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The use of very high resolution numerical models for short range forecasting

by

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A three dimensional non-hydrostatic mesoscale model has been under development in Met.O.11 for about 6 years. The model appears to be numerically robust, and fairly elaborate schemes for representing surface exchanges, boundary layer turbulent fluxes and cloud physics processes have been developed and tested. Tests have also been made on the model's ability to respond to the presence of orography. This paper assesses the possibility of using this model for operational local weather forecasting.

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1. INTRODUCTION

The 10-level model rectangle (with a grid length of 100km) is currently used for 36 hour forecasts. Several years' experience has shown the model to give advice to the forecaster which is generally useful. Realistic frontal rainbelts, areas of convective activity, anticyclonic subsidence etc. are formed after an initial adjustment period (6 - 12 hours) and, provided that the forecaster is aware of the limitations and characteristic errors of the model, he can combine his knowledge of local conditions with the computer products to give forecasts which are superior to those he might give without the model. The relatively coarse grid length (compared with scale on which local forecasts are required i.e. 10km or so) and the vertical resolution are limitations of the 10 level model. There are several ways in which more detailed information can be inferred from the forecasts:- modelling the effects of mesoscale forcing by one dimensional schemes incorporating synoptic scale information at upper levels together with local surface details (e.g.Bell, 1977), the prediction of surface parameters by statistical modelling of the boundary layer (Met.O.11 and Met.O.9 current research programmes) and elaborate model output statistics (MOS) systems (Swedish and United States Weather Services). There is considerable scope for further development of such schemes for application in the U.K.

When considering the requirements for short range forecasts it is important to keep in mind the uses to which they might be put. By far the largest requirement is for 24 hour forecasts. These are used primarily for forward planning, for example, by the general public, farmers, industry etc. The current requirement for forecasts 0 - 6 hours ahead is confined to cases where wastage of a valuable resource might be saved (water, gas, electricity boards) or where severe weather may endanger life or equipment (fog, ice and snow warnings, shipping forecasts, oil rigs during sensitive operations etc.).

What about floods?

In order for short range forecasts to be useful it is necessary both to be able to transmit the information rapidly and for the user to be capable of reacting accordingly (and have sufficient confidence in the forecast to consider it worth reacting). For some industries, such as the building industry, reacting means redeploying labour which may take a day or so to accomplish. Other industries, such as civil aviation, have benefited from technological progress to make them almost weather independent. However, during the coming years the increasing use of on site micro processor control systems and of dial up computer access will make automatic response to forecasts a more feasible proposition.

Aside from current forecasting practises, there are two ways in which 0 - 6 hour forecasts (projected 'nowcasts') might be performed. One is the rapid subjective digestion of data from different sources (radar, satellite, conventional observations, 10-level model output etc), the identification and recognition of mesoscale patterns in the current weather situation and the prediction of future evolution from an assessment of current trends (Browning 1978). A second method is to have a mesoscale model running in 'data assimilation mode' so that it is continually adjusting to its own internal dynamics, to external forcing and to new observations, and then to run it forward in 'forecasting mode' for an appropriate period of time. The former procedure will require some elaborate electronic gadgetry to display the information in a readily comprehensible form (e.g. time lapse patterns on a CRT screen) and will be most useful in cases where existing persistent mesoscale patterns can be recognised. The forecasting aspect of the scheme is essentially linear and it will not be so easy to use when there is a large element of atmospheric adjustment to local forcing. In the case of existing mesoscale organisation the success of the second technique will depend on the degree to which the model is capable of adjusting realistically to both the large scale forcing and the observational data. It will work better in cases where the mesoscale activity is dependent on local forcing (and consequently relatively independent of data). Much of the observed data will not be in a form which can be used directly in the model, and they will have to be converted, using simplistic relationships, into derived data (e.g. observations of cloud and rain may be used to obtain derived vertical velocities and displacement velocities for insertion into the model).

The first of the two short range forecasting techniques will be relatively free from this problem because of the central role of the forecaster in assessing the data. On the other hand the numerical modelling technique could in principle be used to give 24 hour forecasts (or diagnostic interpretations of any synoptic scale forecast) by extending the integration period. Therefore we should think of these two approaches to surface weather forecasting as complementary, either capable of leading to significant improvements in the other if they were integrated at some future date into a comprehensive forecasting system.

