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A GUIDE TO NUMERICAL WEATHER PREDICTION MODELS AND THEIR OUTPUT

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This paper will appear as Chapter 1 of a Technical Note entitled "Methods of Interpreting Numerical Weather Prediction Output for Aeronautical Meteorology" to be published by WMO in 1991. Although the emphasis is on NWP output for aviation purposes, much of the content is relevant to public service forecasting. Permission to quote it should be obtained from the Assistant Director of the above Meteorological Office division.

A GUIDE TO NUMERICAL WEATHER PREDICTION MODELS AND THEIR OUTPUT

1. INTRODUCTION

1.1 History of NWP

The Norwegian V Bjerknes was one of the first to propose forecasting the weather using equations which describe the dynamics and physics of the atmosphere, but it was not until 1922 that L F Richardson set out in his now famous book "Weather Prediction by Numerical Process" the fundamental equations on which many later models have been based. Richardson attempted to carry out a manual integration of his equations on a grid of points 200 km apart on 5 layers of the atmosphere. The prediction of enormous pressure changes was attributed at the time to imbalances in the initial conditions, but it was later realised that the errors were due to numerical instability. The matter remained dormant until the early 1950s when electronic computers became available. A group set up in Princeton, USA performed the first successful numerical forecast with a barotropic model, and opened the way to numerical weather prediction (NWP) as it is known today. The first operational model, producing regular forecasts in real time, was introduced by the Swedish Military Weather Service in 1954 and included an objective analysis scheme.

The extra computing power available in the 1950s and 1960s allowed models to develop from the early barotropic and filtered versions to the fully baroclinic models based on the primitive equations. At the same time more detailed treatment of the physical processes in the atmosphere could be included, and by the late 1960s multi-level models had been developed which produced encouraging forecasts of precipitation.

Developments in objective analysis were rather slower in coming than in numerical models. Some of the first successful schemes were based on the iterative method of successive correction, but early versions did not have a sound theoretical basis and it was realised that variational techniques could give a solution which was optimal in some statistical sense. These have developed into what is known as the optimal interpolation method, which is in widespread use today. For much of the period since 1950 the number of observations of use to NWP have not greatly increased, though the situation is changing now with improvements in satellite technology.

As the accuracy of numerical forecasts improved in the 1970s and 1980s its benefits became widely appreciated, and more countries put resources into powerful computers and high-resolution operational models. The models became increasingly tailored to meet the day to day requirements of the users; global models devoted to medium-range prediction have a late cutoff and take a long time to run, regional and mesoscale models have higher resolution and provide timely local guidance. In 1982, with the setting up of two World Area Forecast Centres (WAFCs) at Bracknell and Washington, the benefits of accurate global forecasts of winds and temperatures were passed on to civil aviation. Today NWP products play a vital role in aviation forecasting and airline flight planning.

1.2 NWP operational systems

The NWP operational system is the complete suite of jobs on a centre's computer system which produces NWP products for the user. It is centred around the data assimilation scheme and the forecast model itself, but other essential components are the database of decoded observations, quality control and preprocessing of observations, the database of post-processed products including graphical and digital output, verification and archiving. Depending on the ranges and regions for which forecasting is being attempted, there will be different models within the operational system; perhaps a global model for aviation winds and medium-range forecasting (more than 48 hours), a regional model for short-range forecasting (up to 48 hours), and a mesoscale model for very-short-range forecasting (up to 24 hours) for the local area. There is a natural association between the range to which forecasts are run and aspects of the operational NWP schedules such as the frequency of forecast runs, the lead time for the availability of products, and the cut-off times for the arrival of observations.

User requirements will strongly influence the design of an NWP operational system. At a World Area Forecast Centre for civil aviation, such as Bracknell, the emphasis is on short-range forecasting, and numerical products are required with a short lead time and with a minimum of two issues daily. This is achieved by running global forecasts from 00 UTC and 12 UTC starting conditions using cut-off times of 0320 UTC and 1520 UTC for the arrival of observations. The model elapse time is about 6 minutes per forecast day which allows a timely availability of the products. Clearly, some important observations from around the world will miss these early cut-off times, and so the relevant data assimilation cycles are repeated with a cut-off at a much later time. Data assimilation methods are described in more detail in section 3.

