general this philosophy will be appropriate over data-rich areas of the world, but in other areas limitations imposed by a lack of data will mean that techniques to measure precipitation over sub-daily periods are inadequate. Over the tropical oceans, where there are no ground-based observations, we must rely on satellite-based systems, such as those proposed by Simpson *et al.* (1988), which will provide daily or monthly estimates.

Over Europe there are considerable amounts of data provided by a dense network of conventional observing stations, weather radars and the Meteosat satellite. Nowcasting systems are in place in some countries and plans are well advanced in many others. Mesoscale models are also nearing operational implementation. In addition, the nuclear accident at Chernobyl in 1986 highlighted the importance of wet deposition in

determining the dispersion and distribution of radioactive nuclides. Hence the need for real-time estimates of precipitation over a wide area has become even more focused in Europe. Since observations over most of Europe are readily available via the WMO Global Telecommunication System, it is appropriate to assume that a combination of ground-based and satellite data offers the most likely means of providing estimates of precipitation which are of acceptable accuracy for these applications. We first consider possible methods of using satellite data.

2. Use of visible and infra-red data

Visible and infra-red data have been most commonly used to make estimates of rainfall and, to a lesser extent, snowfall. The thermal infra-red temperature as measured from a satellite is modified by the atmosphere. The radiation measured when looking down vertically is partly made up of reflected radiation from the surface in the clear-sky situation. If clouds are present then rapid changes in the observed radiant emission from a surface can occur.

Two types of technique for estimating rainfall have been developed, these being known as 'cloud indexing' and 'life-history' methods. (For comprehensive reviews see Barrett and Martin (1981) and Collier, Szejwach and Testud (1988).)

2.1 Cloud indexing method

Cloud indexing was the first technique developed for rainfall estimation. A rainfall coefficient or cloud index was evaluated from features of the satellite cloud-field defined by visible or infra-red images, for example brightness or texture. These indices were then related, via regression equations, to rain-gauge observations of rainfall (e.g. Turpeinen *et al.* 1987). These techniques are most successful for rainfall over periods of days or months, partly because satellite data from polar orbiting platforms are only available every 6 to 12 hours. Regression techniques are used with both polar orbiting and geostationary satellite data, but the procedure involves a high level of subjective interpretation by an analyst. In general these techniques only function well for convective cloud, as opposed to frontal cloud. Pattern recognition techniques using textural or radiance features with cloud models are also being assessed and show some promise (Wu *et al.* 1985, Adler and Negri 1988).

2.2 Life history method

Stout *et al.* (1979) were able to estimate the rainfall produced by convective clouds from the sum of the area of the clouds and the rate of change of that area, that is, volumetric rain rate for a particular cloud, $R_v = a_0 A_c + a_1 (dA_c/dt)$ where A_c is the area of the cloud, dA_c/dt is the rate of change of cloud area, and a_0 and a_1 are empirical coefficients. This type of technique, known as a life-history procedure, requires satellite images at

frequent time intervals which can only be provided by geostationary satellites.

Variants on the Stout *et al.* technique have been produced by Griffith *et al.* (1976, 1978), and Scofield and Oliver (1977a, 1977b). In the latter technique, precipitation in general is favoured by high cloud-brightness (low cloud-top temperature), and heavy rainfall in particular is favoured by low cloud-top temperatures and the growth and merging of clouds.

Improvements to deal more adequately with storm clouds having warm tops have been proposed by Scofield (1981, 1982). The addition of spectral and textural information from geostationary satellite images to the evolutionary data has been investigated by Martin and Howland (1986), and found to produce useful improvements in the tropics.

Negri and Adler (1981) found that thunderstorm-top ascent rates are correlated with maximum storm-radar reflectivities, and the minimum black-body temperature observed during the lifetime of a storm is correlated with the maximum volumetric storm rainfall. In general these techniques produce only acceptable estimates of convective rainfall. However, Negri *et al.* (1984) have concluded that these techniques are unnecessarily complicated for daily rainfall estimation. Recently Motell and Weare (1987) have proposed a simple regression technique for tropical rainfall, but this is very limited in its applicability. Doneaud *et al.* (1987) have proposed a simple procedure in which the area-time-integral of cloud areas over the lifetime of a storm is related to the total rain volume. Initial investigations are encouraging, although again the technique is likely to work well only for convective rainfall.

3. Use of multispectral data

The use of single images, or sequences of images of either visible or infra-red data, has been discussed in the previous section. However, procedures have not proved to be totally reliable as required for operational implementation. Improvements can be obtained by the combined use of data from several spectral bands as described, for example, by Liljas (1982).

Infra-red sensors on satellites provide information on temperature, and thus indirectly on the heights of the tops of clouds. On the other hand visible sensors provide information on the depth of clouds, their geometry and composition. Combination of this information enables recognition of high cloud-tops associated with deep clouds which are likely to produce significant rainfall. Early work on this type of technique revealed problems arising from registration errors between the visible and infra-red images, instrument calibration, time difference between images, and illumination geometry, which caused the results of the early work to be less encouraging than workers had expected. Lovejoy and Austin (1979a) demonstrated that these problems could be overcome.

Several investigations using models of convective processes aimed to tackle the problems from a physical,

rather than a statistical, point of view (Gruber 1973, Wylie 1979). These techniques are able to define rain areas. However, the estimation of rainfall amounts is more problematical, and ground-truth data such as that provided by radar may be needed for calibration of the satellite data when making estimates of rainfall amounts or reliable estimates of rain area. Tsonis and Isaac (1985) have proposed a scheme which uses radar data to define areas of rain or no rain for calibration and subsequently uses the visible and infra-red satellite data only to delineate areas of rain; no quantitative estimates are produced.

The latest generation of satellites provide data with high spatial and cloud-top temperature resolution. Unfortunately these data are not adequate on their own to allow the automated analysis of different cloud types and the separation of these types into clouds producing precipitation and those which are not. In spite of the difficulties the UK FRONTIERS (Forecasting Rain Optimized using New Techniques of Interactively Enhanced Radar and Satellite) system contains an operational implementation of the Lovejoy and Austin (1979a) technique using Meteosat infra-red and visible images together with data from the UK weather radar network. Because the coverage provided by the UK weather radar network is insufficient, even for a 3-hour advection forecast for areas within radar coverage, Meteosat imagery is used to infer probable areas of precipitation outside the area for which good radar data are available. This area depends upon rainfall type and is delineated by the Usable Data Boundary (UDB) (see Brown 1987). To maximize the reliability of the operational system, only rain or no-rain predictions are made at present.

The visible (VIS) and infra-red (IR) data are each divided into 16 classes and a table of 'probabilities' of rain for each class is produced by comparison with the radar data. Prior to correlation the forecaster can, if necessary, manually adjust the registration of the satellite imagery using any visible coastline. Three tables are constructed, visible alone, infra-red alone and visible plus infra-red, the last being a two-dimensional table. The technique using infra-red data alone is similar to that described by Heinemann *et al.* (1987). In order to apply the tables to the satellite data outside the UDB, it is necessary to select a critical probability which differentiates between rain and no rain. This is chosen dynamically, as the probability which predicts an areal extent of rain within the UDB which best matches the extent observed by radar.

The correlation technique often gives the best results using a two-dimensional diagram similar to that shown in Fig. 1, because this contains information on cloud thickness and cloud-top temperature. Visible data alone can be nearly as good, but infra-red data alone are often inferior, particularly in frontal cases, where they can lead to overestimation of the extent of the precipitation ahead of the warm front. However, the correlation method cannot work in certain situations, for example when there is insufficient radar data to form a reliable

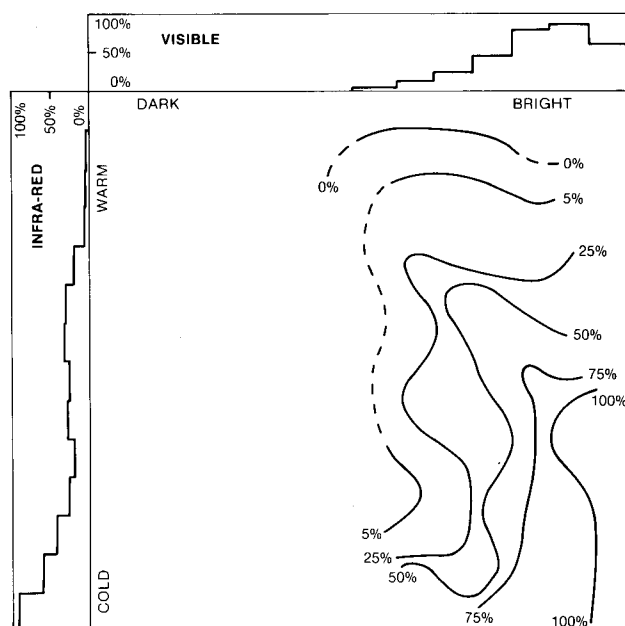


Figure 1. Visible (VIS) and infra-red (IR) rainfall correlation obtained by the FRONTIERS system from Meteosat data at 1130 GMT on 26 February 1987. The percentage chance of rain for any combination of VIS and IR is given. Histograms are also shown in which the percentage chance of rain using VIS only and IR only is given. Note that there is a wide spread of ranges of VIS brightness or IR temperature with greater than 50% chance of rain. This uncertainty is reduced by using both VIS and IR together.

correlation table because most of the precipitation is outside the UDB. Universal correlation tables can then be used, which have been constructed from past experience. If neither technique produces a satisfactory result, either the visible or infra-red imagery can be sliced so that a contiguous range of brightnesses or temperatures represents the rainfall field. If most of the precipitation lies outside the UDB the forecaster must judge the result using available synoptic observations and conceptual models of the distribution of precipitation within the prevailing synoptic archetype.

The final step of the satellite analysis allows the forecaster to modify the satellite-derived rainfall field and merge it with the radar field. Because of the lower reliability of the satellite estimate, rainfall can be added to or subtracted from it subjectively. The radar data are inviolate at this stage. Initially the combined rainfall field is displayed with the satellite estimate inserted beyond the maximum radar range of 210 km. This often leads to gaps between satellite and radar fields so that the forecaster is allowed to bring the satellite estimate up to the UDB wherever he chooses. If unrealistic gaps still persist the forecaster may judiciously merge the satellite field with the radar field inside the UDB. This is justifiable because the UDB is calculated assuming a precipitation field of locally uniform depth, and so cannot perfectly describe the actual limit of radar coverage. Clearly the satellite field should not be used close to the radars where the probability of detection by radar is high.

Unfortunately the look-up tables are often rough when derived in real time, i.e. small and large VIS/IR counts are juxtaposed, and too many counts occur in the no-rain class. It is also found that, in the tables, areas with no data sometimes appear in the middle of areas with data. Such gaps may be filled by manual intervention or automatic interpolation, but it is often better to use a climatological look-up table providing suitably smoothed data. Bellon and Austin (1986) show how this technique may be used to estimate rainfall amounts for convective rainfall. They note that average rainfall rates of less than 0.5 mm h^{-1} that occur at VIS/IR pairs corresponding to high temperatures and low visible counts are mainly a result of improper radar-satellite matching. Such problems arise from uncertainties in the satellite navigation, time differences between the radar and satellite data, or from misalignment between the satellite view of the cloud tops and the level of the radar observations. The rainfall rates of these pairs are set to zero to avoid the generation of spurious areas of small or trace amounts of rainfall. This loss of rainfall of about 20% in the cases studied by Bellon and Austin was allowed for by them by multiplying the data in the look-up table by factor of 1.2. This is not done in the FRONTIERS system.

4. Passive microwave techniques

Passive microwave rainfall measurements are of two types depending upon the effect used to detect precipitation. These types are referred to as the absorption/emission (by raindrops) and scattering (by ice particles) methods. The absorption method (Wilheit *et al.* 1977) uses frequencies below about 20 GHz. It requires a cold background and is therefore applied over the sea, which appears cold by virtue of its low emissivity at these frequencies, and against which the precipitating cloud appears warm. Collier, Szejwach and Testud (1988) list the limitations and uncertainties associated with the absorption method.

The scattering method may be applied over land as well as over the ocean surface. The brightness temperature (the temperature of a black body that would emit the observed amount of radiation) of the precipitating cloud decreases with the number and size of scattering particles. The major scattering effect results from the presence of frozen hydrometeors at the tops of convective clouds (Wilheit *et al.* 1982). It is necessary to derive an indirect relationship between rainfall rate and the amount of ice using cloud models (Wilheit *et al.* 1982, Szejwach *et al.* 1986). This method uses frequencies above 60 GHz and, at present, is the only satellite-based technique for obtaining rainfall over land using passive microwave methods. Fig. 2 summarizes the relationships between rainfall rate and various passive microwave frequencies.