2. REQUIREMENTS

In discussing the requirements for short range forecasting it is important to appreciate that the majority of users express their requirements in terms of services which are currently available (there is no point in asking for the impossible). Consequently if there are substantial improvements in short range forecasts in the future we can expect new requirements to be generated which take advantage of the new techniques. At present we can speculate what these needs might be

(i) Gas and Electricity supply industry: the most important parameters are surface temperature and cloud cover (brightness of natural light). If information on these were available with high enough spatial and temporal detail there could be an increase in efficiency by anticipating areal power demands and switching resources accordingly. This is done to a limited extent at present.

(ii) Water industry: duration and intensity of heavy rain within each catchment area. Information on this could lead to a degree of automation in water management. *Flood warnings?*

Terminal forecasting?

(iii) Civil aviation: unlikely to be any requirements from commercial aviation but an increasing requirement can be expected from private flying, business air traffic and inter airport airtaxi services. There is considerable scope for automation in the provision of detailed briefing information along specified low level flight tracks (perhaps using viewdata systems). The 0-6 hour forecast period would be the most important since most flights in this category will last less than one or two hours.

(iv) Farming: Most weather sensitive farming operations (harvesting, drying, spraying etc) involve the extensive use of machinery which takes time to set up or move. The 24 hour period is consequently likely to be the most useful. Forecasts of shower activity and wind shifts associated with sea breezes or orography, frontal rainfall and other general weather information are required.

(v) Industry: In principle weather sensitive industries such as building and construction could benefit from short range forecasts. In practice, however, they are likely to weigh the costs involved in delaying projects (and meeting costs when forecasts are inaccurate) against the costs of supplying a limited amount of environmental control. As a result they are unlikely to agree to control of their operations by short period weather forecasts although there could be an increasing demand for 24 hour mesoscale information. Certain wind sensitive operations involving moving or assembling large unwieldy items of equipment can however be expected to respond in the 0 - 6 hour period.

(vi) Transport: frost, fog, ice, snow, heavy rain, poor visibility due to low cloud and air pollution are all quantities about which short period information is required and can be reacted to. Much current wastage due to the unnecessary use of de-icing equipment on road and rail might be avoided. Motorway warning signs giving forecasts throughout the length of the motorway could be automatically switched on. Police, fire brigade, ambulance, AA, RAC, BBC motoring unit, road transportation depots and perhaps even driving cabs of long distance road haulage trucks could have automatic consols displaying up to date information and future trends.

(vii) Coastal forecasts: Apart from Gale Warnings, the Met.Office only issues coastal forecasts in a limited way at present. These are transmitted either by the BBC (e.g. forecasts for inshore fishermen) or obtained by personal application to the weather centres. Winds can differ considerably in both strength and direction out to distances of several tens of kilometres, from those measured on land, leading to weather conditions quite different from those described by either the shipping forecasts or the land forecasts. There is probably considerable scope for expansion in this area although, apart from the use of land based view-data, it is difficult to think of any way of transmitting the forecasts except by frequent detailed verbal broadcasts (such a service is already provided for French coastal waters, mainly for current weather and sea state).

(viii) Emergencies: The release of dangerous chemical or radioactive pollution requires a very rapid response. The subsequent drift and deposition depends strongly on the prevailing weather, on details of the low level wind and on the boundary layer structure. Quantitative information of this sort can only be obtained (if it can be obtained at all) from numerical models backed up by versatile trajectory tracing routines. The information contained in currently available synoptic-scale models is insufficient for the purpose. Mesoscale 24 hour forecasts could also be useful in the direction of counter measures in the event of oil pollution at sea and in rescue and salvage operations.

(ix) Armed Forces: Requirements for the armed forces are of three basic types (a) training exercises - use may be made of all available equipment and observing networks (b) limited operational exercises - since these may take place anywhere, only a very limited set of observations can be assumed but the use of home based computers and communications equipment is possible (statistical/climatological techniques may be inappropriate but numerical models could be useful).

