Short Range Forecasting over the United Kingdom using a Mesoscale Forecasting System

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(Manuscript received 23 October 1986, in revised form 13 January 1987)

Abstract

A non-hydrostatic numerical weather prediction model has been implemented on a 15 km grid covering the United Kingdom to provide guidance to local weather forecasters in the period up to a day ahead. The model uses a turbulent kinetic energy formulation for vertical diffusion and carries cloud water as an additional variable. Account of the scales represented has been taken in the convection scheme. Radiation budgets are computed for the surface and the highest cloud top. Surface synoptic reports are incorporated to add mesoscale detail to the initial specification of boundary layer and cloud variables. Trials of the system have shown considerable skill in surface temperature and wind forecasts. The precipitation forecasts are superior to previous numerical models and show a realistic orographic enhancement. Some encouraging cloud and fog forecasts have been obtained.

1. Introduction

The numerical models in current operational use at the UK Meteorological Office give valuable guidance to forecasters on the broad scale atmospheric structure. A grid-length of about 150 km is used for global predictions and half that for the regional (fine mesh) model covering the North Atlantic and Europe. However, even this latter model cannot represent the topographic differences between parts of the United Kingdom which are important for short period forecasting. A mesoscale numerical forecast model with very fine resolution is being developed to tackle this problem with the aim of providing guidance to forecasters on the local variations of weather in the period up to a day ahead. This model is closely tied to the regional model through its boundary conditions so it must be seen as a sophisticated tool for adding detail to the predictions of the coarser models. In particular it will not be able to correct timing errors in systems that are passed through the boundaries. On the other hand, in slow moving situations the topogra-

phically induced effects should be well forecast and should be of considerable help to local forecasters.

2. The forecast model

The model presently has a 15 km grid-length and covers the British Isles (see Fig. 1). With this resolution, a good representation of the orography is achieved, and the coastline, indicated by the zero contour in Fig. 1, has a realistic shape. The mountain ranges are still somewhat lower than reality, eg the Cairngorms reach 800 m rather than the observed 1200 m. Also, the valleys which dissect them are not represented and so their local effects on the weather of cities like Sheffield, for instance, cannot be accounted for. These will have to be added to the model guidance by the forecaster.

The non-hydrostatic equations of motion are used as described in Tapp and White (1976) and Carpenter (1979). If these equations were solved with an explicit numerical scheme, a timestep of a fraction of a second would be necessary. They are therefore split, the terms supporting sound waves being

Fig. 1. Model domain and orography. The grid points have a 15 km spacing and the contour interval is 50 m. The bold contour is at zero metres and indicates the model coastline.

treated implicitly and the remainder explicitly using a leapfrog integration scheme. The implicit terms combine with the continuity equation to give a Helmholtz equation in the second time derivative of pressure. This is solved using ADI techniques. With a grid-length of 15 kms, the effect of the non-hydrostatic terms is merely to alter the gravity wave speeds a little and no significant benefit has been identified in the results. The formulation has been retained, however, to permit use of the model at finer resolutions. The vertical co-ordinate is height above the land surface and the model currently has 16 levels. The lowest level is at 10 m and the spacing increases linearly from

100 m to 1500 m at the top. The highest level at 12010 m is in the stratosphere. This arrangement gives 5 levels in the lowest kilometre, and when expressed in terms of the standard atmosphere, an almost constant spacing of 60 mb from there up to the tropopause.

As in larger scale models, many of the important weather producing processes occur at scales too small for the model to resolve. These processes must be parametrized in terms of scales that are represented. In the following sections, descriptions of these parametrizations are given under the headings of boundary layer, layer cloud, and convective cloud processes.

a. Boundary Layer Processes

The most important boundary layer processes represented in the model are radiation and turbulent diffusion. Both are controlled by the characteristics of the ground, eg its wetness, reflectivity, conductivity and porosity, and the vegetation present. At present, the albedo, the roughness length (z_0) and the surface resistance to evaporation, can be varied. Over the sea, the latter is zero and roughness is related to wind speed through Charnock's formula (Charnock 1955), $z_0 = ku_*^2/g$ with $k=0.0185$ (Wu, 1982) and u_* obtained from the previous timestep. Over land, roughness length is prescribed using the drag coefficient map of Smith and Carson (1977) with an upper limit of 1 m in highland regions. The distribution of resistance to evaporation is derived from the weekly estimates of soil moisture deficit in MORECS (Thompson *et al.*, 1981) assuming a grass surface. At night the resistance is trebled to model the effects of darkness on the transpiration of plants, but it is set to zero if dew is forming. A surface water balance accumulates rain and dew and removes evaporated water. If the surface is wet, the resistance to evaporation is calculated for saturated ground regardless of the prior specification. Run-off limits the water depth to 1 mm unless the surface is frozen when it is permitted to accumulate and the albedo is then increased.

