The objective analysis of relative humidity

By MARGARET J. ATKINS, *Meteorological Office, Bracknell, Berkshire, England*

(Manuscript received September 28, 1973; revised version January 2, 1974)

ABSTRACT

A method of objective analysis of relative humidity is described which makes use of non-isotropic weighting functions. These depend on the gradient of the background field in such a way that observations in a direction along closely packed isopleths have higher weight than those in a direction perpendicular to them. Rainfall predictions with the United Kingdom fine mesh 10-level model are found to be better when based on this humidity analysis than on one using isotropic weighting functions and the results for a particular case are described. The use of surface observations in the lowest layer of the model is discussed and it is shown that it is better to use the surface humidity mixing ratio rather than the surface relative humidity. Resulting forecasts of rainfall are better and do not exhibit diurnal variations found when using surface relative humidity observations.

1. Introduction

The scheme of objective analysis of relative humidity which is the subject of this paper was devised for the 10-level model described by Benwell et al. in 1971. This is a primitive equation model which uses pressure as a vertical co-ordinate and has 10 levels at 100 mb intervals from 100 to 1 000 mb. One version of the model, which is currently operational in the British Meteorological Office, has a resolution of about 300 km on an octagonal area which covers most of the northern hemisphere. A second version, expected to be operational shortly, is for a rectangular area extending over Europe and the North Atlantic and has a resolution of about 100 km, so that frontal scale motions may be represented and associated rainfall forecasts produced.

At one time it was thought that the specification of the initial humidity field was unimportant to the production of rainfall forecasts and that, providing the initial vertical velocity field was correct, the humidity pattern would soon adjust to one which was consistent with the temperature and wind fields. However, as will be shown later in this paper, the rainfall forecasts are sensitive to the initial humidity field and changes in this field give changes in the rainfall forecasts which persist up to between 18 and 24 hours from the initial data time. Since the model is required to produce forecasts of accumulated rain as well as instantaneous rates of rain it is important that the rain produced in the early part of the forecast should be correct. The initial humidity field may also affect the dynamical development in the early part of the forecast, but this has not been demonstrated. These considerations apply mainly to the fine mesh version of the model and therefore the humidity analysis was devised, and later modified, for the fine mesh version and applied unaltered to the coarse mesh version.

The model carries humidity mixing ratio as its moisture variable but the variable analysed is relative humidity. The reasons for this are to some extent historical following subjective analysis procedures. One of the advantages of objectively analysing relative humidity is that it allows the introduction of surface observations of cloud and weather to supplement the upper air data as the former are more easily related to relative humidity than to humidity mixing ratio. It may also be argued that relative humidity is the more important variable to the model, as it determines the onset of rain, and therefore should be analysed. Problems of supersaturation are automatically avoided. The analysed fields of relative humidity are converted to humidity mixing ratio in the same way that the model itself makes conversions,

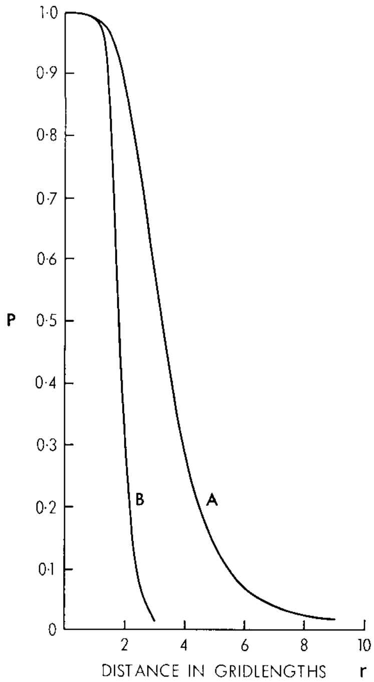

Fig. 1. Distance weighting factors. Curve A is given by $p = 1/(1 + 0.01r^4)$ and is used for the first scan, curve B is given by $p = 1/(1 + 0.01r^8)$ and is used for the second scan.

that is by deriving the saturated humidity mixing ratio from the thicknesses of the layers by means of quartic polynomials.

2. Basic method of analysis

The analysed humidity fields are required for the seven lowest layers of the model as the atmosphere is assumed to be dry above 300 mb. The analysis for each of these layers uses the forecast relative humidity field as a background or first guess field. At the present time the data used are upper air reports of relative humidity at standard levels and surface observations of humidity. Each upper air ascent is linearly interpolated from the standard levels to the mid-point of each layer giving a value which is taken to represent the mean relative humidity over the layer. It is hoped to determine these values more correctly in the future by integrating the ascents through each 100 mb layer using the special point and the standard level data.