(c) full scale operations - use of elaborate equipment cannot be relied on (apart from easily transportable mini-computers) and, except for longer term planning, most of the immediate meteorological advice must be based on conventional techniques and the forecasting experience of the Met.Officers. However, increasing use is being made of automatic control of artillery, missiles, low flying aircraft etc. and meteorological information is likely to be regarded as a necessary input parameter to these systems. The essence of the Royal Navy's role is to be as independent as possible from any shore support, but mesoscale forecasts may be of crucial importance for coastal shipping protection, commando operations and large scale troop landings. Army requirements are for weather advice in the immediate battle area (a radius of about 50km) with a resolution of 2 - 5km. Winds and temperatures are important up to 700mb (principally at lower levels) but upper air soundings may only be available at different times and places from that required.

Numerical models could be useful for filling in spatial and temporal gaps. The main requirement of the RAF is for low level cloud, visibility and turbulence along long flight tracks which may be chosen at short notice. It is difficult to imagine how such information can be provided accurately, if not by numerical models.

3. RELATIVE IMPACT OF LARGE SCALE FORCING AND OBSERVATIONS

For forecasts of many mesoscale features for a short time ahead the most useful information will normally be supplied by a knowledge of present development, but this is not always readily available. Some aspects of the evolving situation can be deduced from animated sequences of pictures obtained from Meteosat and from radar networks, but this type of information is limited to cloud and rainfall. Also the resolution of geostationary satellite information is reduced in latitudes as far north as the UK and at present the areal coverage of the U.K. radar system is restricted. Other information is supplied by hourly surface observations, aircraft winds, and pilot and radiosonde ascents at less frequent intervals. Even if good initial analyses were available their influence would be limited by diurnal modification of the atmospheric boundary layer and by synoptic development. For a synoptic scale advective speed of $10ms^{-1}$ an air parcel would move across Britain in about 14 hours and consequently by 24 hours most of the observational information would be lost out of the down wind boundary. The corollary of this statement is that 24 hour mesoscle forecasts must be obtained from large scale and surface forcing alone. The extent to which this is possible is a matter for experiment, but the traditional practice of experienced forecasters implicitly assumes that it is feasible.

Organised mesoscale activity embedded in the synoptic scale flow (such as frontal rain bands) is unlikely to be quantitatively predictable unless it is detected in the initial data. However, there is some evidence (Browning 1978) that frontal precipitation cells are fairly long lived, and if their development time is short and the large scale parameters governing their growth are adequately represented, it may be possible for a numerical model to predict the character of the rainbelt but not the phase of the rainfall concentrations.

The use of a numerical mesoscale model for short range forecasting is unlikely to be successful if the model does not respond realistically to the large scale forcing, since this will probably be the only source of a good first guess for the three dimensional analysis of observations. If the response to the large scale is realistic then 4D assimilation of observations will continuously correct the model forecast and improve the prospects for quantitative accuracy in the short term. An operational data assimilation scheme will have to have some provision for human intervention which will need to be extremely skillfully executed to ensure that pre-existing mesoscale structure such as the rainbands mentioned above is retained by the model.

The problem of assimilating data into synoptic scale numerical models has been studied extensively. It has been recognised that if an isolated observation, which is inconsistent with the model forecast, is inserted it will give rise to gravity waves which rapidly disperse and dilute the information contained in the observation so that the forecast continues almost unaffected. Since in the atmosphere the wind and mass fields are in approximate geostrophic balance, observations which fail to satisfy this balance will initiate a geostrophic adjustment process. Theory suggests that on scales greater than $2\pi U/f \sim 500$km at mid latitudes (U = wind speed f = Coriolis parameter) the wind speed adjusts to the mass field, while on smaller scales the mass field adjusts to the wind field. The adjustment time is of the order π/f (i.e. a 6 - 12 hours for mid latitudes). This means that on large scales the insertions of pressure information is likely to have the most lasting effect while at low latitudes and on small scales the most influential observations to assimilate are the wind data.