To meet the requirement for more detailed short-range forecasts of meteorological systems on scales which cannot be resolved by global models, regional and mesoscale models offering higher resolution in the horizontal, and in some cases the vertical, make up part of the NWP operational system. They may be run perhaps 4 times a day to provide regular updates on the numerical guidance. Neither can be run entirely on its own as they require values from some larger-scale model at the boundaries. Normally a global model provides boundary values for a regional model, and a regional model provides boundary values for a mesoscale model. Limited-area models require an early cut-off so that the short-range forecasts are received in good time, while global models require a later cut-off to ensure a good coverage of observations from distant parts of the globe. Unfortunately there is a conflict here between the sequence of runs that best meets the operational requirements of a typical forecasting centre (mesoscale, regional, global), and the sequence of runs required to provide the best boundary conditions (global, regional, mesoscale). In the current operational schedules at Bracknell the mesoscale model runs first, followed by the regional model, and finally the global model. Forecasts from an earlier data time, which do not include the impact of contemporary data, provide boundary conditions for the limited-area models, and it is accepted that some degradation of the product may occasionally result.

NWP operational systems require back-up procedures wherever continuity of service is an essential feature. The advent of multiprocessor computers reduces the probability of being unable to carry out an operational run, but reduced processing power may still entail the failure to meet the normal schedule. Back-up products from a previous run are usually used in such instances (eg the previously computed 36-hour forecast replaces an unavailable 24-hour forecast). As a safeguard against prolonged unavailability of a computer, numerical products can be imported from another centre for use in an emergency.

2. FORECAST MODELS

2.1 Basic principles

All NWP models in operational use today solve a form of the primitive equations of motion, which being a statement of the basic laws of physics, provide a description of atmospheric motion on a very wide range of scales. In addition to the main thermodynamic variables of wind and temperature the equations also contain humidity as a variable, allowing moist diabatic processes to be described. The equations are immensely complex and have no analytical solution, so numerical techniques must be used. The meteorological fields at a given time are approximated by a discrete set of numbers which limits the accuracy that can be achieved; motion on large scales will be well represented while motion on smaller scales will either be poorly represented or lie totally beyond the model resolution. Unfortunately, important meteorological processes occur on a very wide variety of space scales and many fail to be resolved by the current range of operational models. However, small-scale meteorological processes cannot be completely ignored as many are a vital component of the whole atmospheric system. Where this is the case their effects are parametrized so that their average contribution on some larger scale may be included in the numerical model. The different parametrization schemes in widespread use at present are described in section 2.3 below.

2.2 Model grids and numerical techniques

There are two commonly-used methods for representing meteorological fields in numerical form; as point values on some grid or as coefficients of the spherical harmonic functions. Associated with these two representations are two different means of providing a numerical solution to the equations of motion; finite-difference methods and spectral methods.

The spherical harmonic functions used to provide a spectral solution are specified by two integers which define the wave number in the east-west direction, and the meridional index in the north-south direction. The number of different spherical harmonic functions used to describe each meteorological field determines the resolution of a spectral model; only those functions representing waves with length greater than some limiting value are used. In two-dimensional wave space the method of truncating the spherical harmonics is usually either rhomboidal or, more commonly, triangular. The prefix T or R of the description of the spectral resolution refers to the truncation method used; for example a spectral model with resolution T106 will apply triangular truncation and resolve all waves up to wave number 106. The spherical harmonics provide a global representation of meteorological variables and enable a rather elegant solution to the dynamical part of the equations to be obtained which is both efficient and accurate. However, where calculations have to be performed locally, such as in the parametrization of sub-grid-scale processes, the spectral method is inappropriate and the meteorological fields have to be transformed to grid-point values. As these parametrization calculations have to be performed at each time step, there are continual transformations from spectral to grid-point representation and back again. The majority of operational global models, including the one at WAFC Washington, use spectral methods.