The method of analysis is based on that described by Atkins (1970). The main problem is that we are attempting to analyse features which can be resolved by the model on a 100 km mesh but which cannot be represented by the sparse network of ocean weather ships in the North Atlantic. These features are on the scale of fronts and they have large gradients of humidity between them. As a result an observation is only representative of a small area and therefore there are very few if any observations available for the analysis of a particular grid point. It is therefore inappropriate to apply the method of polynomial fitting used for height analysis in the Meteorological Office (Bushby & Huckle, 1957; Corby, 1961) and the method chosen is simply to take a weighted mean of the data surrounding each grid point together with the value of the background field at the grid point itself. The method of objective analysis was originally devised for research purposes when no forecast field was available so a background field was derived empirically from the initial field of vertical velocity. In view of this rather poor background field and the large distances between observations in the Atlantic, data were used up to 9 grid lengths (about 900 km) from a grid point although it was estimated that a grid point should not be influenced by observations more than 3 grid lengths away. This was to avoid obtaining a field with concentric circles around each observation in a sparse data area with values of the background field in between. A second scan was made through the field using the results of the first scan as a background field and using observations up to 3 grid lengths from each grid point. This restored the detail in areas of dense data. The formula used for the weighted mean was

$$R = \frac{\sum_i p_i R_i + qR_b}{\sum_i p_i + q} \tag{1}$$

where R_i is an observation of relative humidity expressed as a fraction that is $0 \leqslant R_i \leqslant 1$.

p_i is a weighting factor of the form

$$p_i = \frac{1}{1 + 0.01 r_i^n} \tag{2}$$

where r_i is the distance from the grid point to the observation in grid lengths

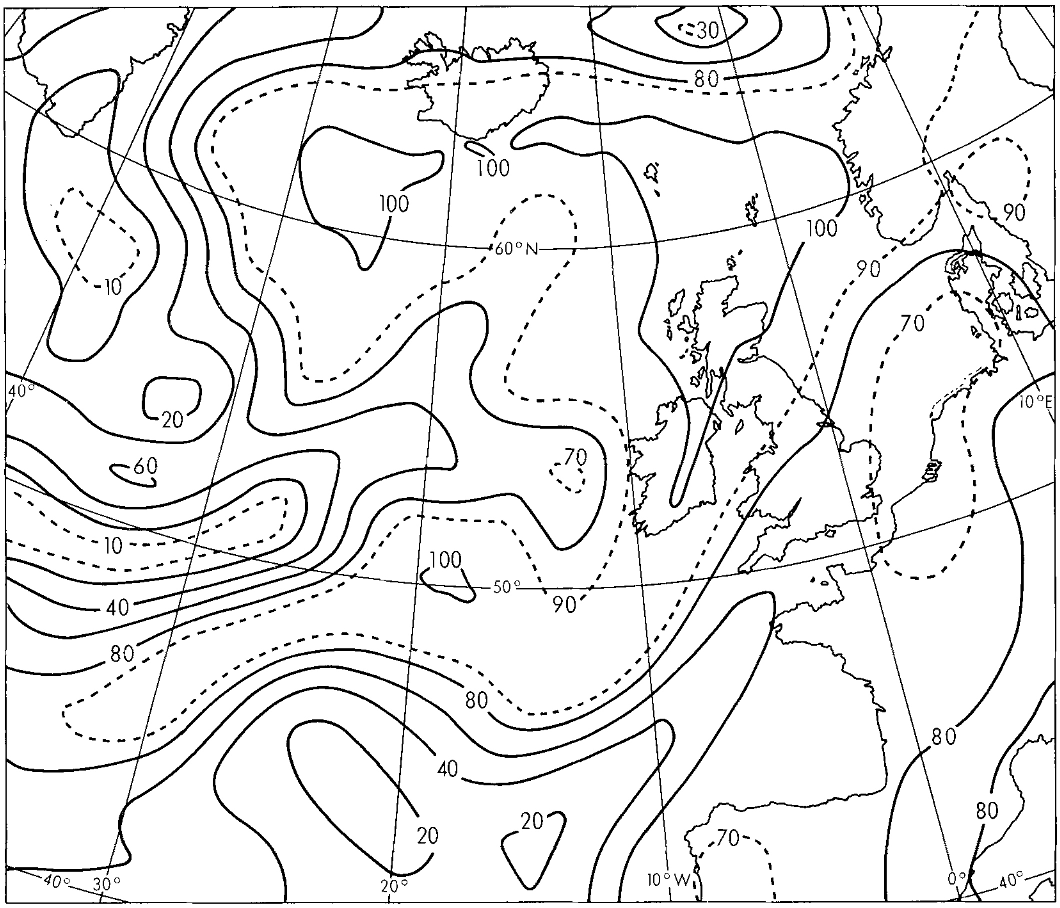

Fig. 2. 850 mb background field of relative humidity for 1 200 GMT 9th November 1972.

$$n = \begin{cases} 4 & \text{1st scan} \\ 8 & \text{2nd scan} \end{cases}$$

R_b is the value of the background field at the grid point, q is the weight of the background field.