This behaviour cannot be extrapolated to the mesoscale. The problem of mesoscale data assimilation is not primarily one of geostrophic adjustment and there is very little information or understanding at present of what processes and what adjustment times are involved. Different mesoscale phenomena probably respond in different ways and are sensitive to different physical parameters. An unpublished experiment, performed in Met.O.11, illustrates the problem as it affects sea breezes. The mesoscale model was started at an initial data time of 0400Z and integrated to 1200Z for a day (14/6/73) on which good sea breezes were observed. Several integrations were then performed starting at 1200Z (when the sea breeze was well developed) with certain mesoscale meteorological fields replaced by values interpolated from the 10-level model rectangle. The same surface forcing scheme was used for all integrations. The idea behind the experiment was that fields taken from the mesoscale model were to be regarded as analyses deduced from a dense mesoscale observational network while those interpolated from the 10-level model were background values for which no observations were available. The different sets of initial data that were used are given in Table 1.

Experiment	Data taken from mesoscale model	Data taken from 10-level model
1	Nil	Winds and temperatures at all levels
2	Winds at all levels	Temperatures at all levels
3	Temperatures at all levels	Winds at all levels
4	Temperatures at lowest level only	Temperatures at all levels except lowest level and convective instability eliminated. Winds at all levels.
Control	Winds and temperatures at all levels	Nil

TABLE 1

Comparing with the control experiment the cases fell into two categories. Experiments 1 and 2 developed sea breezes which were about 2 hours behind those in the control in both intensity and position. Experiments 3 and 4 were almost identical to the control. This suggests that for sea breezes the winds adjust to the mass field (in complete contrast to geostrophic adjustment) and that the only relevant data required for sea breeze forecasts are details of the surface air temperatures (evidently the development of an elaborate wind analysis scheme is unnecessary for sea breeeze forecasts). Clearly many additional experiments of this kind must be made before the sensitivity of forecasts to initial observations is understood.

Certain weather situations may be dependent on synoptic scale weather parameters at high levels (examples are the clearance of fog under an advancing belt of cirrus, the establishment of lee wave structure, regions of mid level convective instability produced by differential advection etc.) and as a result may be less predictable than purely surface forced phenomena. Modification may be necessary to the synoptic scale model to improve the prediction accuracy of such critical upper air quantities.

4. THE MODEL

The present Met.O.11 mesoscale model is non-hydrostatic and has a 61 x 61 array of grid points, a horizontal grid length of 10km over an area covering England and Wales and 10 levels in a depth of 4km. It can be used in any location (it has also been used for simulating sea breezes in Florida) and the horizontal and vertical resolution, the depth and the area of coverage can be varied without altering the computer code. It is written in Fortran and runs in about 1/5 real time on the 360/195. Assuming that CRAY Assembler is 25 times faster than 195 Fortran (this is consistent with tests indicating that CRAY Assembler is 15 times faster than 195 Assembler), a 24 hour forecast could be run in about 12 minutes.

An operational forecast would have to cover a larger area, say 1100km x 1400km. but might not need so small a grid length, 20km perhaps. The depth of an operational model would have to occupy the whole troposphere, with maybe 20 levels, for two main reasons: a considerable depth is required in order to give the correct upward propagation of gravity wave energy (by avoiding a reflective upper boundary) and mid tropospheric developments are important for surface weather (frontal rainbands, some types of thunderstorm). More elaborate physics would be required (the present model is dry and has no radiation scheme or sophisticated boundary layer turbulence parameterisation). Thus, for such a model, we might expect a 24 hour forecast to be performed in 30-40 mins. on the CRAY.

Almost all British Isles surface observations are received at Bracknell by T+20 mins. UK sondes, however, arrive between T+30 and T+90 (though this may improve when Mark III automation becomes universal). Assuming that subjective information can be conveniently displayed, and assuming that adequate procedures have been devised for human intervention in the data assimilation scheme, we might expect mesoscale analyses and 6-hour forecasts in about T+60 mins for a CPU time expenditure of 10 mins. For main synoptic hours this may be delayed until T+120mins.

5. OBSERVATIONS

The observations considered below should all be considered for use in a small scale 4 dimensional data assimilation scheme.

(i) Hourly surface and current weather observations

These can be subdivided into

(a) observations of temperature, humidity, pressure, pressure tendency and wind.

(b) observations of weather, visibility, cloud type and cloud base.