Much work is now being carried out to investigate the ability to measure precipitation of the Special Sensor Microwave Imager 88.5 GHz channels of the US Defense Meteorological Satellite Program, and Barrett

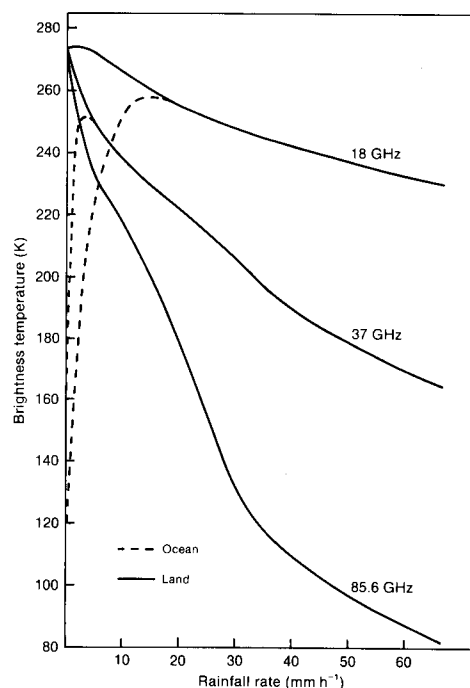


Figure 2. Brightness temperature–rainfall rate relationships at 18, 37 and 85.6 GHz from the radiative transfer modelling of Wu and Weinman (1984). The vertical distribution of hydrometeors was based on averaged radar results and assumed ice precipitation above and liquid precipitation below the freezing level (from Spencer *et al.* (1988) after Wu and Weinman (1984)).

et al. (1988) report early results which are very encouraging for convective rainfall. It remains to be seen to what extent mid-latitude frontal rainfall can be measured.

5. Active microwave techniques (radar)

Measurements of the strength of microwave energy, generated in a radar mounted on a satellite and reflected or scattered from the atmosphere or the Earth's surface, may be made on receipt back at the satellite antenna. The amount of back-scattered energy is related to the surface roughness, orientation, slope and the dielectric constant of the material of which the surface is composed. It also depends upon any rainfall intercepted by the radar beam, as short wavelengths are attenuated by heavy rainfall.

At present, active microwave systems are not being carried on civil satellites, but several satellite launches are planned which will carry radars. For example the Tropical Rainfall Measuring Mission (TRMM) (Simpson *et al.* 1988) includes the proposal to carry a 14 and 24 GHz active radar, together with microwave radiometers operating at 19, 37 and 90 GHz, and a visible/infra-red radiometer, at an altitude of about 300 km.

Although TRMM represents a major step forward in measuring precipitation from space, only part of the global requirement for precipitation data will be addressed. Collier, Szejwach and Testud (1988) summarize a number of combined active and passive microwave systems and assess their performance, cost and complexity. Unfortunately, as the accuracy increases so does the considerable cost and complexity.

6. Accuracy

Since several satellite systems will provide measurements of precipitation using parameters across a wide part of the electromagnetic spectrum, it is important to assess the relative merits and cost-effectiveness of each technique.

Evaluations of some techniques have been carried out (see, for example Johnstone *et al.* 1985), but Table I gives a summary of accuracy achieved, and likely to be achieved, across the whole electromagnetic spectrum from microwave to visible frequencies. Two points emerge from this table. Firstly, that most of the assessments of the accuracy of rainfall totals have been made as integrations over areas greater than 10³ km². However, some techniques are capable of measurement over areas as small as 50 km², or over areas approaching global scales. Secondly, most of the studies have been concerned in the main with the measurement of convective rainfall rather than frontal rainfall. In addition, rainfall amount is not measured with uniform accuracy, and some techniques have to be fine-tuned to measure heavy rainfall.

A combination of the accuracy of rainfall measurements attained by ground-based radar techniques with the data shown in Table I is presented in Fig. 3. This figure indicates that ground-based radar and satellite techniques are complementary.

Bellon and Austin (1986) have concluded that, at present, satellite estimates of rainfall are better than rain-gauge estimates at locations where the nearest rain-

gauge is further than 40 km. Therefore the implementation of such techniques is most useful in the data-sparse regions of the world. In those areas where numerous ground-based measurements are available the best method of measuring precipitation in real-time is likely to involve the blending of these measurements with those derived from satellites.

At present satellite-based techniques are unlikely to outperform ground-based radar within 100 km of radar sites. However, beyond this range satellite data will be useful, particularly in convective rainfall. Currently work is underway to use synoptic observations with

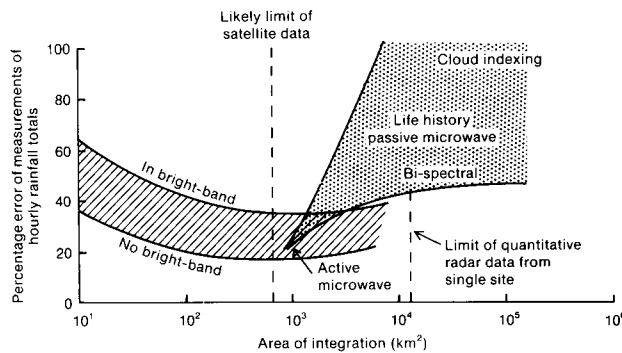


Figure 3. Illustrating the ranges of percentage error of measurements of hourly rainfall total presently attainable by ground-based radar (hatched area) and satellite techniques (stippled area), as functions of the area over which the measurements are assessed. The dashed lines show the upper limit of area over which quantitative radar data from a single radar is obtained, and the lower limit of areal coverage to which satellite data are likely to provide quantitative estimates of hourly rainfall (from Collier 1985).

Table I. Summary of the performance of satellite rainfall estimation techniques (from Collier (1985) partly based upon Lovejoy and Austin (1979b, 1980))

Technique	Area over which estimates are assessed (km ²)	Period of integration (hours)	Estimated or measured percentage error (%)	Sample references describing techniques (rainfall types)
Cloud indexing	10 ⁵ 10 ⁴	24 ½	122 41	{ Follansbee and Oliver (1975) Adler and Negri (1988) (convective/stratiform)
Life-history	10 ⁴ 10 ⁵ 10 ⁴ 6 × 10 ³	1 24 ½ ½	85 55 50 65	{ Griffith <i>et al.</i> (1978) (convective) Wylie (1979) (convective) Stout <i>et al.</i> (1979) (convective)
Bi-spectral	10 ⁵	½–2	49	Lovejoy and Austin (1979a, 1979b) (convective/frontal)
Passive	10 ³	24	70	{ Lovejoy and Austin (1980) (convective/frontal) Wilheit <i>et al.</i> (1973) Spencer <i>et al.</i> (1983)
Active	10 ³ 10 ³	12 30 × 24 (monthly)	20 (when combined with bi-spectral technique) 10	{ The accuracy of this technique is unknown but Lovejoy (1981) suggests the figures given may be possible (see also Collier, Szejwach and Testud (1988)) Simpson <i>et al.</i> (1988) (convective)

satellite data for estimating rainfall (Anderson *et al.* 1986, Aschbacher 1987). In addition, consideration is being given to the use of numerical model output with remotely sensed information. One scheme being implemented operationally in the United Kingdom is outlined in the next section. All this work must be underpinned by comprehensive quality control in order to provide to users estimates of reliability, including its spatial variation.

7. Real-time precipitation analysis over Europe

In order to derive precipitation data over much of north-west Europe for input to the Nuclear Accident Modelling Exercise (NAME), nowcasting procedures, and ultimately, mesoscale models, an analysis package is being developed in the Meteorological Office.

The area covered by the analysis is that north of 20° N between 80° W and 40° E. Initially, work is concentrating over that portion of north-west Europe for which a radar composite image is generated hourly as part of the Commission of the European Communities COST-73 Project (Collier, Fair and Newsome 1988). Over this area precipitation data from the UK numerical forecast models, FRONTIERS and Meteosat are brought together with conventional observations. The many computer systems involved are connected via a local area network (Fig. 4) enabling the various data to be assembled, processed and dispatched in near real time.

The initial phase is nearing completion, and will become operational by the end of 1988. Fig. 5 shows an example of the coverage of data from FRONTIERS, COST-73, the mesoscale model and the fine-mesh model. These data have been combined to give the

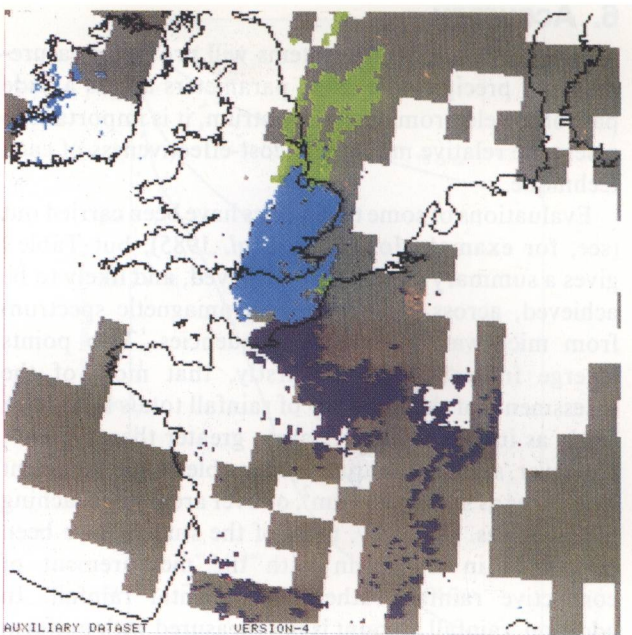


Figure 5. Illustration of the different data sets used to form a composite rainfall field over north-west Europe for 1500 GMT on 25 August 1987. The data sets used are FRONTIERS (blue), COST-73 (purple), mesoscale model (green) and fine-mesh model (brown). The limits of radar coverage and coastlines are shown.

composite rainfall field in Fig. 6. Each data source will have an appropriate confidence factor attached to it, so that when the data are used in NAME (for example) the reliability of the final output may be estimated. The development of quality control procedures, preferably based on objective algorithms, will be an important task in the future. Investigation is underway to assess how best to compare and combine images with synoptic reports.

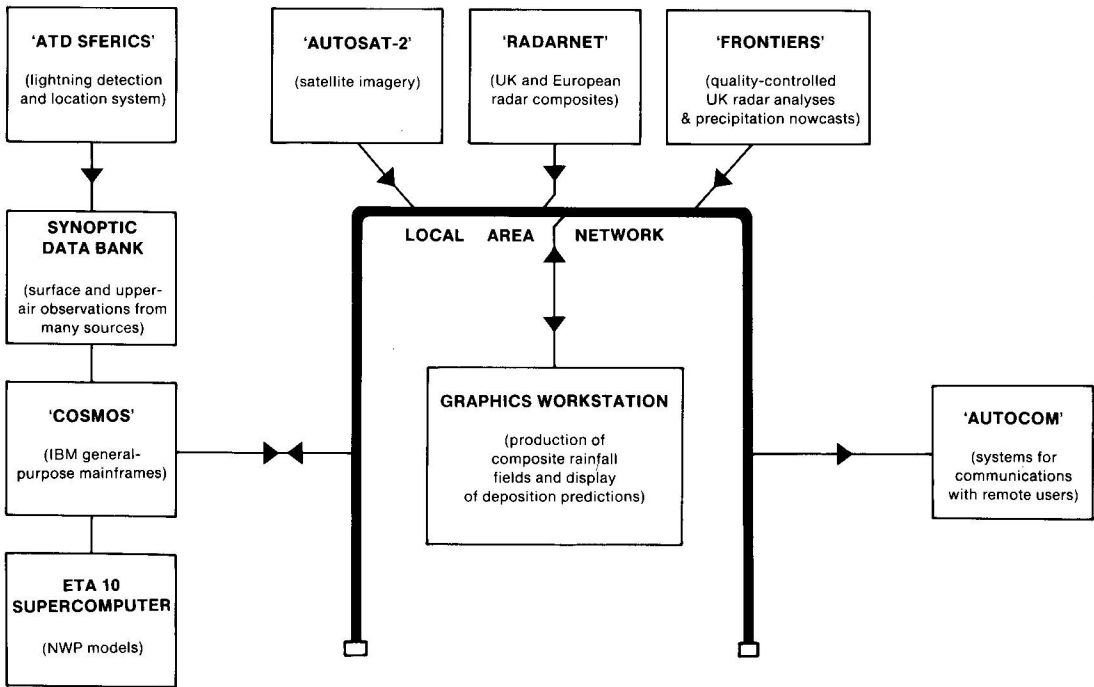


Figure 4. The interconnection of the graphics workstation for wide-area rainfall analysis and other computer systems at Bracknell.