Finite-difference methods are used by the operational global model at Bracknell and by most limited-area models. For reasons of accuracy they require a uniform grid which, in the case of a global model, is one with equal spacings between the grid points in the east-west direction, as well as in the north-south direction. The resolution of a grid-point global model is usually expressed by the number of points between equator and pole, or equivalently the grid spacing in the north-south direction. The higher east-west resolution near the poles provided by a regular latitude-longitude grid cannot unfortunately be used to give a more accurate solution in these regions as it leads to numerical instability. The instability can be avoided by filtering the fields, but this reduces the effective resolution. Advances in numerical techniques over the years have led to the highly efficient finite-difference algorithms which are in use today.

It is not easy to specify what spectral resolution is equivalent to a given finite-difference resolution as the methods of data representation are so different. A T106 model will resolve wave number 106, which is just under 400 km in length, and advect it accurately. A finite-difference model with 100 km grid spacing can represent a wave of length 200 km, but the errors in the numerical approximations to the equations are so large that there is effectively no accuracy at this scale. 3 or preferably 4 grid points are required to provide a reasonably accurate solution to the advection of this wave. As a very simple approximation a spectral truncation of T106 and a 100 km finite-difference grid provide similar numerical accuracy.

The choice of resolution for a limited-area model is highly dependent on the size of the area it covers. The advantages of very high resolution are offset against having a small model area into which errors from the boundaries rapidly propogate. In practice the area covered by regional models is mainly dictated by user requirements and varies greatly from system to system; some centres run regional models which cover perhaps 10 percent of the globe, while others have models covering a much smaller area which are able to resolve some mesoscale structure.

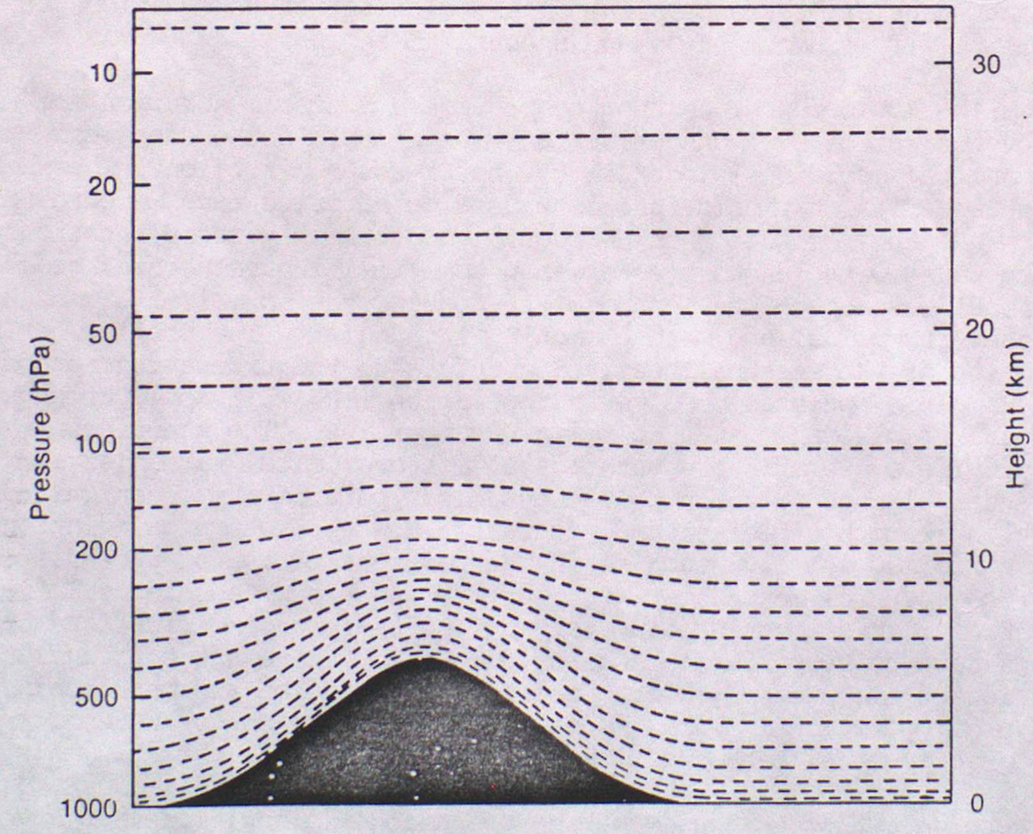

Figure 1. Example of the vertical grid used in a numerical model.