Most of the heat gain at the surface comes from solar radiation. This is strongly affected by the presence of clouds in the atmosphere and is modelled by applying a transmission function (T) which depends on the integrated density of forecast cloud through a column of the atmosphere. The function has been fitted to data obtained from the radiation scheme of Slingo and Schrecker (1982) and has the form

$$T = \exp[-4.3\sqrt{\omega}(1 + \cos^2\alpha/(5.82\sqrt{\omega}))]$$

where ω is the total liquid water path in kg m^{-2} and α is the solar zenith angle. Long wave emission by clouds (L) is also modelled as a function of the total cloud water path following Lind and Katsaros (1982) as

$$L = \sigma[1 - \exp(-70\omega)]T_c^4$$

where σ is the Stefan-Boltzmann constant and T_c is the cloud base temperature.

The other main component of the heat budget at the surface is turbulent diffusion through the lowest layers of the atmosphere. In the model, transport between the surface and first level at 10 m is modelled using Monin-Obukhov similarity theory to calculate the mixing coefficient. A full description of the formulation is given in Carpenter (1979). The surface resistance to evaporation is important here in determining the relative transports of sensible heat and of moisture. Above the 10 m level, the mixing coefficients are determined from a forecast parameter, the turbulent kinetic energy (TKE), and a diagnosed one, the mixing length. The latter increases above the ground until it reaches an empirically defined fraction of the boundary layer depth. The local rate of change of TKE is represented in terms of advection, turbulent transport, local production by shear and buoyancy, and local dissipation. The generation by buoyancy takes account of whether air parcels are saturated and so depends on the fractional cloud cover. Turbulent transport takes TKE upwards from where it is generated near the ground to the boundary layer top, where the resultant entrainment of air from above is an important factor in the boundary layer evolution.

The other important process to be modelled for prediction of boundary layer cloud is the cloud top radiation budget. A similar formulation to that described above for the surface is applied except that short wave absorption rather than transmission is the required parameter. In order to avoid difficulties in specifying the depth of the relevant cloud layer, the short wave absorption is made independent of cloud depth but must not exceed the net loss of long wave radiation. The long wave budget is composed of the cloud top emission to space and the absorption of incoming clear air radiance.

b. Layer cloud precipitation

Cloud is diagnosed as part of the calcula-

tion of non-conservative variables in the turbulence scheme. The subgrid scale relative humidity is first calculated taking account of turbulent variations of the conservative variables and including a term depending on layer depth to model non-turbulent variations. The proportion of saturated air can then be deduced from the mean humidity and its variance by assuming a probability distribution. For simplicity a top hat function is used. Thus as the mean humidity increases, the diagnosed cloud fraction will increase from zero to full cover, the thresholds for the extremes depending on the turbulent intensity and the layer depth. The critical humidity for saturation is over water at temperatures above -15°C unless snow is falling through the layer. Between -40°C and -15°C it lies between the saturation values over ice and water. Below -40°C saturation is over ice at all times. Precipitate is snow at temperatures below -15°C or if the layer is being seeded by snow. Snow falls at about 1 ms^{-1} until it reaches the melting level where it is turned to rain (cooling the air at this level) and falls immediately to the ground. Water clouds produce precipitation, P , locally according to the formula.

$$\frac{dP}{dz} = C_L(1 - \exp(-(m/C_m)^2))m$$

where m is the cloud water mixing ratio and C_L , C_m are empirical constants. In addition, if rain is falling through a cloud layer it accretes water according to the formula.

$$\frac{dP}{dz} = C_A P m$$

where P is the precipitation rate and C_A is an empirical constant.

Below cloud base, precipitation is evaporated as it falls to the ground. Snow is assumed to reach the ground if the freezing level is below 310 m.