The sum is taken over all observations within the specified distance. Figure 1 shows the shape of the weighting factors.

All layers were analysed using upper air data only and then two further scans were made through the 950 mb layer using surface observations of relative humidity with the same weighting factors as for the upper air data. The background field for the first scan was the upper air analysis at 950 mb.

This method was used with a 12-hour forecast field as a background field with a weight of 0.2 when the 10-level model started running on a routine basis early in 1972. In areas of dense data it produced satisfactory analyses which compared well with subjective analyses, but could not be expected to produce much detail in areas of sparse data and was unable to depict frontal zones which a subjective analyst could do using the surface synoptic chart.

The routine running of the 10-level model revealed two deficiencies in the objective analysis scheme which has just been described. The first arises from the manner in which the forecast humidity fields are used in the analysis. The second stems from the method of incorporating surface data into the 950 mb layer analysis. The remainder of the paper will describe how both these deficiencies have been overcome.

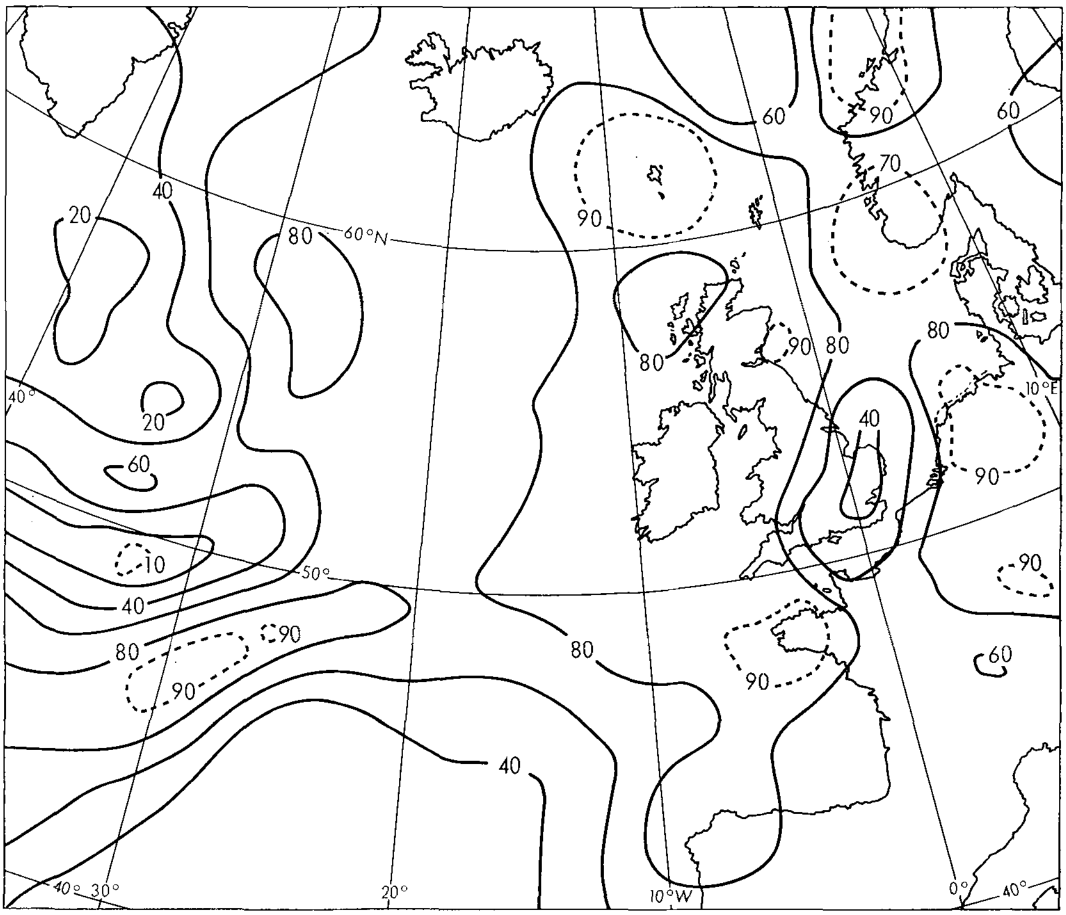

Fig. 3. 850 mb analysed field of relative humidity for 1 200 GMT 9th November 1972 using original analysis method.