Representation in the vertical in most models is defined by values on a set of levels and finite-difference methods are usually used. The highly uneven surface of the earth has always been a major problem to numerical modelling, and terrain-following co-ordinates are a common solution. They take the form of either sigma co-ordinates (pressure of the level divided by the surface pressure), or a hybrid version which approximates to sigma co-ordinates at low levels and pressure co-ordinates at high levels. An example of a vertical grid, typical of many in operational use in 1990, is shown in Figure 1. The distribution of levels is not uniform; there are several closely-spaced levels in the boundary layer which give a reasonable definition of meteorological processes near the surface, and there is slightly higher resolution around 250 hPa to provide a better definition of the vertical structure of jets and the tropopause. Model surface height, or orography, is usually derived from high-resolution data by averaging it, either at the resolution of the model, or at some lower resolution to provide a smoother lower boundary. Where averaged, for example over a 2-degree box, it must be remembered that many meteorologically important features are completely smoothed out. Many centres therefore enhance the average surface height in order to represent more accurately the physical barrier which mountain ranges present to atmospheric flow.

2.3 Parametrization of sub-grid-scale processes

Many meteorological processes occur on scales far too small to be resolved by numerical models on a global domain and yet are essential components of atmospheric dynamics; for instance, convection is a vital process for exchanging heat and moisture vertically within the atmosphere, yet it occurs on typical scales of 1-10 km which is far smaller than the resolution of current models. The effects of such processes on the scale of the model's grid need to be estimated (parametrized) so that they can be included in the numerical solution to the equations. Parametrization calculations are performed separately at each horizontal point of the model grid. Among the various numerical models used for operational forecasting, there are many different ways in which the sub-grid-scale processes are parametrized, and below is a brief summary of some of the general features common to the models in use at most major centres.

2.3.1 Surface processes

Each grid point of the model represents either land or sea depending on whether the proportion of open water in the grid box is less or greater than 50 per cent. Over sea points the surface temperature is specified from an analysis of sea-surface temperature using observations from ships and satellites. Sea-ice points are specified from an analysis of observed ice limits. Land points are allowed various characteristics; for example, surface temperature, snow depth, ice cover, surface roughness, surface wetness, vegetation type and soil type. A soil model containing a number of layers is used to model the sub-surface heat fluxes. The heat balance equation is used to derive the surface temperature and contains terms for the fluxes of incoming solar radiation, outgoing long-wave radiation, sensible heat up into the atmosphere and down into the soil, and latent heat due to evaporation of moisture and melt of snow. The surface wetness is either set at some fixed value, or is predicted by the hydrological cycle within the model. Terms defining the surface water balance include rainfall, evaporation, snow melt, run-off, and water seepage into the deep soil.

The exchanges of heat, moisture and momentum between the surface and the atmosphere are usually calculated from the well-established bulk aerodynamic formulae based on the use of exchange coefficients. These equations require the specification of near-surface values of wind, temperature and humidity which can be derived directly from the lowest level of the model atmosphere, and a value for the roughness length. A strong dependence on the stability, in the form of the bulk Richardson number comes into these equations.

2.3.2 Boundary-layer processes

Most models aim to provide maximum vertical resolution near the surface so that the structure of the atmospheric boundary layer can be represented, however, the 3-6 model levels which lie in the lowest kilometre in most large-scale models are barely sufficient to describe more than the simplest features. Turbulent mixing plays an essential role in determining the structure of the boundary layer and occurs on scales far smaller than the model resolution. Its parametrization in numerical models is usually achieved by the equations of diffusion using coefficients derived from mixing-length theory. These introduce a strong dependence on local stability or Richardson number. One meteorological process poorly represented by this form of parametrization is shallow convection. It is vital for maintaining the depth of mixing within the boundary layer, particularly over the oceans where moisture plays an important role. In many models the effects of shallow convection are parametrized separately.