(i)(a) At present, this is the only source of reliable observations of the primary dynamical variables with a complete areal coverage. The fact that the observations are limited to the surface is a major deficiency, but if a sparse network of upper air observations ((ii), (vi)) can be used to provide the vertical detail, the surface observations might provide the horizontal detail required for a full three dimensional analysis. Since a poor analysis of the dynamical variables will produce a rapid degradation in the quality of the other fields (vertical velocity, humidity and cloud), most effort should be put into the observations and analysis of wind, temperature and pressure. The best use of surface observations of these variables is the most urgent problem in mesoscale and small scale analysis.

(i) (b). These observations are similar in type to satellite (iv) and radar (v) observations in that they give qualitative information that is not easy to interpret in terms of the model fields. Observations of visibility should improve forecasts of visibility either by providing a varying factor relating reality to the model fields or by giving an estimate of pollution. Observations of cloud type and base could be interpreted in terms of boundary layer structure and might be extremely useful, but the accuracy of cloud base estimates would have to be proved. A further use of these data would be to categorise air mass types and, by analysing boundaries between types, use this information to improve the horizontal extrapolation of data provided at a limited number of sites e.g. radio sondes (ii).

(ii) Radio sondes

The 12-hour interval between ascents and the spacing of radio sonde stations are designed to meet synoptic needs. Nevertheless, at present they give the only direct measurements of vertical structure and will be invaluable. Their use is well tried and the only major work required is to discover the extent to which the information they provide can be extrapolated in the horizontal, as described under (i) (a).

(iii) Pilot Balloons

For certain types of phenomena the wind field is likely to become increasingly important as the scale decreases. If this is the case, it will be important to obtain frequent direct and high density measurements of horizontal wind velocity. This will only be provided by pilot balloon ascents, and a study should be carried out into the cost effectiveness of improving the coverage of pilot balloon ascents. High level observations are not required, so the balloons used need to reach an altitude of only about 4km. Three hourly observations would help to resolve diurnal variations and a horizontal resolution better than 100km is unlikely to be justified in view of the probable limitations of model resolution (20km:- see section 4).

(iv) Satellite observations

Satellite observations, particularly Meteosat, could be used to provide guidance for human intervention in the analysis, but any intervention in frequent mesoscale analysis is not likely to be as effective or practical as the present intervention in the operational synoptic procedures. Observations of cloud type and cloud top height could provide useful information about the boundary layer structure and as in (i) (b), about air mass type. Displacement velocities should be investigated as a source of information about wind velocities, but the results are not likely to be as useful in these latitudes as GOES winds in the tropics.

(v) Radar observations

Radar observations are of rainfall only and are limited by the range of the radar. Possibilities exist for interpreting rainfall observations in terms of ascent, and estimates of vertical velocity would be useful and important if they were reliable, and if the horizontal velocities are known reasonably accurately. If either of these conditions is not satisfied the dynamical development of the model forecast will rapidly alter the initial vertical motion field. Again, radar can be used to provide displacement velocities and the usefulness of these should be investigated. Winds derived by radar and by satellite might be combined and calibrated with conventionally determined winds to give additional information at a distance from sonde ascents. Empirically derived quantities (vorticity, divergence, deformation) might also be obtained from cloud and rainfall fields and subsequently used to modify wind fields.

(vi) ADSEL and ASDAR

D.A.Forrester (1978) has discussed the availability of aircraft derived meteorological data for frequent and extremely rapid analysis. These data have been divided into those obtained during cruising, and those obtained during ascent and descent. Jet aircraft do not cruise at heights less than 5km, so these data are probably of limited use for surface weather forecasting (exceptions have been noted above). However, the data obtained during landing and take-off will be useful provided that manoeuvering and temperature lags do not degrade the observations too greatly. Only Heathrow, Gatwick, Shannon and Prestwick are likely to have aircraft of the type involved and observations will probably be limited to daytime. The impact could be similar to 3 hourly radio sonde ascents at Shannon and Prestwick, which both cover significant gaps in the present radio sonde coverage, and 1 hourly radio sonde ascents at Heathrow and Gatwick, where the increased frequency will enhance the information obtained from Crawley.

(vii) Climatological observations

These could be used to study the spatial autocorrelations and provide a means for interpolating between synoptice observations. This information should improve the usefulness of observations for analyses, and provide corrections that can be applied to grid point forecasts before applying these to particular locations.