3. Improved use of forecast fields

The first of the deficiencies in the analysis procedure was brought to light by the examination of rainfall forecasts. On the whole, 24-hour forecasts of rainfall rates were better than 12-hour forecasts. On closer examination it was found that the forecast fields of relative humidity, which had adjusted to the model's temperature and wind fields, showed considerably more detail than the analysed fields. This detail included long narrow tongues of moist air with steep gradients on either side which could be identified as fronts on the surface synoptic charts. In order to forecast more rain in the early part of an integration it was necessary to have an analysis which was similar in character to the forecast fields of relative humidity and which thus corresponded more closely to the dynamics of the model. The 12-hour forecast fields of relative humidity used as background fields were fairly well adjusted to the model's dynamics in spite of some poor rainfall forecasts, and it was expected that those resulting from an improved analysis would be even better. The analysis scheme has therefore been modified to incorporate this information by making the weight of an observation depend on the gradient of the background field in such a way that it is high in the direction of the isopleths of the background field and low in the perpendicular direction. The weight also depends on the magnitude of the gradient so that when the isopleths are

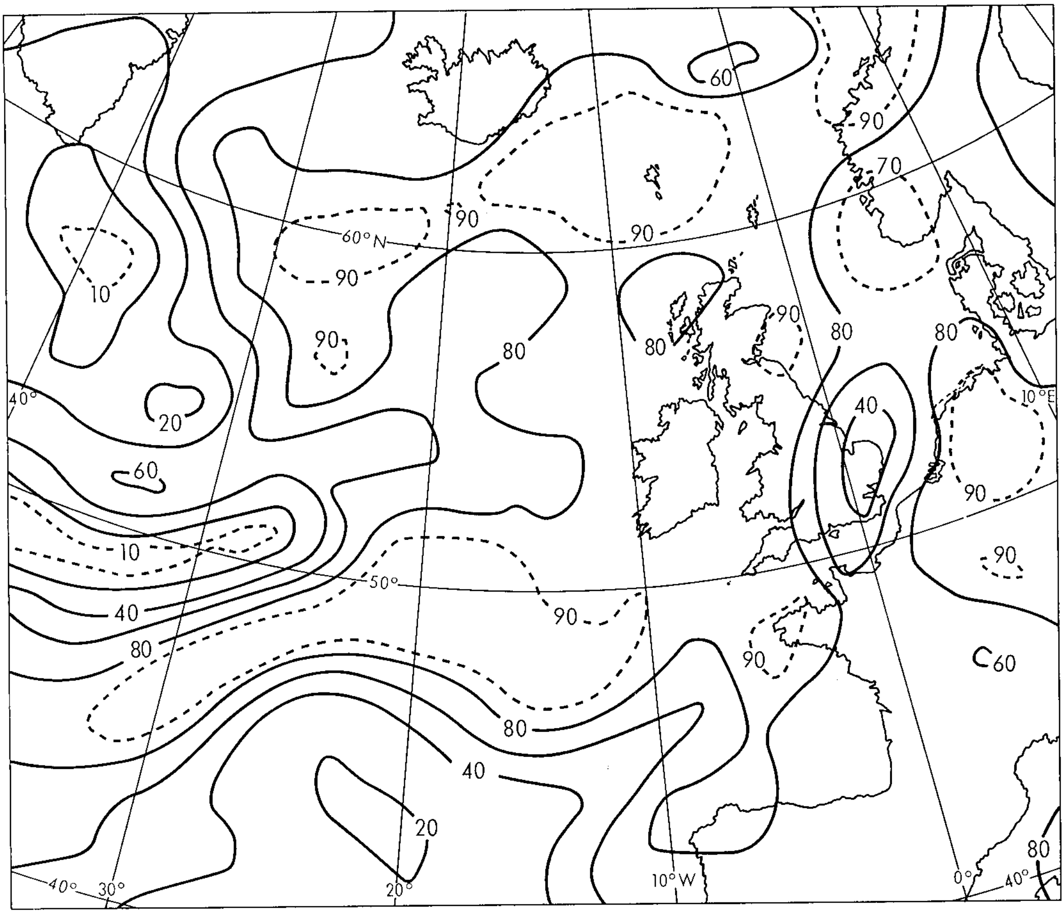

Fig. 4. 850 mb analysed field of relative humidity for 1 200 GMT 9th November 1972 using the revised analysis method which includes non-isotropic weighting functions.

closely packed the weight of an observation in a direction perpendicular to them is very low, even at quite small distances. This procedure has the effect that a frontal zone in the forecast field in a sparse data area will be preserved in the analysed field. If the front in the forecast field is slightly displaced it will be analysed in a better position if there is at least one observation in the actual frontal zone.