c. Convective cloud processes

In large scale models, cumulonimbus clouds are modelled by parametrizing the mean effect of a large number scattered throughout

a general area of instability. This approach is inappropriate for a model with a grid length of the same order as the largest clouds. On the other hand, a gridlength of less than two kilometres would be required to resolve the main features of a convective cloud. It has therefore been judged necessary to parametrize them while recognising that a satisfactory representation of the dynamics involved will not be obtained. The scheme used in the model is based on that described by Fritsch and Chappell (1980). An important departure from schemes used in large scale models is that the cloud has a specified lifetime of an hour. The cloud can move during its life but the details of the cloud's life cycle are not modelled. Its growth, maturity and dissipation are all averaged out over its lifetime. The cloud mass flux is parametrized as a function of the maximum deviation of the pseudoadiabatic of a parcel lifted from cloud base from the environment temperature sounding. The criterion for cloud formation is dependent on the formulation of the boundary layer scheme and in the present model is determined by testing the stability to lifting of layers that already have at least 1 okta of cloud, normally produced by upward turbulent transport of moisture. The updraught is modelled as an entraining plume with inflow below cloud base and outflow where the buoyancy is reduced to zero. The downdraught cools by evaporation below cloud base before spreading out in the lowest three layers of the model. The net mass fluxes from the updraught and downdraught are fed into the model dynamics and result in grid scale subsidence. Finally, air from the updraught and downdraught is mixed into the environment to simulate the dissipation process. Rainfall is determined as a proportion of the total moisture condensed in the updraught, the proportion having an empirical dependence on mean shear and humidity. The remaining condensate is mixed into the environment.

There is clearly a danger of overlapping between the precipitation produced by the convective and stratiform schemes but this has little impact on the predicted rainfall

intensities except in the case of organised mesoscale convective systems. The present formulation of the model is not suitable for simulating these systems for other reasons including the height of the top level.

3. Initialisation

The representation of the initial state of the atmosphere is of critical importance to the quality of forecast that can be expected from the model. As with large scale models, the constraints of near-geostrophy must be satisfied if a stable forecast evolution is to be obtained. However, a short range forecast model must also be correctly initialised with cloud if the temperature and precipitation are to be realistically forecast.

Three sources of data are currently used to initialise each forecast. They are an interpolation of the latest fine mesh forecast (a 6 hour forecast), a 3 hour mesoscale forecast and the surface synoptic observations. It is hoped to include radar rainfall rates and satellite cloud top heights soon. A cycle of 3 hour mesoscale forecasts is maintained throughout the day permitting a continuous passing forward of mesoscale forecast data where observations are not available. The interpolation from the fine mesh model is a complex process since the models are based on different map projections, have a different vertical co-ordinate and different orography. The interpolated fine mesh data are used to replace the large scale component of the mesoscale forecast above the boundary layer. The moisture distribution, all variables in the boundary layer, and short wavelength detail at all levels are retained from the mesoscale forecast. The resulting 'hybrid' forecast data are then corrected by the use of surface synoptic observations. At present the techniques used are purely objective but interactive facilities are being developed and it is intended that the human analyst will be able to influence the process at all stages.

At the surface, temperature, humidity and wind observations are first used to correct the first guess values of these variables. When a well mixed boundary layer is present in the atmosphere, it can be assumed that

information about the surface quickly reaches the boundary layer top. The corrections at 10 m are therefore applied with decreasing weight at higher levels up to a diagnosed boundary layer top.

Surface observations are also used to analyse the cloud amount at each model level and the precipitation rate using the mesoscale forecast as a first guess. The model's precipitation scheme is then used to define the cloud water mixing ratio which, with the analysed cloud depth, will give the analysed rainfall rate. At the 10 m level, fog observations are used to provide cloud water values.

Some comparison runs have indicated that the forecast is quite sensitive to the enhancement of initial conditions described above and, in particular, to the cloud data and surface temperature.

4. The Operational Trial

Trials of the forecast system started in 1984. The results were sufficiently encouraging for an extended trial of two forecasts per day to be started in April 1985.

The objective assessment of this trial has been carried out at all UK observing stations for most observed variables and permits great flexibility in the comparisons that can be made. It has been supplemented by various subjective assessment techniques including comparison with a subjectively produced Local Area Forecast for Bracknell each day. Since December 1985, forecast temperatures have been compared with those forecast by Weather Centres for regional gas boards.

In general, the synoptic scale evolution predicted by the mesoscale model differs little from the fine mesh model, as intended. At its present stage of development it should therefore be seen as a detailed diagnostic tool which enables the effects of topographic variation to be taken into account and, by using more sophisticated physical parametrizations, enables the variables required by forecast users to be predicted directly. Its ability to forecast these variables is now considered.