The observations discussed above fall into two categories

A) Direct observations of primary variables (i)(a), (ii), (iii), (vi) and

B) Observations, usually novel, of other variables (i) (b), (iv), (v) .

For the most part, the observations in (B) must be interpreted, using rather tenuous arguments, in terms of fields that deviate rapidly from their initial values when the wind and temperature fields are in error. Before expending great effort in the use of novel arguments and observations, it is important to understand the processes and fields that control the dynamics of small scale systems, and thus to understand what observations are required for the production of a reliable forecast. In the interim it seems most likely that a better use of the surface observations (i) (a) and improved coverage of pilot balloon ascents will give the best results.

At present all observations that are used to produce objective analyses are stored in a single data bank. In view of the possible increase in the volume of data available for mesoscale and small scale analyses, and the speed with which the data would be required, the establishment of a second data bank dedicated to short range forecasting should be considered.

6. IMPLEMENTATION

At present, the proposal is to develop a four dimensional data assimilation scheme for mesoscale analysis and short range forecasting, and to use it as the basis for forecasts up to 24 hours, though in the first instance tests will be done without an assimilation scheme. In view of the extent to which local weather is forced by the large scale situation, it is expected that the relative importance of the model boundary conditions (specified by synoptic scale models) and the initial conditions will be very different to that found in large scale models. The success of the four dimensional data assimilation probably depends on the ability of the model to respond realistically to large scale forcing, and this is a matter for further experiment. If the success shown by the sea breeze case study (Carpenter, (1978)) is found to be representative then, as well as providing the basis for four dimensional data assimilation, the model will be useful as a diagnostic tool for interpreting large scale forecasts in the absence of data.

The work that is required to develop this facility can be estimated as follows.

(i) Model development. The ability of the model to treat the effect of orography correctly is still being tested. (1 man year). The present boundary conditions provide a good basis for further development and work well in the present case study, but the treatment of the upper boundary needs further study, and some upstream roughness is still generated at outflow boundaries. This is a very important aspect of the model and considerable attention should be given to the ability of large scale information to pass through the boundaries into the model ($\frac{1}{2}$ man year). A realistic treatment of boundary layer turbulence, clouds, liquid water and radiation must be developed (2 man years).

(ii) Data assimilation and forecast studies. Many case studies must be carried out to discover the quality of the forecasts that the model can achieve, and which aspects of local weather it is realistic to expect to forecast. In addition, experiments must be carried out into the effect of errors in the initial conditions, and which aspects of the initial conditions determine the quality of the subsequent forecasts. A 4D data assimilation scheme would need to be designed in a way which ensured that sensitive parameters were correctly related in the analysis. Some of these forecasts could be carried out during a quasi operational assessment phase (3 man years). It is not expected that work will be needed on a dynamic initialisation, since, in a four dimensional assimilation scheme, the necessary adjustment can be achieved by using damped integration algorithm or time smoothing. However, the technical aspects of this proposal will require development ($\frac{1}{2}$ man year).

(iii) Analysis and initialisation. In this context initialisation is of the static variety e.g. the proposals of Carpenter (1978). In order to ensure that observations are used to the best effect, it is important to discover the best way of using the equations for the approximate balance that we expect to find at any time between the various model fields (non divergent flow, hydrostatic balance, the Ekman layer equations). A full analysis scheme, including discovering the statistics of model forecast errors, must also be developed (3 man years).

(iv) Observations. It is clear from Section 5 that establishing the best use of the observations is effectively an open ended project. The combination of surface and radio sonde data is the most urgent problem (1 man year).

(v) General Research

This estimate of the work required has made no allowance for separate scientific studies that are of interest in their own right and could lead to major improvements in forecasting. Studies of cumulus development and of airflow past orography are in progress. Studies of the generation of rainbands and of the break up of stratocumulus would be useful, and work on these matters should be started without delay. Over a period of four years, it is realistic to expect that considerable effort will be spent in this area (3 man years).

This rough estimate refers to scientific work (additional programming support will also be necessary). It indicates that the project is considerable, but the total of 14 man years means that a prototype mesoscale forecasting system might be achieved in the early 1980's.

7. REFERENCES

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