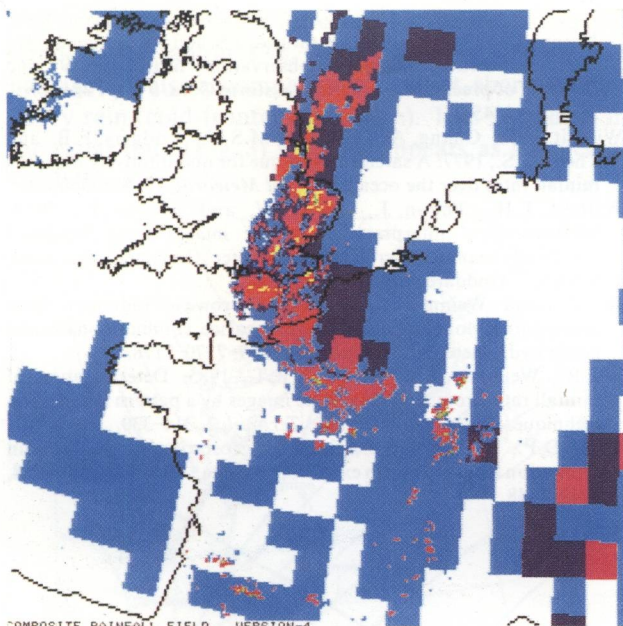


Figure 6. Composite rainfall field for 1500 GMT on 25 August 1987. The colours represent different rates of rainfall as follows: blue $< 1 \text{ mm h}^{-1}$, purple $1\text{--}2 \text{ mm h}^{-1}$, pink $2\text{--}4 \text{ mm h}^{-1}$, red $4\text{--}8 \text{ mm h}^{-1}$, yellow $8\text{--}16 \text{ mm h}^{-1}$, green $16\text{--}32 \text{ mm h}^{-1}$ and brown $> 32 \text{ mm h}^{-1}$.

8. Conclusion

Europe is fortunate to have a variety of different meteorological data available in near real time, but other regions of the world could benefit from the data-combination approach to the analysis of precipitation. Global weather prediction models now provide products which are widely distributed. The combination of the numerical model data with satellite data and local observations, even if they are not as extensive as in Europe, will result in estimates of precipitation which are more reliable than using satellite data alone. This is one way of extending the use of existing ground-based weather radar installations such that their data benefit a much wider area than that defined by the limits of the radar coverage.

References

- Adler, R.F. and Negri, A.J., 1988: A satellite infrared technique to estimate tropical convective and stratiform rainfall. *J Appl Meteorol*, **27**, 30–51.
- Andersson, E., Gustafsson, N. Meuller, L. and Omstedt G., 1986: Development of meso-scale analysis schemes for nowcasting and very short-range forecasting. Norrköping, Swedish Meteorological and Hydrological Institute.
- Aschbacher, J., 1987: Combination of Meteosat and synoptic data to determine rainfall: a case study. *Meteorol Atmos Phys*, **37**, 212–218.
- Barrett, E.C. and Martin, D.W., 1981: The use of satellite data in rainfall monitoring. London, New York, Academic Press.
- Barrett, E.C., Kidd, C. and Bailey, J.O., (1988): The special sensor microwave images (SSM/I): a new instrument with rainfall monitoring potential. (To appear in *Int J Remote Sensing*.)
- Bellon, A. and Austin, G.L., 1986: On the relative accuracy of satellite and raingauge rainfall measurements over middle latitudes during daylight hours. *J Clim Appl Meteorol*, **25**, 1712–1724.
- Brown, R., 1987: The use of Meteosat data in the FRONTIERS nowcasting system. In Proceedings of the 6th Meteosat scientific users meeting, Amsterdam, 25–26 November 1986. Darmstadt, EUMETSAT.
- Collier, C.G., 1985: Remote sensing for hydrological forecasting. In Rodda, J.C. (ed); Facets of hydrology, volume II. Chichester, New York, John Wiley.
- Collier, C.G., Fair, C.A. and Newsome, D.H., 1988: International weather-radar networking in western Europe. *Bull Am Meteorol Soc*, **69**, 16–21.
- Collier, C.G., Szejwach, G. and Testud, J., (1988): Measurement of precipitation from space. To be published by European Space Agency.
- Doneaud, A.A., Miller, J.R. jun., Johnson, L.R., Vonder Haar, T.H. and Laybe, P., 1987: The area-time-integral technique to estimate convective rain volumes over areas applied to satellite data — a preliminary investigation. *J Clim Appl Meteorol*, **26**, 156–169.
- Follansbee, W.A. and Oliver, V.J., 1975: A comparison of infrared imagery and video pictures in the estimation of daily rainfall from satellite data. Washington DC, NOAA, Technical Memorandum No. NESS 62.
- Griffith, C.G., Woodley, W.L., Browner, S., Teijeiro, J., Maier, M., Martin, D.W., Stout, J. and Sikdar, D.N., 1976: Rainfall estimation from geosynchronous satellite imagery during the daylight hours. Boulder, Colorado, NOAA, Technical Report No. ERL 356-WMP07.
- Griffith, C.G., Woodley, W.L., Grube, P.G., Martin, D.W., Stout, J. and Sikdar, D.N., 1978: Rain estimation from geosynchronous satellite imagery — visible and infrared studies. *Mon Weather Rev*, **106**, 1153–1171.
- Gruber, A., 1973: Estimating rainfall in regions of active convection. *J Appl Meteorol*, **12**, 110–118.
- Heinemann, P.H., Martsof, J.D. and Gerber, J.F., 1987: Combination of manually digitized radar and GOES IR for real-time display of rainfall intensity. *J Clim Appl Meteorol*, **26**, 1046–1049.
- Johnstone, K.J., Hogg, W.D., Hanssen, A.J., Niitsoo, A. and Polavarapu, V.L., 1985: An evaluation of some satellite rainfall estimation techniques. In 6th Conference on hydrometeorology, Indianapolis 29 October–1 November 1985. Boston, American Meteorological Society.
- Liljas, E., 1982: Automated techniques for the analysis of satellite cloud imagery. In Browning, K.A. (ed); Nowcasting. London, New York, Academic Press.
- Lovejoy, S., 1981: Combining visible and infrared techniques with LAMMR for daily rainfall estimates. In Atlas, D. and Thiele, O.W. (eds); Workshop report on precipitation measurements from space. Greenbelt, Maryland, NASA — Goddard Space Flight Center.
- Lovejoy, S. and Austin, G.L., 1979a: The delineation of rain areas from visible and IR satellite data for GATE and mid-latitudes. *Atmos–Ocean*, **17**, 77–92.
- , 1979b: The sources of error in rain amount estimating schemes for GOES visible and IR satellite data. *Mon Weather Rev*, **107**, 1048–1054.
- , 1980: The estimation of rain from satellite-borne microwave radiometers. *Q J R Meteorol Soc*, **106**, 255–276.
- Martin, D.W. and Howland, M.R., 1986: Grid history: a geostationary satellite technique for estimating daily rainfall in the tropics. *J Clim Appl Meteorol*, **25**, 184–195.
- Motell, C.E. and Weare, B.C., 1987: Estimating tropical Pacific rainfall using digital satellite data. *J Clim Appl Meteorol*, **26**, 1436–1446.
- Negri, A.J. and Adler, R.F., 1981: Relation of satellite-based thunderstorm intensity to radar-estimated rainfall. *J Appl Meteorol*, **20**, 288–300.
- Negri, A.J., Adler, R.F. and Wetzel, P.J., 1984: Rain estimation from satellites: an examination of the Griffith–Woodley technique. *J Clim Appl Meteorol*, **23**, 102–116.
- Scofield, R.A., 1981: Analysis of rainfall from flash flood producing thunderstorms using GOES data. In Nowcasting: mesoscale observation and short-range prediction. Proceedings of an international symposium, 25–28 August 1981. Hamburg, European Space Agency, No. SP-165.
- , 1982: A satellite technique for estimating rainfall from flash flood producing thunderstorms. In Proceedings of the international symposium on hydrometeorology, Denver, Colorado, June 13–17 1982. Bethesda, American Water Resources Association.
- Scofield, R.A. and Oliver, V.J., 1977a: A scheme for estimating convective rainfall from satellite imagery. Washington DC, NOAA, Technical Memorandum No. NESS 86.
- , 1977b: Using satellite imagery to estimate rainfall from two types of convective systems. In 11th Technical conference on hurricanes and tropical meteorology, December 13–16 1977, Miami Beach. Boston, American Meteorological Society.

- Simpson, J., Adler, R.F. and North, G.R., 1988: A proposed Tropical Rainfall Measuring Mission (TRMM) satellite. *Bull Am Meteorol Soc*, **69**, 278–295.
- Spencer, R.W., Hinton, B.B. and Olson, W.S., 1983: Nimbus-7 37 GHz radiances correlated with radar rain rates over the Gulf of Mexico. *J Clim Appl Meteorol*, **22**, 2095–2099.
- Spencer, R.W., Goodman, H.M. and Hood, R.E., (1988): Precipitation retrieval over land and ocean with the SSM/I. Part I: Identification and characteristics of the scattering signal. (To appear in *J Atmos and Oceanic Technol*.)
- Stout, J.E., Martin, D.W. and Sikdar, D.N., 1979: Estimating GATE rainfall with geosynchronous satellite images. *Mon Weather Rev*, **107**, 585–598.
- Szejwach, G., Adler, R.F., Jobard, I. and Mack, R.A., 1986: A cloud model — radiative model combination for determining microwave T_B-rain rate relations. In Second conference on satellite meteorology/remote sensing and applications, Williamsburg, May 13–16 1986. Boston, American Meteorological Society.
- Tsonis, A.A. and Isaac, G.A., 1985: On a new approach for instantaneous rain area delineation in the midlatitudes using GOES data. *J Clim Appl Meteorol*, **24**, 1208–1218.
- Turpeinen, O.M., Abidi, A., and Belhouane, W., 1987: Determination of rainfall with the ESOC precipitation index. *Mon Weather Rev*, **115**, 2699–2706.
- Wilheit, T.T., Chang, A.T.C., King, J.L., Rodgers, E.B., Niemann, R.A., Krupp, B.M., Milman, A.S., Stratigos, J.S. and Siddalingaiah, H., 1982: Microwave radiometric observations near 19.35, 92 and 183 GHz of precipitation in tropical storm Cora. *J Appl Meteorol*, **21**, 1137–1145.
- Wilheit, T.T., Chang, A.T.C., Rao, M.S.V., Rodgers, E.B. and Theon, J.S., 1977: A satellite technique for quantitatively mapping rainfall rates over the oceans. *J Appl Meteorol*, **16**, 551–560.
- Wilheit, T.H., Theon, J., Shank, W. and Allison, L., 1973: Meteorological interpretation of the images from Nimbus-5 electrically scanned microwave radiometer. Greenbelt, Maryland, NASA — Goddard Space Flight Center.
- Wu, R., and Weinman, J.A., 1984: Microwave radiances from precipitating clouds containing aspherical ice, combined phase, and liquid hydrometeors. *J Geophys Res*, **89**, 7170–7178.
- Wu, R., Weinman, J.A. and Chin, R.T., 1985: Determination of rainfall rates from GOES satellite images by a pattern recognition technique. *J Atmos and Oceanic Technol*, **2**, 314–330.
- Wylie, D.P., 1979: An application of a geostationary satellite rain estimation technique to an extratropical area. *J Appl Meteorol*, **18**, 1640–1648.

551.515.8

An introductory review of fronts. Part II: A case-study

D.A. Bennetts, J.R. Grant and E. McCallum
Meteorological Office, Bracknell

Summary

This paper, on frontal meteorology, is one of a series of teaching papers on mesoscale meteorology developed at the Meteorological Office College. Part I described important dynamical aspects of both the formation and structure of frontal zones (Bennetts et al. 1988), and Part II illustrates the main features through a case-study of a cold front which crossed the United Kingdom on 13 January 1983.

In Part I simple conceptual models were developed. Here, in Part II, those models are discussed in more detail with the help of a case-study of a cold front. The paper is not intended to be a comprehensive review.

1. Introduction

Over the past decade there has been a considerable number of theoretical and observational studies into the formation and structure of frontal zones. Much of this work has followed directly from the new mesoscale observational techniques that were developed in the late 1960s and 1970s, and from modern computers that permit numerical modelling to take place on a similar spatial resolution to that of the observational data.

The paper has been divided into two parts. Part I (Bennetts *et al.* 1988) discussed how frontal zones form, what determines their overall structure and the nature of sub-frontal-scale perturbations. In Part II, a case study is presented to illustrate many of the conceptual models that were developed in Part I. The case study is of an active cold front that crossed the United Kingdom on 13 January 1983.

2. The case-study

The synoptic situation used to illustrate the concepts developed in Part I (Bennetts *et al.* 1988) occurred on 13 January 1983. An active cold front moved south-eastwards across England and Wales during the early hours of the morning. The surface analysis for 0000 GMT is shown in Fig. 1. A small wave depression running north-eastwards along the front had delayed the movement of the front south-eastwards late on the 12th but by 0000 GMT on the 13th the wave had moved away into the North Sea.