2.3.3 Large-scale precipitation

The air at a grid point may become supersaturated as a result of ascent or radiative cooling, and precipitation formed from condensation falls as rain or snow. In some models condensed water or ice may be allowed to remain suspended at the grid point, in which case cloud water or cloud ice is kept as a separate variable and a more realistic representation of clouds is achieved. As the precipitation falls through drier and warmer layers below, its evaporation and, in the case of snow, melting are taken into account with the corresponding transfers of latent heat. In this way the lowering of the freezing level in heavy precipitation can be realistically forecast.

2.3.4 Convective precipitation

A wide variety of convective parametrization schemes are used in operational models and it is impossible to consider them all. Many use schemes, originally developed by Kuo, which assume that convection can only take place at grid points where the model has convergence of moisture. Once this criterion is satisfied a depth of convective cloud is estimated from the vertical temperature and humidity profile. The moisture convergence is used to create cloud; a fraction of the water remains in the cloud layer where it moistens the environment, while the rest precipitates and heats the environment through the release of latent heat.

A different approach is taken in the global and regional models used at Bracknell where a parametrization method based on parcel theory is used. The scheme considers the average characteristics of an ensemble of plumes given some initial buoyancy. As they rise through the model layers they are modified by moist diabatic processes and environmental entrainment. Convection ends when the plumes are no longer buoyant, and at this point they are detrained into the surrounding environment. This type of scheme provides some kind of convective adjustment within a vertical column of the atmosphere, and other types of schemes have been developed which achieve the same end.

As with large-scale precipitation, convection schemes allow for the evaporation of rain and melting of snow in the layers below the cloud base. Not surprisingly, in view of the completely different approaches taken by different parametrization schemes, model precipitation forecasts in areas where convection is dominant are strongly dependent on the type of scheme in use.

2.3.5 Radiation

The heating rate due to radiation is computed as the divergence of the net radiative fluxes which can be conveniently divided into two types; short wave due to incoming solar radiation and long wave due to black-body emissions from atmospheric gases, clouds and the earth's surface. Short-wave fluxes typically depend on solar zenith angle, cloud, and the albedo of the surface, while long-wave fluxes depend on the amount and temperature of the emitting medium, and its emissivity. The contribution from each radiatively-active constituent of the atmosphere (water vapour, carbon dioxide and ozone) are quite different and have to be calculated separately.

The equations governing the radiative fluxes in the atmosphere are very complicated and their solution requires exceptionally large computer resources. All operational forecast models take a number of short cuts; for example, the equations are simplified and the fluxes are calculated infrequently. Radiative heating and cooling rates provided by such detailed parametrization schemes are highly dependent on the forecast humidity fields from the model. Unfortunately, humidity is poorly observed in the atmosphere and of all the model variables it is the least well forecast. Systematic errors can often develop in the model humidity fields and there can be some undesirable feedbacks through the radiation scheme. For this reason it is often found that simple radiation schemes, which lack this dependence on forecast humidity, are surprisingly successful in forecast models.

2.3.6 Gravity-wave drag

Recently interest has centred on the importance of gravity waves in the momentum exchange between the earth's surface and the free atmosphere. Flow over a rough surface or mountains will generate gravity waves on scales smaller than the model grid lenth. They propagate upwards until they dissipate, often in the stratosphere. All parametrizations of the effect make it dependent on the standard deviation of the orography and on the stability of the lowest model layers. The drag only occurs to any significant degree over mountains at high latitudes in winter. In its absence most models show rather too much zonal flow and a tendency to fail to develop blocking patterns.

3. DATA ASSIMILATION

3.1 Observations used in NWP

Table 1 lists the types of observations usually used within NWP, and gives the typical numbers received over the GTS within a 24-hour period. There is considerable similarity in the way observations are used in different numerical systems and, to illustrate the general practice, the Table indicates for each variable whether or not it is used for data assimilation by the system at Bracknell. Figure 2 shows the typical global distribution of observations within one 6-hour time window centred on 12 UTC.