The weighting factor for an observation becomes

$$\frac{1}{1+0.01\,|\mathbf{r}_i|^n+1000(\nabla R_{bi}\cdot\mathbf{r}_i)^2} \tag{3}$$

where $\mathbf{r}_i$ is the position vector of the ith observation relative to the grid point. The magnitude is expressed in grid lengths.

∇R_{bi} is the gradient of the background field at the ith observation point in fractional relative humidity per grid length.

$$n=\begin{cases}4 & \text{1st scan}\\ 8 & \text{2nd scan}\end{cases}$$

This revised analysis scheme was incorporated into the suite of programmes for the routine forecasts in July 1972 and subsequent rainfall forecasts were of a noticeably higher standard. In order to demonstrate the effects of the revised analysis on a particular case the data for 1200 GMT 9th November 1972 were reanalysed using the old analysis method. Figs. 2, 3, and 4 show the 850 mb background field, old and modified analysis respectively. Fig. 5 shows the actual surface synoptic situation. The front,

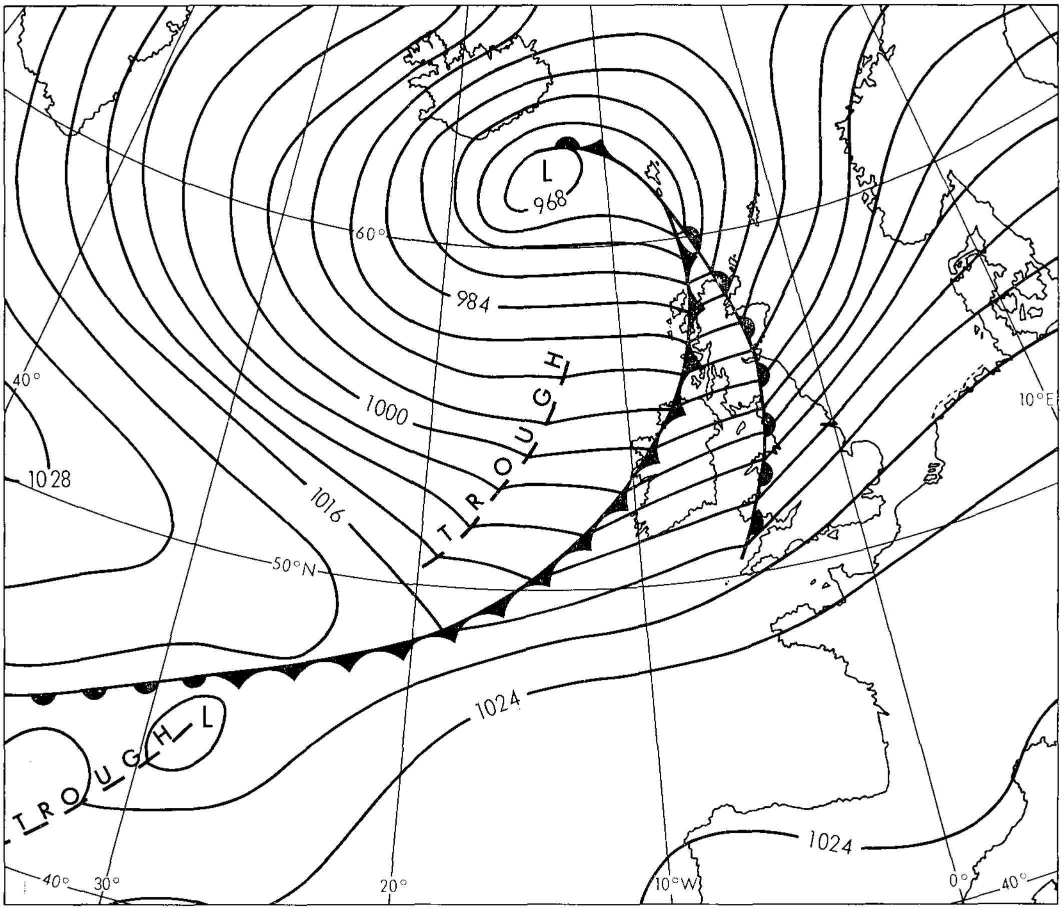

Fig. 5. Surface pressure analysis for 1200 GMT 9th November 1972.

to the south west of the British Isles, which lay between weather ships J and K and was therefore not apparent in the upper air humidity data, has been preserved in the revised analysis.

A 24-hour forecast was run from each of these two analyses using the same height analysis. The forecast surface pressure patterns were good and almost identical but there were significant differences in the rainfall forecasts. The forecast from the revised analysis will be called "forecast A" and that from the original analysis "forecast B".