Fig. 2 is a satellite photograph which shows the position of the frontal cloud at 0317 GMT (by which time the front was over central England), and shower clouds to the west of the United Kingdom which are associated with the cold upper trough. The frontal passage was marked by a very sharp wind veer (typically

120°), a large pressure kick and a substantial drop in temperature (about 8°C in 15 minutes). The frontal passage was also accompanied by a short, sharp burst of heavy rain (cold-frontal squall line). This is evident in the radar data (Fig. 3) where it appears as a series of small line elements.

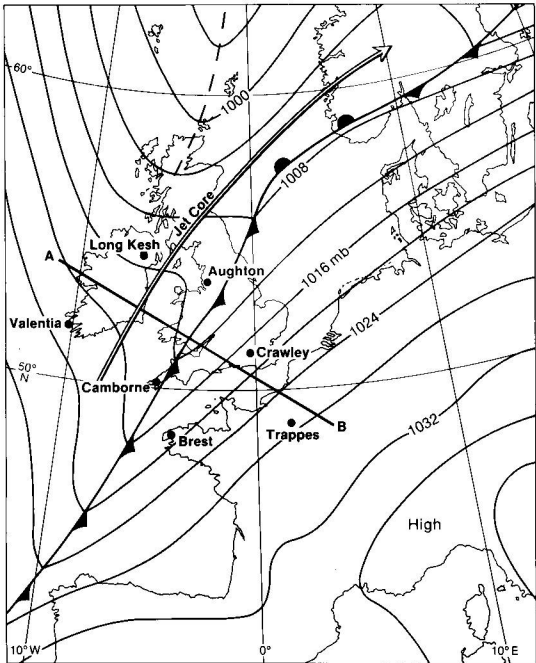


Figure 1. Surface analysis for 0000 GMT on 13 January 1983 showing the surface position of the cold front, the associated jet stream, and the line of the cross-section AB. The upper-air stations referred to later in the text are also shown.

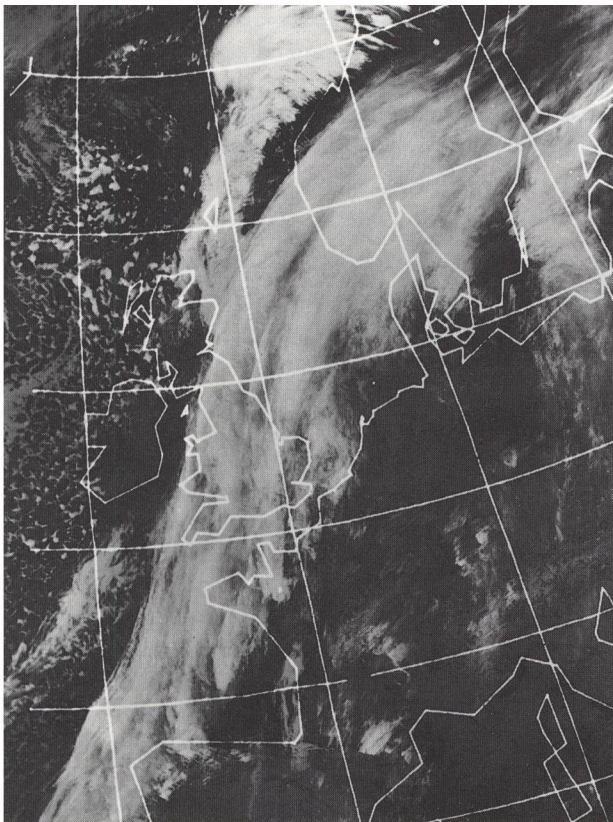


Figure 2. Satellite photograph taken at 0317 GMT on 13 January 1983. Photograph by courtesy of University of Dundee.

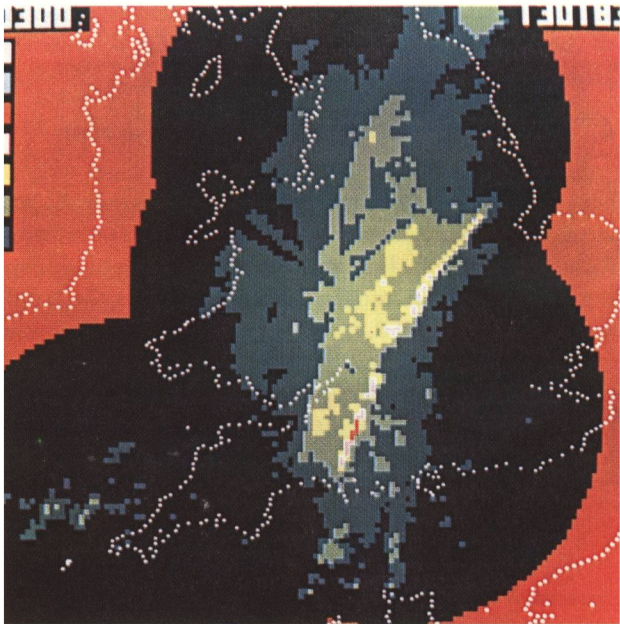


Figure 3. Radar network picture for 0300 GMT on 13 January 1983 showing rates of rainfall. Within the network area, areas of white, pink, red and light blue indicate heavy rain, yellow and green indicate moderate rain and dark blue indicates light rain.

3. General structure of the frontal zone

A cross-section along a line perpendicular to the cold front (300°–120°) was constructed using the 0000 GMT 13 January radiosonde ascents from Valentia, Long Kesh, Aughton, Camborne, Brest, Crawley and Trappes. The position of this cross-section relative to the front is shown by the line AB in Fig. 1. At this time the front was moving at 9 m s^{−1} along the line AB, which is taken to be the x-axis. The data are presented in the following diagrams — Fig. 4, wind component perpendicular and relative to the cold front, Fig. 5, wind component parallel to the cold front, and Fig. 6, cross-section of wet-bulb potential temperature and absolute momentum (*M*) surfaces. A general description of the main features will be given, followed by a comparison with the conceptual models developed in Part I.

In Fig. 6 the cold-frontal zone is delineated by the 4–7 °C θ_w surfaces (on the left of the diagram) and for convenience these surfaces are also outlined on Figs 4 and 5. Note the sharp nose to the frontal surface close to the ground. Also evident, bottom centre of Fig. 6, is a closed 10 °C θ_w contour which is nearly coincident with a velocity maximum of 28 m s^{−1} in Fig. 5. These two features identify a low-level jet (the conveyor belt) and, to help identification, the 10 °C θ_w contour is superimposed on Fig. 5.

In the top left-hand corner of Fig. 5 the upper-level jet stream, with a measured maximum speed of 59 m s^{−1}, can be readily identified. Note also that well ahead of the front, near the ground, bottom right of Fig. 4, the air is moving towards the front at 10 m s^{−1}. Although this looks rather unusual it will be recalled that the motion is relative to the frontal surface which is moving at 9 m s^{−1}. In fact, this air is moving at 1 m s^{−1} relative to the ground. In contrast, the air within the boundary layer

some 100 km ahead of the front has a speed close to that of the front, and is moving at some $5\text{--}8\text{ m s}^{-1}$ over the ground.

4. Air motion within the frontal zone

Since ascending air within the frontal zone will, in general, be saturated, i.e. the air will conserve θ_w , the streamlines in the cross-frontal direction can be inferred from Figs 4 and 6. Just ahead of the surface cold front the low-level air is moving rapidly towards the front, and hence (constant θ_w) must rise up over the nose of the front. Note that to achieve this rapid acceleration of the air near the front requires there to be a nearby ‘source’, such as would be provided by the ‘rearward sloping

ascent’ model, Fig. 7(a) (copied from Part I, Fig. 6(a)), in which some of the air from the warm conveyor belt leaks up over the cold front.

Behind the cold front the air also moves towards the front, except within the boundary layer. Such motion is consistent with the ideas shown in the conceptual model, Fig. 7(b) (copied from Part I, Fig. 7).

Turning now to some of the details of the conceptual models. In section 5 of Part I, a link was established between the difference in speed of the jet core just ahead of the cold front (see Fig. 5) from that of the surrounding air, and the scale over which the jet decayed on the warm (in Fig. 5, the right hand) side. The approach assumed that the low-level jet was in thermal

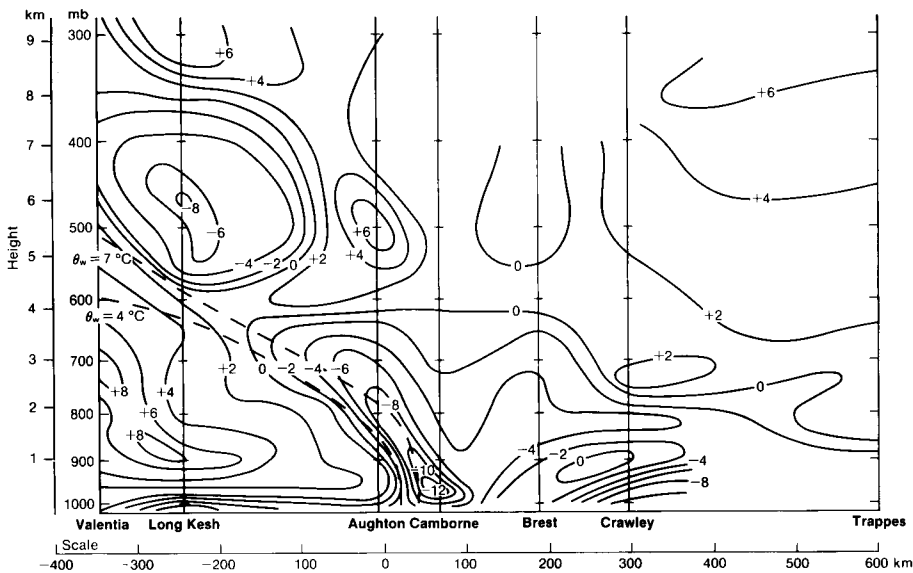


Figure 4. Cross-section along the line AB in Fig. 1 at 0000 GMT on 13 January 1983 showing the wind component in m s^{-1} perpendicular and relative to the front (which was moving west to east at 9 m s^{-1}). Positive values depict winds blowing west to east. The isotach labelled -12 m s^{-1} at 970 mb above Camborne indicates low-level air moving rapidly towards the front, as discussed in the text. The frontal zone is outlined by the θ_w values of 4 and 7°C . Radiosonde ascents are indicated by the vertical lines.

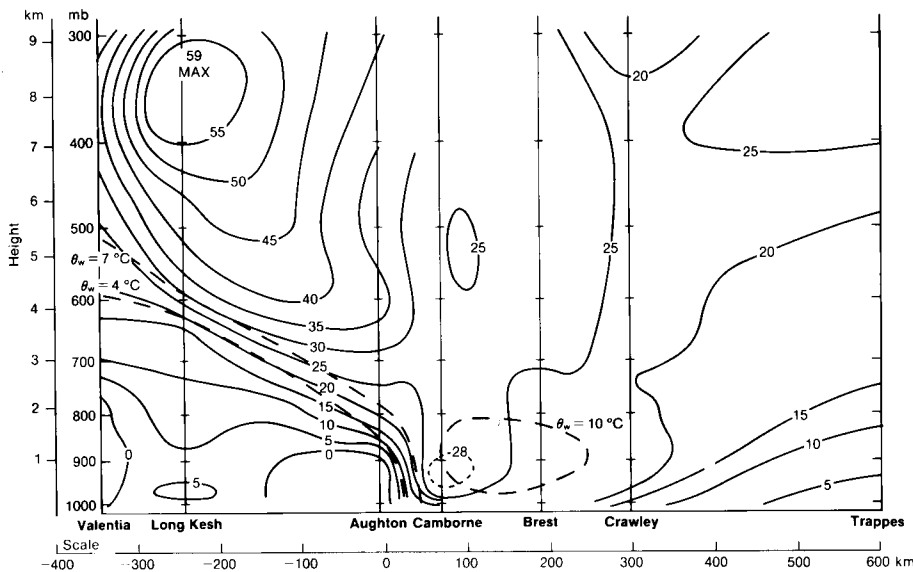


Figure 5. Cross-section along the line AB in Fig. 1 at 0000 GMT on 13 January 1983 showing the wind component in m s^{-1} parallel to the front. Positive values are winds blowing from the south-west, and into the paper. The upper-level jet appears above Long Kesh and the low-level jet is evident over Camborne. The frontal zone is outlined by the 4 and 7°C θ_w values and the warm conveyor belt picked out by the 10°C θ_w isotherm.