Observation type	Number per day	mslp	temperature	geopotential	wind	relative humidity
Surface land	15000	X	(X)		(X)	(X)
Ships	2800	X	(X)		X	(X)
Fixed buoys	300	X	(X)		X	(X)
Drifting buoys	1200	X	(X)		(X)	
TEMPS	1400		X	(X)	X	X
PILOTS	700				X	
Aircraft reports	4200		X		X	
Cloud-motion winds	6700				X[1]	
Sat. soundings 500km	3500			X[2]		(X)
Sat. soundings 120km [3]	50000		X[2]			(X)

TABLE 1. Number of observations available for NWP. Use by the data assimilation system at Bracknell:

X used
(X) not used
1 certain cloud-motion winds at high latitudes and high levels are excluded
2 soundings over land are excluded
3 soundings at 120 km resolution are not available on GTS

3.1.1 Surface land

Surface reports in SYNOP code provide the basic information on the pressure field over land. Only one observation from any station is normally presented to each data assimilation cycle (see section 1.3.3 below); for a model with a 6-hour cycle only the 00, 06, 12 and 18 UTC observations are used. Most global models only use the values of pressure; regional and mesoscale models with higher resolution often make use of more of the information in the report (perhaps wind, temperature and cloud).

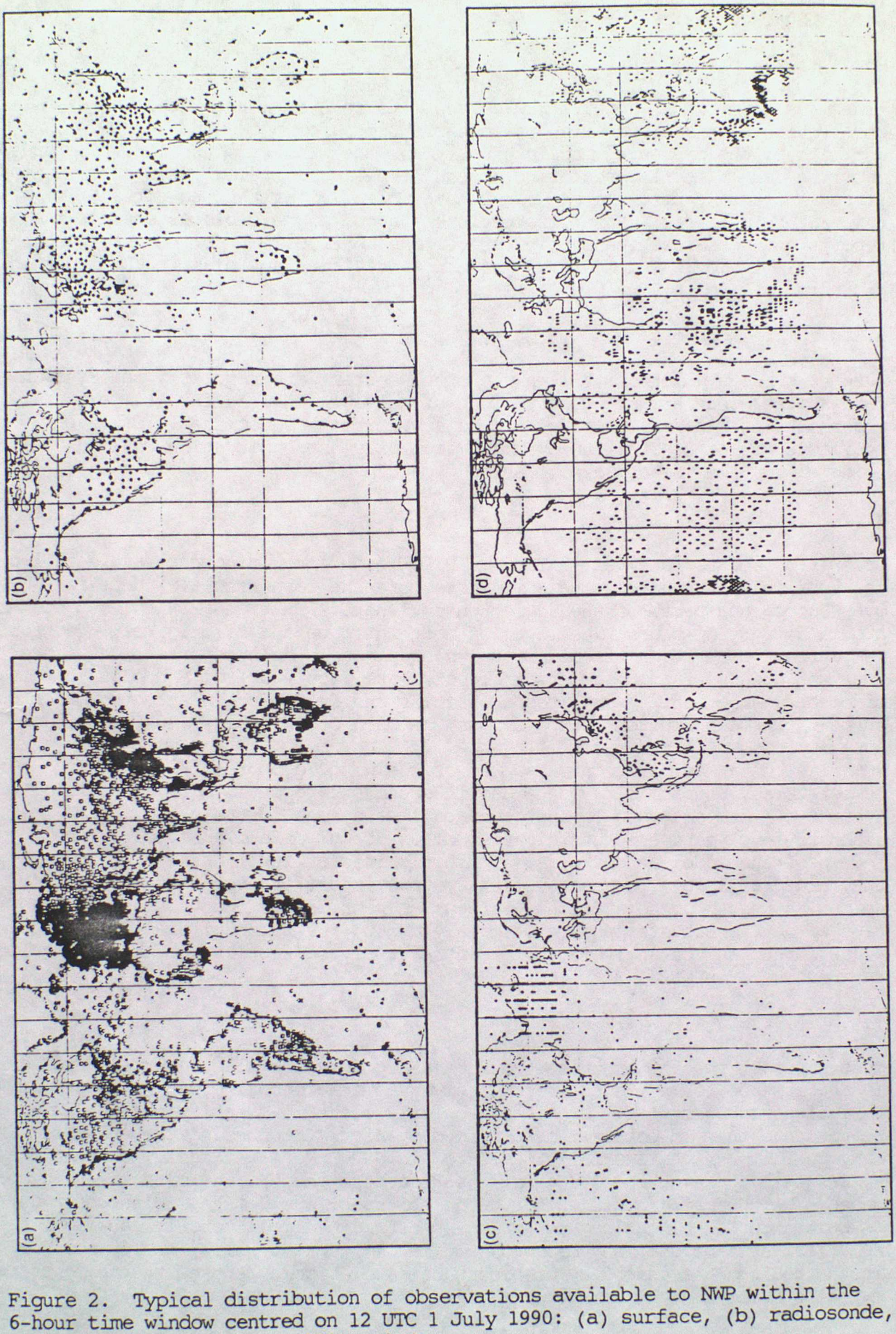

Figure 2. Typical distribution of observations available to NWP within the 6-hour time window centred on 12 UTC 1 July 1990: (a) surface, (b) radiosonde, (c) aircraft, and (d) satellite winds.

3.1.2 Surface marine

Ships, fixed buoys, platforms and riggs report at some or all of the four main synoptic hours, 00, 06, 12, and 18 UTC. Because many rely on manual transmission methods, reports may be received several hours after the observation time and some miss the cut-off times for data used in NWP. In addition to the pressure, models usually use the wind from the report because over the sea it is representative of the large-scale field. Ship observations of sea-surface temperature are used in the creation of the sea-surface temperature analysis. Ship observations are not as reliable as surface-land reports and certain ships particularly prone to error may not be used in the data assimilation. A common type of error is a constant bias in the reported pressure.

3.1.3 Drifting buoys