During the period of the forecast the frontal system moved steadily eastwards across the British Isles. The warm front had little rain associated with it and cleared eastern England by 1900 GMT 9th November 1972. The cold front was very active and was associated with a belt of widespread moderate and some heavy rain which moved through the south west of England between 0000 GMT and 0600 GMT 10th November 1972 and cleared the south east of England by 1200 GMT 10th November 1972.

There were distinct differences in the rate of rainfall patterns at the 6, 12 and 24-hour forecast stages, forecast A giving twice as much rain falling over parts of the west of England at the 12-hour stage. These differences are best shown in the forecasts of accumulated rain and can be seen to have persisted to between 18 and 24 hours. Figs. 6 and 7 show that forecast A produced considerably more rain than forecast B. This was an improvement as previously the 10-level model had under-estimated the rain, and indeed comparison with actual grid square averages showed that forecast A was

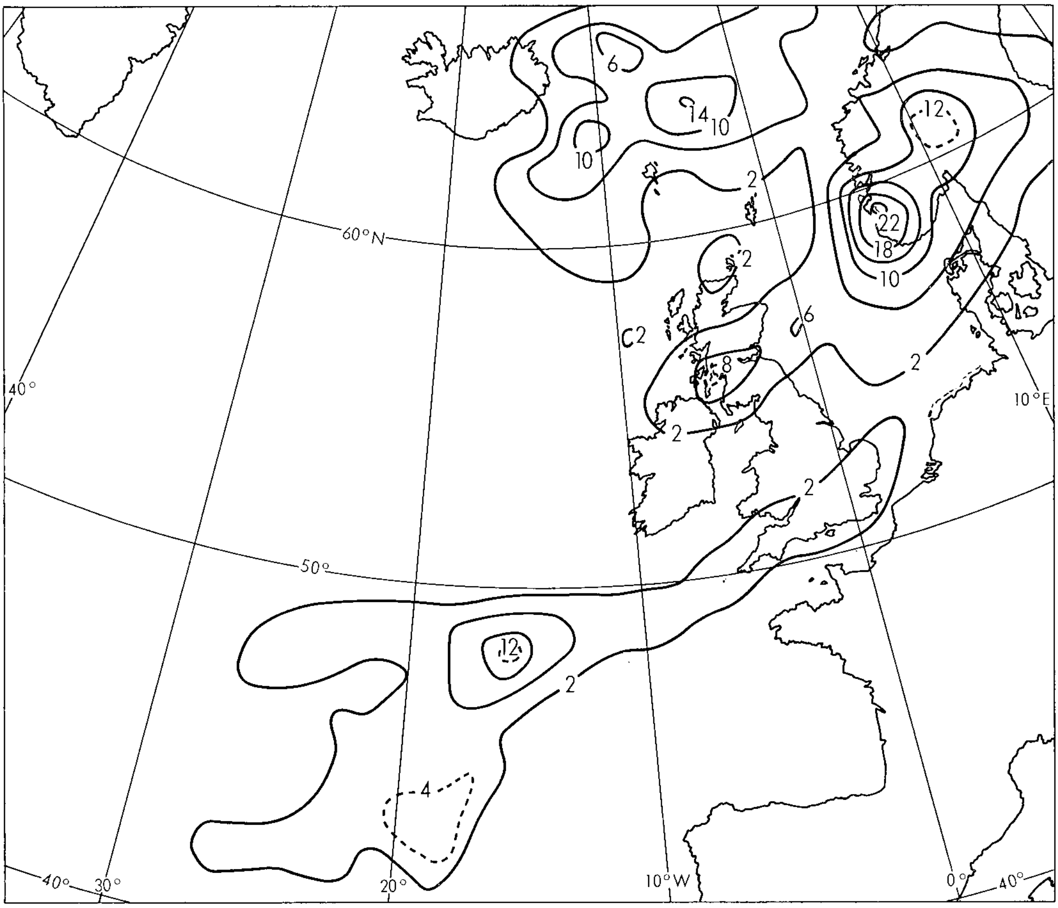

Fig. 6. 18-hour forecast of accumulated rain based on the original relative humidity analysis. The isopleths begin at 2 mm and are then drawn at 4 mm intervals.

better. The sequence of events was also better represented in forecast A as it showed a well established belt of rain crossing the country between 0000 GMT and 1200 GMT 10th November 1972, whereas in forecast B the rainfall belt was still intensifying up to 0600 GMT 10th November 1972.

4. Improved use of surface humidity observations

The second fault in the analysis also showed itself in the rainfall predictions. Forecasts based on midnight data tended to give more rain than forecasts based on midday data. This was particularly noticeable in summer when belts of rain would disappear and reappear on successive forecasts. This diurnal oscillation was traced to variations in the initial moisture content of the 950 mb layer caused by diurnal variations in the surface relative humidity observations used directly in the 950 mb layer.