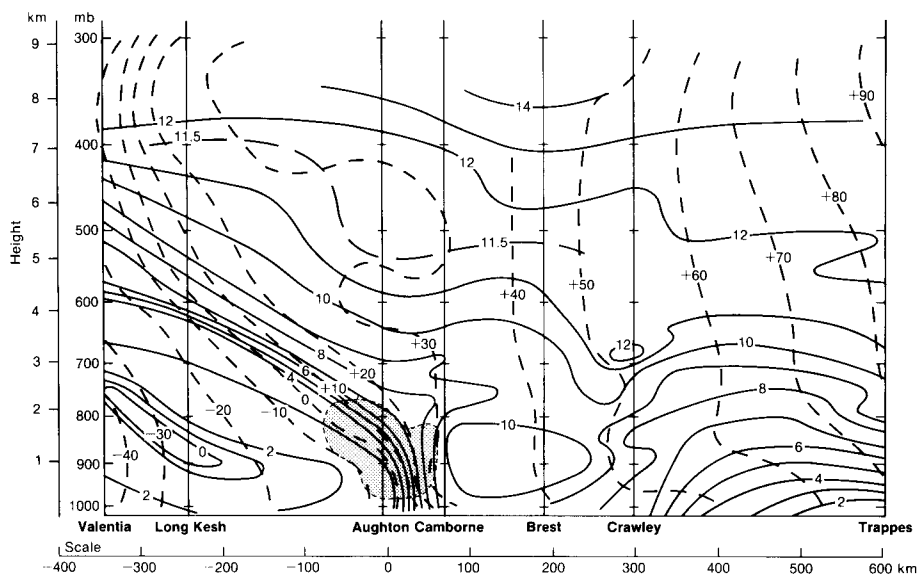


Figure 6. Cross-section along the line AB in Fig. 1 at 0000 GMT on 13 January 1983 showing θ_w surfaces (solid lines) ($^{\circ}\text{C}$) and M surfaces (m s^{-1} — dashed lines). The stippled region within the frontal zone marks the area in which θ_w and M surfaces are parallel, and hence (see text) the area in which Conditional Symmetric Instabilities may be expected to develop.

wind balance. The validity of that assumption can now be investigated. Thermal wind balance is defined by the following equation (see Part I, section 2, equation (6));

$$\frac{\delta v}{\delta z} = \frac{g}{f\theta_0} \frac{\delta\theta}{\delta x}$$

where $g=10 \text{ m s}^{-2}$, $f=10^{-4} \text{ s}^{-1}$, $\theta_0=280 \text{ K}$ and the constant $g/(f\theta_0)$ has an approximate value of $300 \text{ m s}^{-1} \text{ K}^{-1}$. Although fields of potential temperature (θ) have not been shown in the paper, the data showed that θ changed by 7 K over a distance of 80 km in the vicinity of the jet. This calculation may be roughly checked by noting that, at a given level, $\delta\theta/\delta x$ is very nearly equal to $\delta\theta_w/\delta x$, and then referring to Fig. 6.

Fig. 5 shows the height of the jet to be about 1000 m and therefore the thermal wind equation predicts the jet-core speed to be

$$\delta z \times 300 \times 7/(8 \times 10^4) \approx 26 \text{ m s}^{-1}.$$

This is to be compared with an observed value of 28 m s^{-1} . The jet would appear to be in near-thermal-wind balance.

Return now to the relationship between the jet-core excess speed and the scale of the jet. In this case the jet core is some $3\text{--}5 \text{ m s}^{-1}$ faster than the surrounding air and therefore the minimum distance over which the jet can decay is $30\text{--}50 \text{ km}$. This is in fair agreement with the scale found in Fig. 5, although the distance between the radiosonde ascents makes an accurate comparison impossible.

Overall, the case-study illustrates many of the features that were discussed in Part I namely:

- (a) The ageostrophic cross-frontal circulation, modified by frictional effects (Fig. 7(b)).
- (b) The presence of the warm conveyor belt (Fig. 7(a)).
- (c) The presence of a low-level jet.
- (d) The conceptual model in which warm air from the conveyor belt leaks up over the cold front (Fig. 7(a)).

- (e) Thermal wind balance within the low-level jet.
- (f) The asymmetry in the structure of the low-level jet.

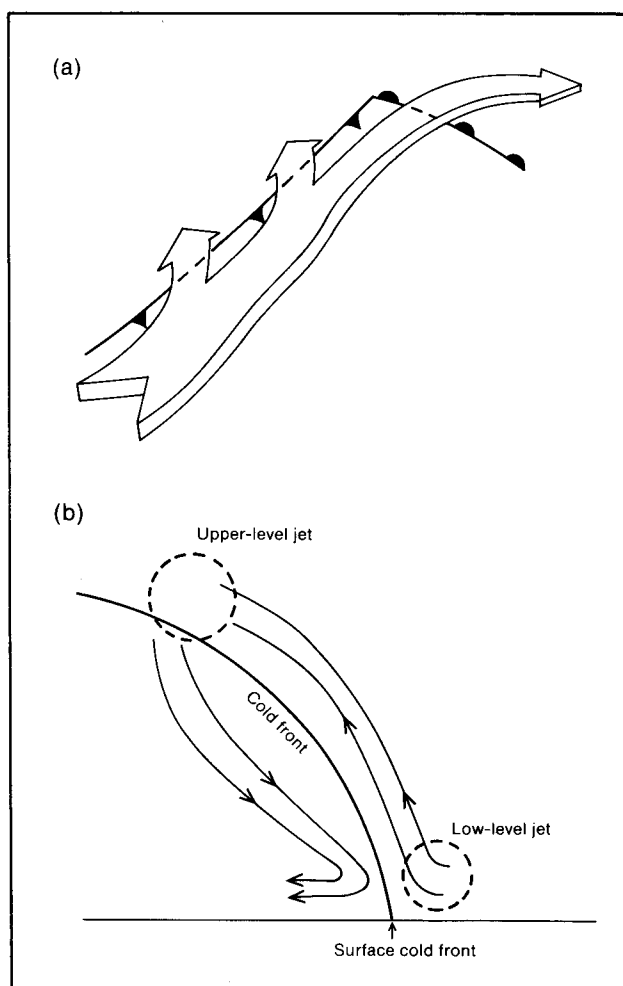


Figure 7. (a) The motion within the warm conveyor belt relative to the surface fronts (Fig. 6(a) of Part I). Depicted is the model showing rearward sloping ascent, and (b) cross-frontal ageostrophic motion when the effects of turbulent diffusion are included (Fig. 7 of Part I).

5. Absolute momentum surfaces

In section 6 of Part I the concept of absolute momentum (M) and its conservative nature within a frontal zone was introduced. In the present case-study, these surfaces are shown superimposed onto the wet-bulb potential temperature (θ_w) surfaces, Fig. 6. There is an arbitrary constant of integration in the calculation of the M surfaces and this has been chosen so that the M surface which is coincident with the surface cold front has a zero value.

Below about 700 mb, within the frontal zone (–100 to 0 km on the x -axis), the M and θ_w surfaces are nearly parallel (stippled region in Fig. 6). Thus a parcel of saturated air moving up the frontal surface would apparently have little difficulty in conserving both quantities. Further up the frontal zone, and away from the frontal zone, the two surfaces do cross. The zone well away from the front can be immediately dismissed since, in that region, there is no requirement for M to be conserved — see Part I, section 6. The two regions of interest, the stippled area and the area in the top left-hand corner of Fig. 6, require separate analysis.

The stippled region is the most difficult to analyse. It will be recalled from Part I, section 6 that whenever θ_w surfaces are steeper than M surfaces, energy is released spontaneously. Therefore whenever such a situation occurs, energy is transferred from the larger scale to the smaller scale instabilities, thereby restoring the atmosphere to a neutral state in which M and θ_w surfaces are again parallel. In consequence, regions in which θ_w surfaces are (to a significant degree) steeper than M surfaces are unlikely to occur, and will be exceptionally difficult to detect by anything other than the most thorough analysis. The implication therefore is that regions such as that stippled in Fig. 6, where M and θ_w surfaces are approximately parallel, are likely to contain

Conditional Symmetric Instabilities (CSIs); either that or instabilities are about to develop.

Evidence of such instabilities should be sought in the rainfall patterns, and indeed Fig. 3 does exhibit irregularities, of the expected scale, in the appropriate region, between the surface front and Aughton.

The second region of interest, where M and θ_w surfaces cross, is in the upper part of the frontal surface (–100 to –400 km on the x -axis in Fig. 6). Here, however, M surfaces are steeper than θ_w surfaces and therefore (as shown in Fig. 10 of Part I) this is a region which is stable to CSIs. In partial confirmation of this, Fig. 3 shows a reasonably uniform area of rain to the western edge of the precipitation zone, although this cannot be taken as conclusive proof due to the poor resolution (because of the range and consequent height of the radar beam) of the data and the generally light precipitation in that area.

Thus, while the case-study does not prove the theory for rainband formation, it does exhibit many of the features that one would expect to find associated with CSIs. The analysis also illustrates that M surfaces can be drawn using synoptic-scale data, at least to an accuracy adequate for the identification of areas likely to exhibit sub-frontal-scale instabilities, and hence rainbands.

Acknowledgements

We would like to thank all the staff and students at the Meteorological Office College who have helped in the development of this work. We are also grateful to Dr R.W. Riddaway for the advice that he has given us during the writing of the paper.

Reference

- Bennetts, D.A., Grant, J.R. and McCallum, E., 1988: An introductory review of fronts. Part I: Theory and observations. *Meteorol Mag.*, **117**, 357–370.

Direct use of satellite sounding radiances in numerical weather prediction

J.R. Eyre

Meteorological Office Unit, Hooke Institute, Oxford

A.C. Lorenc

Meteorological Office, Bracknell

Summary

Recent research on satellite sounding data and numerical analysis techniques has explored new ways of using the satellite data within numerical weather prediction (NWP) systems. It is now expected that greater benefit could be derived from these data if they were assimilated more directly into the NWP fields, rather than via independently retrieved profiles of temperature and humidity. The theory behind the new approach is outlined, and some aspects of the implementation of these ideas at the Meteorological Office are described.

1. Introduction

Atmospheric sounding radiometers on meteorological satellites do not measure temperature and humidity profiles; they measure the thermal radiation emitted to space at a number of spectral intervals, and these radiances may be used to derive profile information. At first sight this may seem to be a purely semantic point, but in fact it is an important distinction which must be understood if satellite soundings are to be used in numerical weather prediction (NWP) in an optimal manner.

Until recently satellite products have been used in NWP as though they were direct measurements of atmospheric profiles. The historical reason for this is clear, NWP analysis schemes have been designed and tuned to make full use of radiosonde data, and when satellite soundings first arrived they could be used most easily if they were processed to resemble radiosonde profiles. Indeed it is interesting to speculate how analysis methods would have developed if satellites had come first and radiosondes had been invented later. The characteristics of these two sources of information on atmospheric thermal structure are very different. Radiosonde data have high resolution in the vertical, but in the horizontal the observing system is absent over much of the world and, at its best, of lower resolution than current NWP models. Satellite sounders provide global coverage at high horizontal resolution, but their information concerning vertical structure is comparatively small because of the width of the weighting functions (see, for example, Smith *et al.* 1979, Eyre and Jerrett 1982). These characteristics should be recognized when trying to make the best use of the data.

The 'retrieval' or 'inversion' process, whereby satellite radiances are converted to atmospheric profiles, has some rather subtle properties and error characteristics (Eyre 1987). The problem is mathematically ill-posed —

an infinite number of profiles are consistent with the radiance measurements, and additional constraints are required to choose between the possible profiles. This means that the retrieved profile will contain both observed information (from the radiances) and unobserved information imposed by the constraints. This leads to errors in the retrievals which are correlated in both the vertical and horizontal, and these characteristics have made the data difficult to use effectively in conventional NWP analysis schemes.

In addition to problems associated with the characteristics of satellite data, we must also be aware of the quality they must attain to be useful in NWP. In the European and North Atlantic areas, typical errors in a NWP background field (i.e. 6- or 12-hour forecast) of tropospheric temperature are about 2 K. Moreover, forecast errors are quite weakly correlated in the vertical, and satellite sounders' weighting functions are broad. When we put this information together quantitatively, we find that a typical forecast error translates into a much lower error in satellite-measured brightness temperature (equivalent black-body temperature) — about 1 K for a tropospheric temperature sounding channel. In other words, before the satellite passes over an area we know what it is going to measure to an accuracy of about 1 K. Hence, for the satellite measurements to be useful in NWP their errors must be very low, and this applies not only to the instrumental errors but also to the errors associated with the operations of calibration, processing and interpretation. Therefore it can be seen that the requirements of modern NWP models place very high demands on all aspects of the measurement and processing of the satellite data. This is certainly true for current sounding data from the TIROS Operational Vertical Sounder (TOVS) on the NOAA satellites (see Smith *et al.* 1979), but it will be

equally true for the Advanced TOVS (ATOVS) instruments to be flown on the next generation of polar-orbiting satellites from about 1993 (Pick 1986). ATOVS will improve considerably over TOVS in terms of horizontal resolution, performance in cloudy conditions, sensitivity to humidity, cloud, precipitation, and other aspects. However, it will not improve significantly on vertical resolution in the troposphere, and the requirements for careful attention to all aspects of the data processing and interpretation will remain.