Automatic buoys which drift with the ocean current are regularly released in data-sparse ocean areas. Observations of pressure, sea-surface temperature, and sometimes wind are received via polar-orbitting satellites. Data are available for each satellite overpass, but only one observation will be selected for use in each assimilation cycle.

3.1.4 Upper air

Upper-air reports received in TEMP or PILOT code, providing accurate detail of the vertical structure of the atmosphere, are the cornerstone of data for NWP. Over Europe and parts of the Soviet Union, where 2 TEMP and 2 PILOT reports are provided every 24 hours, the cover of data in space and time is very good for the current generation of operational global models. In contrast, data cover over the oceans is poor; upper-air reports are received from a declining number of ocean weather ships, some research ships and from certain selected merchant ships which make frequent trips across the main ocean basins (ASAP reports).

Numerical data assimilation makes use of the wind, geopotential (or temperature), and humidity contained in upper-air reports. Many operational systems perform analyses on the standard levels, and for this the standard-level data are sufficient. Some systems perform analyses on the levels of the model and make use of the significant-level data as well where they are available. There are often systematic differences in the reported height at neighbouring stations, largest at high levels and varying with the time of day, which are presumably mainly due to instrumental bias. To obtain a consistent height analysis, some centres apply corrections to the data before they are used in NWP.

3.1.5 Aircraft winds

Most aircraft reports are received in AIREP code which allows certain freedom in the message format, but unfortunately automatic decoding cannot handle all variations successfully. Problems regularly occur in identifying navigation beacons and the mid-point winds provided by aircraft crossing the Atlantic, and many useful observations fail to be used in NWP. More seriously, a great many AIREPs fail to reach the GTS at all as Figure 2c shows; the data cover is good on some of the main routes in northern latitudes, but in the Indian Ocean and on routes to South America and Africa reports are almost totally lacking. All numerical systems use the reported winds from aircraft which, apart from errors in the coding, are generally of high quality. At some centres the temperatures may also be used.