(i) *Surface Temperature*

The lowest mesoscale model level is at 10 m which enables it to be more responsive to the surface than the fine mesh (first level at about 25 m) but still leaves a problem of how to diagnose a temperature for comparison with surface observations at screen level. At present, the average of the surface soil temperature and the 10 m temperature is used. We have not attempted to use more sophisticated techniques implied by the Monin-Obukhov similarity theory as serious errors can generally be related to the cloud forecast rather than to details of the interpolation between 10 m and the ground. The sensitivity to cloud is greatest at night in winter and in the day in summer. Table 1 shows percentages of max/min forecasts within given tolerances for each month between August 1985 and June 1986. All observing stations are verified including those which fall in the model sea. Most of the maximum temperature errors greater than 4° can be attributed to such topographical differences. Sub-grid scale variability accounts for differences of at least 1°. A more detailed assessment of surface temperature forecasts for a few individual stations has been carried out in comparison with those prepared sub-

Table 1 Percentages of maximum and minimum temperature errors within specified limits for each month from July 1985–June 1986.

Month	Max			Min		
	≤1°	≤2°	≤4°	≤1°	≤2°	≤4°
August	45	77	98	47	79	98
September	45	75	97	44	73	94
October	53	82	98	40	68	93
November	53	85	98	38	63	88
December	58	85	97	43	70	93
January	58	88	99	45	74	95
February	38	74	97	33	59	88
March	51	79	97	38	70	95
April	51	82	98	39	69	93
May	31	58	90	36	65	93
June	30	58	88	27	55	86

jectively for issue to gas boards. Table 2 shows the results expressed as percentages of forecasts within 2° of observed. The afternoon forecasts were issued by the forecaster at the same time as the model results were available and show that in most months, the forecasts are of similar quality for 15 GMT. The overnight forecast for 09 GMT shows that the model is generally slightly worse. However the forecaster did not issue his forecasts until 5 hours after the model results were available in this case.

Table 2 Percentages of forecasts for model (MES) and forecaster (FCR) within 2° of observed at 6 locations for December 1985 to June 1986 a) Forecasts for 15 GMT issued at 07 GMT for model and forecaster b) Forecasts for 09 GMT issued at 19 GMT from the model and 00 GMT from the forecaster.

	SOUTHAMPTON		GLASGOW		MANCHESTER		WATNALL		RHOOSE		LWC		NEWCASTLE	
	FCR	MES	FCR	MES	FCR	MES	FCR	MES	FCR	MES	FCR	MES	FCR	MES
a) Dec	93	90	—	—	90	93	78	89	—	—	100	92	—	—
Jan	96	100	100	93	97	93	100	97	97	77	90	97	93	90
Feb	82	95	92	96	96	92	100	77	85	81	96	92	100	85
Mar	79	75	93	100	86	92	83	79	100	79	96	88	—	—
Apr	83	79	90	83	—	—	79	88	78	78	—	—	—	—
b) Dec	100	71	—	—	94	75	89	78	—	—	—	—	—	—
Jan	96	92	82	89	82	85	95	81	89	63	—	—	79	86
Feb	95	40	83	70	91	95	92	79	100	75	—	—	92	92
Mar	82	86	85	88	92	58	76	55	96	61	—	—	—	—
Apr	81	78	79	83	—	—	83	75	81	77	—	—	—	—

(ii) *Wind*

The placement of the lowest level at 10 m is an advantage when comparing with observations over land which are measured at 10 m. This is borne out by objective verification of the wind speed which has shown that most stations have an RMS error of under 5 knots.

Comparisons with subjectively forecast winds for Bracknell have been assessed on a 5 point scale of relative accuracy with a small difference being one of over 5 knots or 1 point on the 16 point compass, and a large one being over 10 knots or 2 points. Table 3 gives the percentages of occasions in each category for May 1986 and shows that the model is capable of improving on existing subjective techniques.

(iii) *Cloud*

Comparisons of cloud cover forecasts with subjective forecasts for Bracknell have been made in 3 categories—up to half cover, up to 6 oktas and over 6 oktas. The results for April are given in Table 4 and show that the model is only slightly inferior to current

Table 3 Percentages of occurrence of given differences in the error of wind prediction for Bracknell in May 1986.

	1200 GMT (T+6)	1500 GMT (T+9)	1800 GMT (T+12)
Model much worse	0	0	0
Model a little worse	14	14	21
Same quality	52	65	54
Model a little better	31	21	25
Model much better	3	0	0

Table 4 Comparison of Bracknell cloud cover forecasts for April 1986. Categories are up to half cover, up to 6 oktas and over 6 oktas. The score is the difference between the error in categories of the two methods. Each entry is given as a percentage.

	SCORE	9-12 GMT	12-15 GMT	15-18 GMT
Model worse	-2	3	3	0
	-1	20	20	23
	0	54	64	54
Model better	1	23	13	23
	2	0	0	0

Fig. 2 Forecast cloud base from T+1 to T+12 on 3 days in April 1986 compared with observations at London Heathrow Airport.

subjective techniques.