Conventional methods for using satellite data — through schemes for converting radiances to profile information, completely separate from NWP systems into which the profiles are to be assimilated — are being re-examined in the light of the problems discussed above. Attention is now focusing on how some of the problems may be removed or minimized if the radiance information is used more directly within the NWP system. The ideas involved are not specific to satellite data and may be applied to many types of ‘indirect’ observation, i.e. measurements of quantities not represented in the NWP models but related to those represented in some physical manner which is well understood (see Lorenc 1986). A useful analogy here concerns the use of wind observations in analysing the thermal field; in extra-tropical latitudes winds are indirect observations of the thermal field because they are related through geostrophic considerations. Similarly, measurements of radiance may be used when analysing the temperature field because the two are linked through the radiative transfer equation.

In the remainder of this paper, the theory underlying the direct use of radiances will be outlined and some practical aspects of the implementation of such a scheme discussed.

2. Theoretical considerations

The purpose of data assimilation in NWP is to find the best analysis of the atmospheric state for the subsequent forecast. It involves seeking the state which gives the best fit to the available observations and background information (to within their expected errors) and applying appropriate additional constraints concerned with dynamical or physical processes. Many analysis schemes may be considered conceptually as minimizing some ‘cost’ or ‘penalty’ function which measures the departure of the analysed state from the observations, the background and other information (see Lorenc 1986). For example, the cost function $J(\mathbf{x})$ for the NWP analysis field \mathbf{x} could be represented as:

$$J(\mathbf{x}) = (\mathbf{x} - \mathbf{x}_b)^T \cdot \mathbf{B}^{-1} \cdot (\mathbf{x} - \mathbf{x}_b) + (\mathbf{y}\{\mathbf{x}\} - \mathbf{y}_o)^T \cdot (\mathbf{O} + \mathbf{F})^{-1} \cdot (\mathbf{y}\{\mathbf{x}\} - \mathbf{y}_o) + \text{other terms}, \quad (1)$$

where \mathbf{x}_b is the background field, \mathbf{B} is its expected error covariance, \mathbf{y}_o is the vector of observations, \mathbf{O} is their expected error covariance, $\mathbf{y}\{\mathbf{x}\}$ is the ‘forward model’, an operator for interpolating from the model state \mathbf{x} to

the observation points, and \mathbf{F} is the expected error covariance of the forward model.

The ‘best’ analysis is that which minimizes $J(\mathbf{x})$ in equation (1). The first term in this equation represents the closeness of fit of the analysis to the background field, the second term the fit to the observations, and ‘other terms’ any additional penalties from other dynamical or physical constraints. Here we are mainly concerned with the second term and in particular how it can represent satellite sounding observations.

There are of course many different analysis schemes but the differences between most of those used in practice in NWP may be shown to be different ways of approximating the solution to minimize equation (1). For example, if we ignore ‘other terms’, assume \mathbf{B} , \mathbf{O} and \mathbf{F} to be constant and the observations \mathbf{y}_o to be linearly related to the model state \mathbf{x} , then the minimum value of $J(\mathbf{x})$ occurs when

$$\mathbf{x} = \mathbf{x}_b + \mathbf{B} \cdot \mathbf{K}^T \cdot (\mathbf{K} \cdot \mathbf{B} \cdot \mathbf{K}^T + \mathbf{O} + \mathbf{F})^{-1} \cdot (\mathbf{y}_o - \mathbf{y}\{\mathbf{x}_b\}), \quad (2)$$

where $\mathbf{K} = d\mathbf{y}\{\mathbf{x}\}/d\mathbf{x}$. This is familiar to NWP analysts as one form of the optimum interpolation equation. If \mathbf{y}_o is taken to be a vector of satellite radiances, it is also familiar in the satellite sounding field as the minimum variance retrieval equation (Rodgers 1976). This illustrates that NWP analysis and satellite sounding inversion are similar mathematical problems and suggests that, in the context of NWP, we might consider them as one combined problem.

Returning to the second term of equation (1), if the observations are direct (i.e. of the same variable as represented by the NWP model) then the operator $\mathbf{y}\{\dots\}$ may be relatively simple, just representing an interpolation in time and space to the observation point. If the observations are indirect, then the operator $\mathbf{y}\{\dots\}$ is more complicated. In the case of satellite radiances it includes a radiative transfer calculation to find the radiances $\mathbf{y}\{\mathbf{x}\}$ which would be measured from an atmospheric state \mathbf{x} . In this case \mathbf{O} represents the errors in the measured radiances and \mathbf{F} the forward model error which includes expected error in the radiative transfer calculation. If, on the other hand, the radiances are first converted by a separate system to retrieved profiles, then these may be used as observations \mathbf{y}_o . This considerably simplifies the ‘forward model’ but leads to very complicated observational errors. They have strong correlations in the vertical and horizontal and also bias properties which are very difficult to handle. It is primarily the difficulty in representing correctly the true characteristics of satellite retrieval errors which inhibits their proper exploitation in NWP. Previously, satellite retrievals have been derived with too little attention as to how they will be used in NWP, and they have been applied without sufficient consideration of their true information content.

The radiances themselves have error characteristics which are easier to represent within the analysis formalism than those of retrieved profiles. Radiance

measurements and calculations may contain significant biases which must be carefully monitored and allowed for, but this is a relatively straightforward problem and is comparable to that of dealing with the bias characteristics of radiosonde data. When analysing directly from radiances, the need for an 'inversion' or 'retrieval' operation is not removed but is transferred into the data assimilation system where, in principle, it may be handled better. In this way we can expect to improve the exploitation of the many strengths of satellite sounding data while making proper allowance for their weaknesses.

3. Implementation

In the theory presented above, if x represents the full three-dimensional NWP model state in all its variables, then the computation and minimization of the cost function represents a huge numerical problem. In future it may be practicable to attempt it, but at present certain approximations are necessary. The approach adopted in the scheme recently developed for operational use in the Meteorological Office (Lorenc *et al.* 1988) involves several, including splitting the vertical and horizontal aspects of the analysis: for each datum, a 'vertical analysis' first spreads the information at the observation's own horizontal location on to the vertical levels of the NWP model, then, at each level, the information is analysed to the model grid-points. This strategy is adopted for all data types, and for satellite sounding data it takes the following form. At each sounding location, first calculate the difference between the measured radiances and those calculated from the NWP model's background field (interpolated to the sounding location); then use these radiance increments to calculate increments to the model's temperature and humidity field at all levels. If the radiances (or brightness temperatures) are linearly related to the model parameters, then equation (2) gives the solution to this vertical analysis problem. In other words, it is the same as a conventional retrieval with the model background profile and its expected error covariance as constraints (rather than some climatological information or historical 'library' of profiles, as in many retrieval schemes). In the subsequent horizontal analysis, allowance should be made for the fact that the vertical analysis for each sounding has used the background information and will therefore contain errors which are correlated with the background and hence also with vertical analyses for adjacent soundings. A strategy for doing this has been proposed by Lorenc *et al.* (1986).

The Meteorological Office's Local Area Sounding System (LASS) for receiving and processing TOVS data from the European and North Atlantic areas has been described by Turner *et al.* (1985). In 1987 the retrieval stage was changed to use forecast information and thus resembles the 'vertical analysis' described above. Although this processing is still performed separately from the main NWP system, it is now done in such a way that it is mathematically equivalent to the direct assimilation of

radiance data (provided that the retrieved profiles are subsequently assimilated in a compatible manner). Direct use of radiance data and 'forecast-background' retrievals may be thought of as the same theoretical approach; the difference between them is mainly a logistical one concerning whether the satellite data processing is completely integrated with the NWP system or (as at present) physically separated from it. In either case, the basic elements of the data processing involved are the same.

The process of assimilating radiance information is illustrated in Fig. 1. At the top we have measured radiances, calibrated and perhaps pre-processed in certain ways. At the bottom the NWP suite is represented by a continuous cycle of data assimilation and forecast processes. To assimilate radiance information, the background field is interpolated to the location of the radiance data and converted into radiances through an appropriate radiative transfer (or ‘forward’) calculation. These are compared with the measured radiances and the radiance increments converted back into the increments to variables of the NWP model through an ‘inverse’ operation and then interpolated to model grid-points. At present only the processes in the smaller dashed box are performed within the NWP data assimilation and the rest externally by LASS. In future it may be preferable, for reasons of computational economy and theoretical consistency, to perform all the operations in the larger

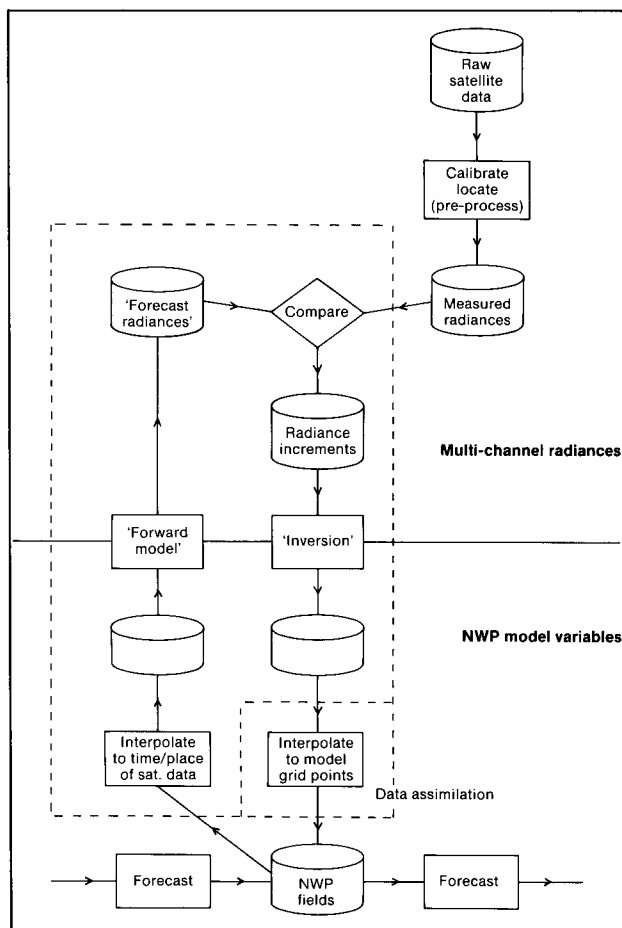


Figure 1. Illustration of the direct assimilation of radiances.

dashed box within the NWP suite. The NWP suite will then directly assimilate radiances physically as well as conceptually.

The present LASS performs an inversion based on equation (2) to convert cloud-cleared brightness temperatures to temperature and relative-humidity profiles, and it makes the assumption that they are linearly related. This is quite a reasonable assumption for the temperature inversion problem but not really satisfactory for humidity. It would be preferable to represent correctly the non-linear relations between observed radiances and atmospheric parameters. In the pre-processing stage of the present LASS scheme, the conversion of raw radiances to cloud-cleared brightness temperatures involves assumptions about the atmospheric profile and the cloud characteristics. The assumptions are inappropriate in some situations, causing errors and biases in the retrieved profiles. Knowledge of the atmospheric structure and clouds, from improved satellite instruments and forecast models, is improving, and so it may be advantageous to transfer the pre-processing step into the inversion problem. If we wish to invert the raw, potentially cloud-affected radiances, the problem becomes highly non-linear and we are forced to address it as such. Research is in progress on these aspects of the problem (Eyre 1989, Lorenc 1988).

4. Conclusions

It is now recognized that we should be seeking to use satellite radiances to give the best NWP analyses and subsequent forecasts, not to produce good retrievals for their own sake. This change of emphasis has led to increased activity on more direct ways to use radiance information in NWP.

The Meteorological Office is already processing TOVS data using a scheme involving forecast information which may be thought of conceptually as a direct

assimilation of radiance information. Future developments are likely to address the closer physical integration between the satellite data processing and NWP suites, to improve the treatment of non-linear aspects of the problem and to explore the advantages of extending the current vertical (one-dimensional) analysis of radiances to a fully three- or four-dimensional approach to data assimilation. In these ways we hope to move from a situation whereby satellite soundings are treated as 'poor-quality radiosondes' to one in which they are exploited according to their true information content.

References

- Eyre, J.R., 1987: On systematic errors in satellite sounding products and their climatological mean values. *Q J R Meteorol Soc*, **113**, 279–292.
- , (1989): Inversion of cloudy satellite sounding radiances by nonlinear optimal estimation; theory and simulation for TOVS. (Submitted to *Q J R Meteorol Soc*.)
- Eyre, J.R. and Jerrett, D., 1982: Local-area atmospheric sounding from satellites. *Weather*, **37**, 314–322.
- Lorenc, A.C., 1986: Analysis methods for numerical weather prediction. *Q J R Meteorol Soc*, **112**, 1177–1194.
- , 1988: Optimal nonlinear objective analysis. *Q J R Meteorol Soc*, **114**, 205–240.
- Lorenc, A.C., Adams, W. and Eyre, J.R., 1986: The analysis of high resolution satellite data in the Meteorological Office. In Proceedings of the workshop on high resolution analysis, Reading, 24–26 June 1985. Reading, ECMWF.
- Lorenc, A.C., Bell, R.S., and MacPherson, B., 1988: Developments in data assimilation at the UK Meteorological Office. In 8th Conference on numerical weather prediction, Baltimore, 22–26 February 1988. Boston, American Meteorological Society.
- Pick, D.R., 1986: Operational sounding of the lower atmosphere using millimeter waves. In Proceedings of the 16th European microwave conference, Dublin.
- Rodgers, C.D., 1976: Retrieval of atmospheric temperature and composition from remote measurement of thermal radiation. *Rev Geophys Space Phys*, **14**, 609–624.
- Smith, W.L., Woolf, H.M., Hayden, C.M., Wark D.Q. and McMillin, L.M., 1979: The TIROS-N operational vertical sounder. *Bull Am Meteorol Soc*, **60**, 1177–1187.
- Turner, J., Eyre, J.R., Jerrett, D. and McCallum, E., 1985: The HERMES system. *Meteorol Mag*, **114**, 161–173.