A study was carried out to discover the statistical relationships between the mean values of relative humidity and humidity mixing ratio over the lowest 100 mb of the atmosphere and the corresponding surface values. Both the mean and surface values were obtained from the special points of radiosonde ascents. The mean value of the humidity mixing ratio was found by linearly interpolating the dewpoint at 10 mb intervals between the special points (this approximates to drawing a straight line

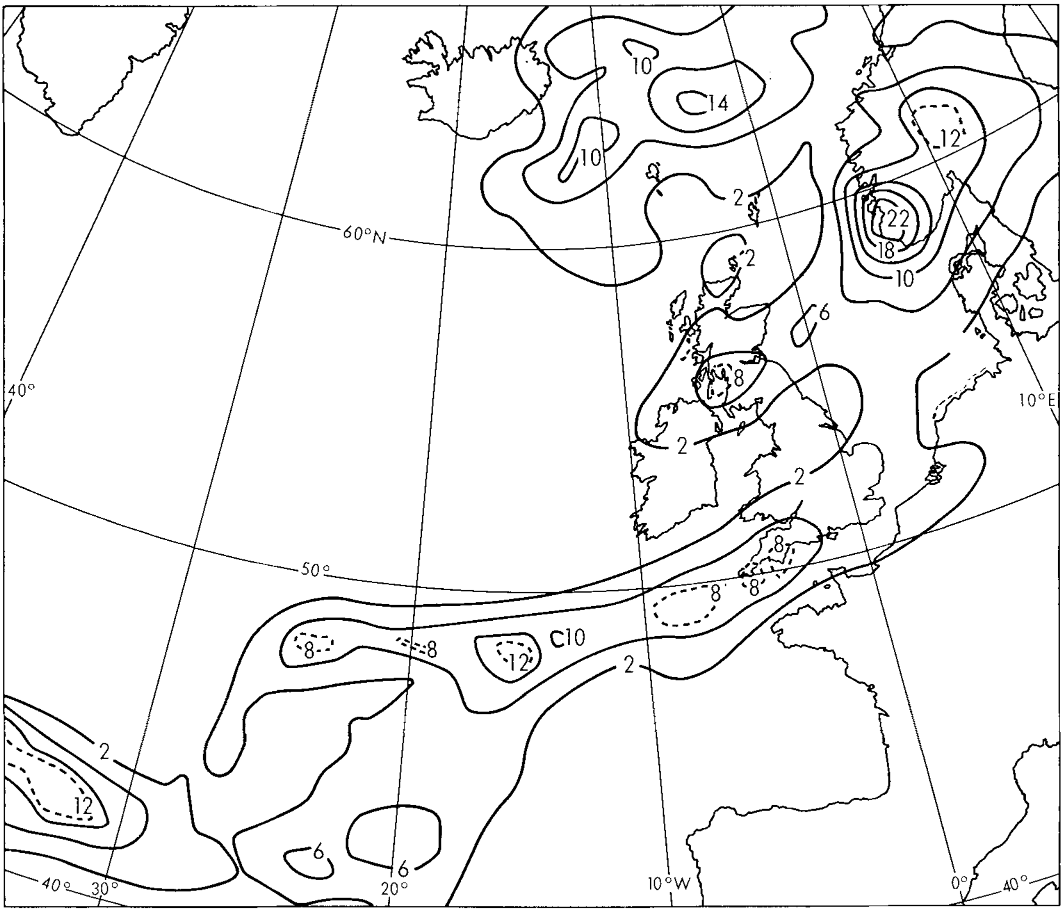

Fig. 7. 18-hour forecast of accumulated rain based on the revised relative humidity analysis, which includes non-isotropic weighting functions. The isopleths begin at 2 mm and are then drawn at 4 mm intervals.

on a temperature-entropy diagram) and then converting to humidity mixing ratio and integrating this through the 100 mb layer. The mean relative humidity was derived using a saturated humidity mixing ratio calculated from the mean temperature of the layer. This latter procedure slightly over-estimates the relative humidity due to the non-linear dependence of saturated humidity mixing ratio on temperature, but this does not seriously affect the results. This study was carried out for a number of different groups of stations in Europe and the North Atlantic and also for different seasons. The results for humidity mixing ratio were essentially the same in each case. The correlation between the surface value and the mean for the lowest 100 mb was good, ranging between 0.70 and 0.97. The corresponding correlations for relative humidity varied from one group to another, values ranging between 0.35 and 0.92. For humidity mixing ratio the mean value for the lowest 100 mb was about 0.8 times the surface value; this held true for both 0000 GMT and 1200 GMT.