Forecasts of cloud base have proved a more difficult problem. The potential usefulness of the model in forecasting cloud base can be gauged from the comparisons with observations in Fig. 2. They show the evolution of the main cloud base at Heathrow Airport through a 12-hour period for 3 days in April 1986 when there was early morning low cloud. To facilitate comparison, the observations have been classified into the same height bands as used in the model, and each band has then been given a representative height (ie 500', 1000', 2000', 3000' and over 4000'). In all 3 cases there are only minor errors in the forecast of lifting of the low cloud and, despite the poor vertical resolution, they would have given useful guidance to a professional forecaster.

(iv) *Visibility*

At present this is the least promising

Fig. 3 9 hour prediction of fog areas for 0300 GMT 2/7/1986 compared with observations of fog within one hour of that time.

model prediction. In general, too much fog is predicted. There are indications that a 15 km resolution description of the topography is inadequate for fog prediction. The model is also poor at forecasting sufficiently light winds for a physically correct description of fog formation. It is clear therefore that for some time the model will be unable to rival subjective techniques of fog prediction. An example of the model's present capability in forecasting fog is shown in Fig. 3. It shows that the model correctly identified most of the areas where fog occurred but that fog was also predicted elsewhere. This assessment must be treated with caution, however, since most of the forecast areas lie between observing stations.

(v) Precipitation

The precipitation pattern usually follows that of the fine mesh model. However, due to its finer resolution orography, the mesoscale model has a much better representation of orographic enhancement and rain shadow. A comparison between forecast and observed 12 hour accumulations, summed for December 1985 is shown in Figs. 4, 5. The general pattern is in excellent agreement contrasting

Fig. 4 Sum of the 12 hour rainfall totals for each forecast in December 1985, plotted at each observing station in millimetres and contoured at 50, 100, 200, 300 mm.

Fig. 5 Observed monthly rainfall map for December 1985 compiled from synoptic and climatological rainfall observations.

Fig. 6 Precipitation distribution at 1500 GMT 29/5/1986. (a) composited radar observations, (b) 9 hour mesoscale model forecast.

with the fine mesh model where the totals were less than half the actuals over the western hills.

Forecasts of precipitation distribution are difficult to verify in a way that reflects their usefulness, particularly in showery situations. A successful forecast of showers is therefore presented to illustrate the model's potential. On 29th May 1986 the fine mesh model and the subjective guidance based on it suggested that very few showers would occur. Figs. 6, 7 show a comparison of the composited radar rainfall fields and mesoscale model predictions for 1500 GMT and 1800 GMT. Light shaded areas show the boundary of light precipitation while the solid shading indicates significant showers of over 1 mm/hr rain rate. At 1500 GMT the model has correctly kept all significant showers to the

Fig. 7 Precipitation distribution at 1800 GMT 29/5/1986 (a) composited radar observations (b) 12 hour mesoscale model forecast.

eastern half of the country with the most active area in the Thames estuary. Much of East Anglia has been correctly predicted as dry. By 1800 GMT, the significant showers have been mainly confined to a north-south line passing through London. The model has also identified this organisation of the rain, although it has kept rather too many showers to the east.

Snow is distinguished at present if the 310 m temperature is below freezing. Figs. 8, 9 compare a 12 hour prediction of rain and snow areas with the verifying observations for 1800 GMT on 7th January 1986. A belt of precipitation spread into the country ahead of a frontal system in the south west became slow moving and ultimately relaxed away eastwards. The precipitation turned to snow as it moved northeastwards and a quasi-

Fig. 8. Observed precipitation distribution at 1800 GMT 7/1/1986.

stationary dividing line between rain and snow became established as shown in Fig. 8. This line is well reproduced in the 12 hour forecast shown in Fig. 9 including the indication of an area of rain to the east of the snow near the Thames estuary. The forecast overpredicted the intensity of both rain and snow as shown by the larger areas of moderate precipitation in Fig. 9. It also predicted some light precipitation over high ground in the northeast of England which was not observed.

5. Conclusions

A fine scale forecast model has been developed for short range forecasting for the British Isles. Many of the physical parametrizations have been specially written to take account of the scales represented by the model. A sophisticated scheme for analysis of surface synoptic reports has been developed for preparing fine scale initial data of the boundary layer and cloud fields. The complete system has been under regular test since the beginning of 1984 and has produced some encouraging results. Work has now started on finding the best ways of dis-

Fig. 9. 12 hour prediction of the precipitation distribution for 1800 GMT 7/1/1986.

seminating and using the model results as operational guidance.

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