551.593.653(4):551.506.1

Noctilucent clouds over western Europe during 1987

D.M. Gavine

29 Coillesdene Crescent, Edinburgh EH15 2JJ

Summary

The sightings of noctilucent cloud reported to the Aurora Section of the British Astronomical Association during 1987 are presented.

Table I summarizes the noctilucent cloud (NLC) reported to the Aurora Section of the British Astronomical Association during 1987. The times (UT) are of reported sightings, not necessarily the duration of a display.

'Negative' nights (Table II) are now based on the judgement of two or more experienced observers north of 54°N with clear or nearly clear sky conditions over the period of the night when NLC is likely to occur.

Despite a great deal of tropospheric cloud and bad weather over Britain and western Europe at the height of the NLC 'season', the large number of positive sightings on clear or partly clear nights suggests another year of high incidence of the phenomenon. Reports were received from 31 amateur observers widely distributed throughout Britain, 4 in Denmark and 1 in the Netherlands, 11 British meteorological stations including the weather ship *Cumulus* at *Lima* (57° N, 20° W) and 4 stations of the Royal Netherlands Meteorological Institute. The excellent Danish group co-ordinated from Bornholm by Mr Olesen has again submitted panoramic photographs and reports of a very high standard. Positive observations by the Finnish astronomers and of the observers in Alberta, Canada, are briefly listed in Table III. The former publish summaries in the periodical *Ursa Minor* of the URSA Astronomical Association (Laivanvarustajankatu 3, SF-00140, Helsinki 14). The 8 positive sightings from Canada are remarkable in that no less than 4 were coincident with aurora. As from the summer of 1988 an amateur North

American NLC network will be operational and publishing data. Mr Mark Zalcik (# 2, 14225 82 Street, Edmonton, Alberta T5E 2V7) has kindly agreed to act as co-ordinator, and will be pleased to receive observations. Summaries will be exchanged between the networks.

Details of individual displays, and instructions for the observation of NLC, may be obtained from the author. All data are ultimately transferred to the Balfour Stewart Archive in the University of Aberdeen.

The author thanks all amateur and professional observers for their work, particularly Mr David Frydman who regularly puts in all-night watches from Helsinki and Wembley, near London, and supplies excellent photographs; also Dr M. Gadsden (Aberdeen), Mr R. Livesey (Director, BAA Aurora Section), Mr N. Bone (Director, Junior Astronomical Society, Aurora Section), Dr B. Zwart (Netherlands), Mr V. Mäkelä (Finland), Mr M. Zalcik and Mr J.Ø. Olesen, for useful advice and contributions.

Table I. Displays of noctilucent clouds over western Europe during 1987

Date — night of	Times UT	Notes	Date — night of	Times UT	Notes
20/21 May	0010	NLC suspected very low in sky at Swansea.	28/29 June	2315–0305	Bright billows at <i>Lima</i> , faint veil and bands at Wick, St. Andrews and Stirling.
30/31	2130–2145	NLC suspected at elev. 40° at Bracknell.	29/30	0048	NLC trace suspected overhead at Kirkwall but no NLC in clear sky at Edinburgh and Morpeth.
9/10 June	0120–0125	Faint NLC at Maastricht, elev. 4°.	1/2 July	2200–0307	Moderately bright veil, bands and billows observed at 14 stations as far S as Essex and Swansea. Photographed at Tayport but most of Scotland clouded over. Max. elevs 30° Tayport 0145, 21° Morpeth 2230, 35° Todmorden 0245, 10° Marham 0045.
11/12	0000–0330	Extensive but rather faint, all forms, observed over S. England, Wales and N. Ireland. Maximum elev. 65° at Witham, Essex, 0200; 60° at Basingstoke 0240.	2/3	2145–0240	NLC at 3 Netherlands stations. Bright bands and whirls at Kølvrå and Vildbjerg, Denmark, max. elev. 18° at 2325.
12/13	2245–0115	Faint bands then veil and billows at Morpeth, max. elev. 13° at 0115.	4/5	2230–0244	Faint NLC in cloud gaps at Edinburgh 2230–2330. Veil, bands and billows seen by two London observers 0155–0244, elev. 16°, photographed by Mr Frydman.
15/16	2200–2320	NLC patches in tropospheric cloud gaps at Morpeth and Castleford, Yorks.	5/6	0100–0215	Faint bands at Morpeth, elev. 7°, faint NLC at Stirling, visible only with binoculars.
16/17	2300–0220	Thin veil over ¾ of sky at Wick. Faint horizontal bands visible as far south as Yorkshire, best seen at Dumbarton.	6/7	2205–2220	Faint patches at Castleford, faint bands at Wisbech.
17/18	2245–0230	Moderately bright and extensive display, all forms, described mainly as radiating bands from N horizon. Observed at 15 stations as far S as Bedford, and in N. Ireland. Max. elev. 50° at Morpeth 0200.	7/8	2255–0200	Faint bands and billows in Scotland, max. elev. 80° at Sumburgh 0200.
18/19	2300–0100	Faint veil and patchy bands, N. Ireland, Dundee (elev. 20°), Edinburgh.	9/10	2335–0135	NLC in tropospheric cloud at Kirkwall 2335. Bands to elev. 6° at Eerbeek, Netherlands. Bands, billows and whirls from 0055 at Vildbjerg and Rønne, elev. 38° at Vildbjerg, 0135.
19/20	2330–0215	Moderately bright veil and bands, N. Ireland and Isle of Man. Photographed by Mr McConnell at Lincoln (elev. 9°). Faint band at Rønne, Denmark.	10/11	0210–0230	Bright billows at Maastricht, elev. 8°.
22/23	2245–0150	Faint bands at Todmorden 2245, bands in S. Midlands from 0140, elev. 10° at Bedford.	11/12	0130–0215	Faint bands at Edinburgh, max. elev. 10°.
25/26	2228–0130	Faint veil and bands in central Scotland, max. elev. 18° at St. Andrews 2350. Visible at Cambridge 2228–2245 to elev. 5°.	14/15	2145–2225	Small, low and bright NLC: veil, bands and billows at Copenhagen and Vildbjerg.
27/28	0045–0300	Bright bands and billows to 12° at <i>Lima</i> . Bright bands to elev. 11° at Copenhagen.			

Date — night of	Times UT	Notes	Date — night of	Times UT	Notes
16/17 July	2200–2330	Faint to moderate bands in tropospheric cloud, central Scotland.	30/31 July	0205–0300	Faint, all forms, at Morpeth. Max. elev. 39° at 0300.
20/21	2115	Faint band at Alro, Denmark, elev. 20°.	1/2 Aug	0145–0319	Faint bands and billows at Morpeth, to 7°.
23/24	2100–0027	Bright, extensive display observed at Helsinki by Mr Frydman. Faint veil over most of sky, veil and bands, whirl structure later, elev. 45° at 2i47.	2/3	2140–2321	Faint veil and bands at Helsinki, to 6°. Possible veil at Swansea 2140 but no NLC at 2200.
26/27	2040–2238	Moderate display, all forms, in tropospheric cloud at Helsinki.	4/5	2256	Billows at Sumburgh, to 5°.
27/28	2155–2304	Large faint NLC patches at Castleford, NLC in tropospheric cloud gaps at Wakefield and Basingstoke.	6/7	2134–2145	Swansea: suspect veil very low.
28/29	2200–2253	Faint veil and bands in cloud gaps, Morpeth and Helsinki. Aurora at Morpeth 0123–0131.	10/11	2200	Swansea: suspect NLC in cloud gaps.
			18/19	2040–2220	Faint bands at Kirkwall.

Table II. Nights adjudged to have negative sightings of NLC (Finland excluded)

May 15/16, 18/19, 19/20, 31/June 1; June 1/2, 23/24, 24/25, 29/30, 30/July 1; July 8/9, 24/25.

Table III. Positive NLC sightings in Finland and Alberta, Canada

Finland:
May 26/27, 28/29; June 21/22, 23/24, 27/28, 28/29; July 2/3, 4/5, 7/8, 9/10, 11/12, 13/14, 23/24, 26/27, 28/29; Aug 2/3.

Alberta:
June 10/11*, 12/13*, 22/23, 24/25*; July 1/2, 17/18*, 19/20 (suspected), 26/27.

* Occasions when NLC was coincident with aurora.

Reviews

Acidification of freshwaters, by M. Cresser and A. Edwards. 178 mm × 253 mm, pp. viii+136, *illus.* Cambridge University Press, 1987. Price £19.50, US \$34.50.

It is good to read a common-sense account of a subject that has been marked over the last 18 years and more by a lot of good scientific research but also by controversy, media distortion and, on a few occasions, by very angry exchanges. The debate is, of course, whether it is air pollution that is principally responsible for the acidification of freshwaters in northern Europe and North America, and the concomitant decline in fish populations and species which has been so evident in the last few decades, or whether these effects are due to other causes. Much hangs on the answer. To take but just one example, the cost of extracting a sizeable fraction of the sulphur dioxide from the emissions of the CEGB's fossil-fuel power stations would be as high as several billion pounds.

Almost inevitably such a well-balanced book does not conclude with a simple all-embracing answer supporting just one side of the argument. The issue is too involved for that. In so far as such a complex issue can be summarized, it proceeds as follows; acidifying air pollutants entering the atmospheric surface layer are often intercepted by vegetation which may alter the deposition rate and modify the ionic nature of water reaching the ground. According to the vertical and horizontal profiles of the soil and the amount of water involved, the pH of the water may be dramatically modified. On emerging into streams or into lakes the pH may again change as a result of changes in carbon dioxide content and by mixing. Even in the absence of air pollution the drainage water can be highly acidic. Both the vegetation and the soil character are subject to strong modification by man, both dependent on and independent of pollution.

Thus the nature of the freshwater depends on many factors; the level of air pollution, wet and dry deposition

rates, the nature of the soil and its vertical and horizontal structure, the way water percolates through or over the soil into the streams, the effect of slopes and of vegetation, farming practices (in all its many facets, including the use of fertilizers and liming) and the way this has changed over the last 200 years, the role of forestation and deforestation, the way the ionic nature of the drainage water changes once it enters the streams and lakes, and how the fish and other freshwater dwellers react to this water of variable pH and its other mineral content. These and other factors are considered in some detail in the book in the light of the evidence from a host of experimental studies.

The authors conclude that recent acidification has to be viewed against the backdrop of a gradual but inevitable and natural acidifying development of all soils. This development can be delayed or accelerated by climatic changes or by man's activities. Thus each catchment must be considered individually. In some circumstances, acid rain may lower surface soil pH significantly over a few decades when the soil-plant-water ecosystem has become stressed by sulphate saturation of anion exchange sites within soil structure. However more generally there is no unequivocal evidence for soil acidification caused mainly by acid depositions from the atmosphere. Changes in land use as outlined above can equally produce rather rapid changes in drainage water pH, and these changes have happened very significantly over the last few hundred years (but particularly in the last few decades) and will continue in the future.

Thus the book, whilst not exonerating the air polluters, points to other major man-produced influences, all of which have to be viewed against many natural and sometimes more dominant processes.

This understandable book is well written and well produced, and is recommended to all working in this multi-discipline area.

F.B. Smith

Environmental meteorology, edited by K. Grefen and J. Löbel. 163 mm × 246 mm, pp. xi+661, *illus.* Dordrecht, Boston, London, Kluwer Academic Publishers, 1988. Price Dfl. 280.00, US \$149.00, £84.00.

Conferences and symposia have definite positive uses. New ideas can be discussed and argued over with your peers, new acquaintances can be made, links can be made with other Institutions carrying out similar studies to your own, and so on. But one thing conferences are not generally good for is producing balanced informative textbooks on any subject, unless the meeting deliberately sets out to attract a few eminent speakers each of whom is burdened with presenting a well-balanced review, and which collectively are comprehensive and complementary. Alternatively, some giant in the subject may be persuaded to extract, from the whole panoply of papers presented, a logical and readable condensation. Of course any attendee at such a meeting wants to have

copies of some papers which were particularly interesting and relevant to himself, but in this day and age, it is generally no great task for individual authors to come armed with a handful of quite professional-looking copies of his presentation produced on his Office PC, to hand out as required to other particularly interested participants.