The analysis procedure for 950 mb was therefore changed so that a 950 mb relative humidity was calculated for each surface observation within the area of the rectangular grid using the equation

$$R_{950} = 0.8 r_0 / r_{s950} \tag{4}$$

where r_0 is the surface humidity mixing ratio

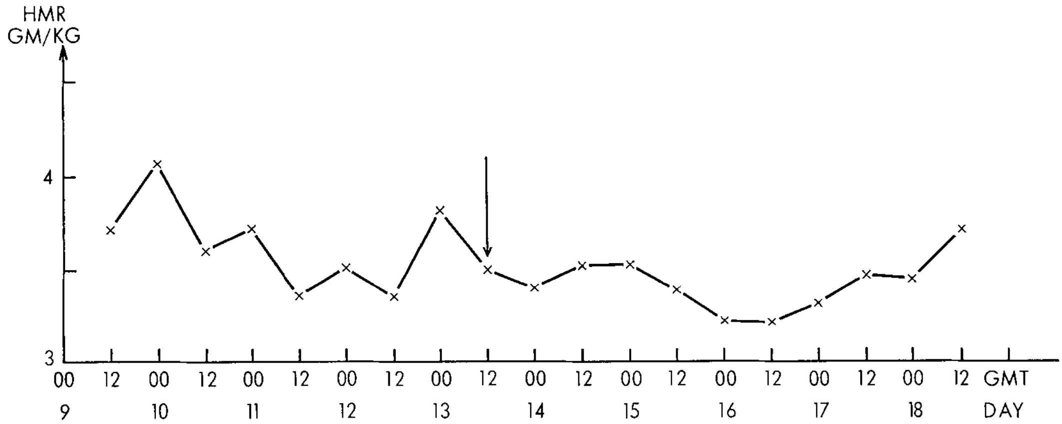

Fig. 8. Graph showing the variation of the spatial mean of the analysed 950 mb humidity mixing ratio over the rectangular grid during the period 9th to 18th February 1973. The method of analysing the 950 mb layer was changed at 1 200 GMT 13th February 1973. This eliminated the diurnal variation that was apparent before that time.

and r_{s950} is the saturated humidity mixing ratio derived from the analysed 950 mb partial thickness.

The introduction of this procedure eliminated the diurnal variation in the initial moisture content of the 950 mb layer. This is shown very clearly in Fig. 8 which gives the spatial mean of the analysed 950 mb humidity mixing ratio for the days before and after the change-over. No trace of a diurnal variation can now be found in the rainfall forecasts.

5. Conclusion

These results show that short range forecasts of rainfall are highly dependent on the initial humidity fields and therefore these need to be specified as correctly as possible. A number of further improvements are under experiment at the present time. These include, as has already been mentioned, the use of the complete ascent including the special points to derive the layer mean relative humidities and the use of surface observations, mainly of cloud and present weather, to infer upper level relative humidity.

REFERENCES

Atkins, M. J. 1970. Objective analysis of upper air height and humidity data on a fine mesh. *Meteorological Magazine 99*, 98–110.

Benwell, G. R. R., Gadd, A. J., Keers, J. F., Timpson, M. S. & White, P. W. 1971. The Bushby-Timpson 10-level model on a fine mesh. Scientific Paper No. 32. HMSO, London. 59 pp.

Bushby, F. H. & Huckle, V. M. 1957. Objective analysis in numerical forecasting. *Quarterly Journal, Royal Meteorological Society 83*, 232–247.

Corby, G. A. 1961. Some experiments in the objective analysis of contour charts. *Quarterly Journal, Royal Meteorological Society 87*, 34–42.

ОБЪЕКТИВНЫЙ АНАЛИЗ ОТНОСИТЕЛЬНОЙ ВЛАЖНОСТИ

Описывается метод объективного анализа относительной влажности, использующий неизотропные весовые функции. Последние зависят от градиента основного поля таким образом, что наблюдения в направлении вдоль тесно сходящихся изоплет имеют высокий вес, чем наблюдения в перпендикулярном направлении. Предсказания дождя с помощью 10-уровенной модели с учащенной сеткой, применяемой в Великобритании, оказались лучше, когда они основывались на этом анализе влажности, а не на использовании изотропных весовых функций. Описываются результаты для одного частного случая. Обсуждается использование наблюдений у поверхности на самом нижнем уровне модели и показано, что лучше использовать отношение смеси на поверхности, чем относительную влажность. Прогнозы дождя оказываются лучше и не обнаруживают суточных колебаний, появляющихся при использовании над относительной влажностью у поверхности.