As you may have guessed by now, I don't like most published Proceedings. This volume, almost entirely devoted to problems of air pollution, is no exception, although to be fair it does contain three review papers. The first by K. Hörschle discusses the important problem of how to get representative meteorological data for various scales of time and space as part of a measuring programme for air pollution. The second review by Garland, Nicholson and Derwent of Harwell is an excellent summary of the problems associated with estimating the wet and dry deposition of trace substances from the atmosphere. The final review is by W. Kuttler who presents a splendid detailed review of the spatial and temporal character of the urban atmosphere and climate. These three papers on their own are worth anyone's shelf space. Otherwise my enthusiasm is definitely lukewarm. The volume contains (with unspoken apologies to the forests of the world) 661 pages of papers of variable quality: some are good, and many are interim reports of unfinished work or are specific to particular localities, few of which (if any) have been properly refereed.

F.B. Smith

Books received

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

The changing atmosphere, edited by F.S. Rowland and I.S.A. Isaksen (Chichester, New York, Brisbane, Toronto, Singapore, John Wiley and Sons, 1988. £39.95) contains papers from a Dahlem Workshop discussing the state of knowledge in many facets of the subject, with emphasis on changes in the trace gases and aerosol particles. Historic changes are included, and related to the results of human activity.

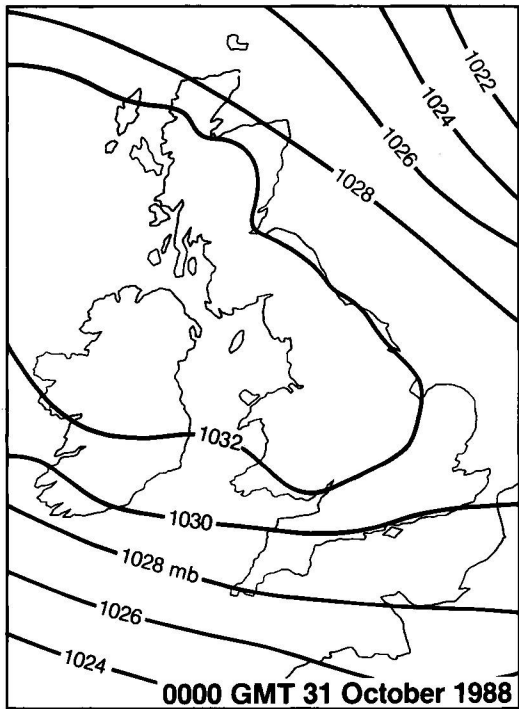
The climate of China, by M. Domrös and G. Peng (Berlin, Heidelberg, New York, London, Paris, Tokyo, Hong Kong, Springer-Verlag, 1988. DM 228.00) is a reference manual of the subject, especially in climatology and geography. There is a statistical section based on long-term averages, and the recent advances in research of the subject in China are included.

Long and short term variability of climates, edited by H. Wanner and U. Siegenthaler (Berlin, Heidelberg, New York, London, Paris, Tokyo, Springer-Verlag, 1988. DM 48.00) includes papers presented at a symposium held at Bern on 10–11 October 1986. It is volume 16 of the series Lecture Notes in Earth Sciences.

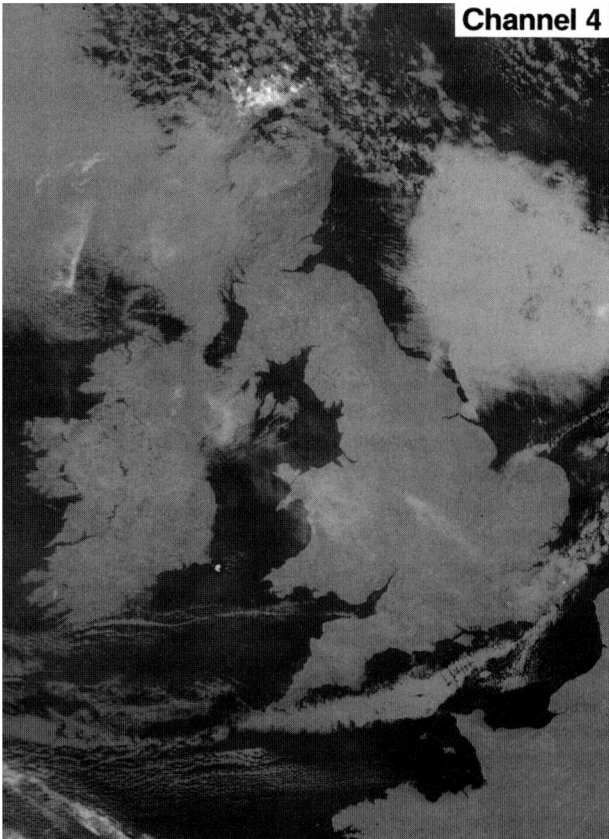
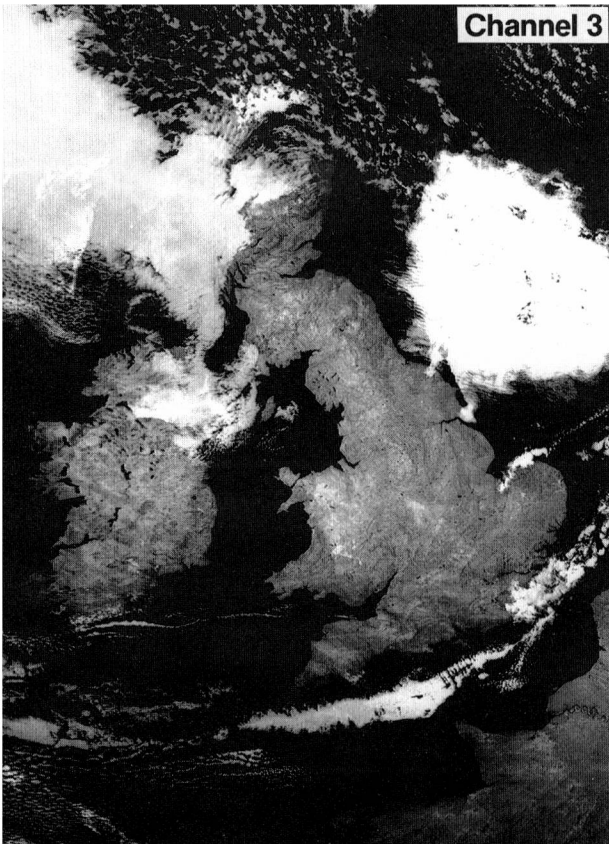
Satellite photographs — 31 October 1988 at 0206 GMT

During the hours of darkness, NOAA satellites now routinely transmit data from infra-red channels 3 and 4 and, during daylight, visible channel 2 and infra-red channel 4, the change being made at local dawn and dusk as appropriate. Channel 3 pictures are similar to channel 4 except that in channel 3, warm clouds (or fogs) appear colder (whiter) and thin cirrus appears warmer (darker) than in corresponding channel 4 data*. Channel 3 information adds little to that of channel 4 at cirrus levels, since cirrus is seen clearly in channel 4. However, in cases where low cloud or fog-top temperatures are similar to those of the underlying surface, boundaries are indistinct in channel 4, but often clearly seen in channel 3, especially when images are displayed with high contrast across the range of temperatures in which low clouds occur.

In the pictures shown, with patches of low cloud present over the British Isles, the cloud and land surfaces are radiating at similar temperatures (channel 4 image) making it difficult to locate the inland penetration of cloud. However, in channel 3, the cloud areas are all whiter than the land, the high contrast magnifying this effect. In particular, the extent of cloud over central Scotland and Northern Ireland can be clearly seen. The channel 3 image also shows variations of surface temperature over the cloudless land. One drawback of the enhanced channel 3 data is that the inherent noise, which can be seen as vertical bands over and to the north of Ireland, is also enhanced.



* For further information regarding the properties of channel 3 see: Eyre, J.R., Brownscombe, J.L. and Allam, R.J.; Detection of fog at night using Advanced Very High Resolution Radiometer (AVHRR) imagery, *Meteorol Mag*, 113, 266-271.



Photographs by courtesy of University of Dundee.

Meteorological Magazine

GUIDE TO AUTHORS

Content

Articles on all aspects of meteorology are welcomed, particularly those which describe the results of research in applied meteorology or the development of practical forecasting techniques.

Preparation and submission of articles

Articles for publication and all other communications for the Editor should be addressed to the Director-General, Meteorological Office, London Road, Bracknell, Berkshire RG12 2SZ and marked 'For *Meteorological Magazine*'.

Articles, which must be in English, should be typed, double-spaced with wide margins, on one side only of A4-size paper. Tables, references and figure captions should be typed separately.

Spelling should conform to the preferred spelling in the *Concise Oxford Dictionary*.

References should be made using the Harvard system (author, date) and full details should be given at the end of the text. If a document referred to is unpublished, details must be given of the library where it may be seen. Documents which are not available to enquirers must not be referred to.

Tables should be numbered using roman numerals and provided with headings. We consider vertical and horizontal rules to be unnecessary in a well-designed table; spaces should be used instead.

Mathematical notation should be written with extreme care. Particular care should be taken to differentiate between Greek letters and Roman letters for which they could be mistaken. Double subscripts and superscripts should be avoided, as they are difficult to typeset and difficult to read. Keep notation as simple as possible; this makes typesetting quicker and therefore cheaper, and reduces the possibility of error. Further guidance is given in BS1991: Part 1: 1976 and *Quantities, Units and Symbols* published by the Royal Society.

Illustrations

Diagrams must be supplied either drawn to professional standards or drawn clearly, preferably in ink. They should be about 1½ to 3 times the final printed size and should not contain any unnecessary or irrelevant details. Any symbols and lettering must be large enough to remain legible after reduction. Explanatory text should not appear on the diagram itself but in the caption. Captions should be typed on a separate sheet of paper and should, as far as possible, explain the meanings of the diagrams without the reader having to refer to the text.

Sharp monochrome photographs on glossy paper are preferred: colour prints are acceptable but the use of colour within the magazine is at the Editor's discretion. In either case contrast should be sufficient to ensure satisfactory reproduction.

Units

SI units, or units approved by WMO, should be used.

Copyright

Authors wishing to retain copyright for themselves or for their sponsors should inform the Editor when they submit contributions which will otherwise become UK Crown copyright by right of first publication.

It is the responsibility of authors to obtain clearance for any copyright material they wish to use before submitting it for publication.

Free copies

Three free copies of the magazine are provided for authors of articles published in it. Separate offprints for each article are not provided.

January 1989

Editor: B.R. May
Editorial Board: R.J. Allam, W.H. Moores, P.R.S. Salter, P.G. Wickham

Vol. 118
No. 1398

Contents

	Page
Real-time analysis of precipitation using satellites, ground-based radars, conventional observations and numerical model output.	
C.G. Collier, D.M. Goddard and B.J. Conway	1
An introductory review of fronts. Part II: A case-study.	
D.A. Bennetts, J.R. Grant and E. McCallum	8
Direct use of satellite sounding radiances in numerical weather prediction.	
J.R. Eyre and A.C. Lorenc	13
Noctilucent clouds over western Europe during 1987. D.M. Gavine	16
Reviews	
Acidification of freshwaters. M. Cresser and A. Edwards. <i>F.B. Smith</i>	18
Environmental meteorology. K. Grefen and J. Löbel (editors). <i>F.B. Smith</i> :	19
Books received	19
Satellite photographs — 31 October 1988 at 0206 GMT	20

Contributions: It is requested that all communications to the Editor and books for review be addressed to the Director-General, Meteorological Office, London Road, Bracknell, Berkshire RG12 2SZ, and marked 'For *Meteorological Magazine*'. Contributors are asked to comply with the guidelines given in the *Guide to authors* which appears on the inside back cover. The responsibility for facts and opinions expressed in the signed articles and letters published in *Meteorological Magazine* rests with their respective authors. Authors wishing to retain copyright for themselves or for their sponsors should inform the Editor when submitting contributions which will otherwise become UK Crown copyright by right of first publication.

Subscriptions: Annual subscription £28.00 including postage; individual copies £2.50 including postage. Applications for postal subscriptions should be made to HMSO, PO Box 276, London SW8 5DT; subscription enquiries 01-211 8667.

Back numbers: Full-size reprints of Vols 1-75 (1866-1940) are available from Johnson Reprint Co. Ltd, 24-28 Oval Road, London NW1 7DX. Complete volumes of *Meteorological Magazine* commencing with volume 54 are available on microfilm from University Microfilms International, 18 Bedford Row, London WC1R 4EJ. Information on microfiche issues is available from Kraus Microfiche, Rte 100, Milwood, NY 10546, USA.

ISBN 0 11 728474 2 ISSN 0026-1149

© Crown copyright 1989. First published 1989