Few, if any, aircraft fitted with ASDAR in the late 1970s are still reporting, but more units are being fitted on selected modern aircraft. They provide automatic communication via satellite of observations every 7.5 minutes in level flight, and more frequently in ascent and descent. During the 1990s new air/ground links via satellite will provide a means of transmitting a great many more aircraft observations to NWP centres than were sent in the 1980s.

3.1.6 Satellite winds

Estimates of wind from the motion of clouds observed from geostationary satellites (SATOBs) are received regularly on the GTS. The problems in deriving wind from cloud motion are numerous and include the assignment of a cloud height, the identification of cloud development and orographic effects. Height is usually related to the cloud brightness temperature but this may not represent the level at which the main bulk of the cloud is moving. Most SATOBS are received at jet-stream levels or in the boundary layer (the tracking of trade-wind cumulus is a major source of these observations). In jets there is often a strong negative bias in the wind speed although the direction is usually reliable. Observations are received from 4 satellites (Meteosat, GOES E, GOES W, GMS) 4 times a day covering an area within approximately 50 degrees of latitude or longitude of the satellite position. A fifth satellite, INSAT, provides limited cover over the Indian Ocean at 06 UTC. Because of the large speed biases in middle-latitude jets, some of these observations are not used in numerical assimilation systems.

3.1.7 Satellite temperatures

Instruments on board polar-orbitting satellites measure upward radiative fluxes at a number of wave lengths in the infra-red and microwave spectrum. The procedures for retrieving temperatures from radiances are complex and require amongst other things the provision of a first-guess profile, which will introduce additional errors. Radiances contaminated by the effects of clouds must also be eliminated and this process is called cloud clearing. The amount of cloud detected within the region of the sounding gives an indication of its likely accuracy and this is used to influence the weight given to the observation within the numerical system. Satellite temperatures are received from 2 polar-orbitting satellites on the GTS at 500km resolution, and over a 6-hour period a global cover of soundings is obtained. Some centres with good links to Washington receive the data at 250 km or 120km resolution.

The vertical resolution provided by each sounding is poor, especially at low levels, but fine horizontal detail can be identified on occasions. Lacking good vertical structure, and being inherently not as accurate as the average radiosonde, soundings over land below 100 hPa are not used in most numerical systems. Over the oceans they are a valuable source of data in middle latitudes, especially in the southern hemisphere where impact studies have show much reduced forecast quality in their absence.

3.2 Quality control

Before presenting observations to a data assimilation system it is essential to weed out those clearly erroneous ones which may seriously degrade the quality of the analyses. Several different quality-control checks may be performed:

(a) Checks on the code format, etc.

(b) Internal consistency checks on the data within one observation.

(c) Temporal consistency checks on observations from one source.

(d) Checks that the observations are reasonably close to climatology.

(e) Checks that the observations are reasonably close to the model first guess or background (a forecast from the previous analysis).

(f) Checks for spatial consistency with neighbouring observations (buddy checks)

Items under (a) include the identification of unintelligible code, and checks to ensure that the latitude, longitude and observation time fall within possible limits. Internal consistency checks (b) include, in the case of radiosonde reports, identification of unreasonable lapse rates and wind shears, and inconsistencies between the various parts of the message. Temporal consistency checks (c) ensure, for instance, that the reported pressure and tendency from a surface observation are consistent with an earlier observation from the station, or, in the case of moving stations such as ships or aircraft, that the reported position is consistent with the position reported at an earlier time. Checks under (e) make use of accuracy of model fields which contain information on observations made at earlier times. A more complex buddy check (f) ensures consistency with neighbouring observations.

The results of all the quality control checks (a) to (f) are combined to produce a single final flag indicating whether or not the observation is to be used by the data assimilation scheme.

3.3 Assimilation methods

A numerical data assimilation scheme provides the initial state required to start a numerical forecast; that is, a value for each model variable at the given analysis time at each point of the model's grid in the horizontal and vertical. It is essential for the system to make full use of all the meteorological data available at all times of day, even though the model may only be used every 12 hours to produce forecasts. There are large areas of the globe with few meteorological observations of any kind and an initial analysis cannot be created by the use of a single set of observations valid at a given time; a means of filling in the gaps in space and time between observations is therefore required, and for this an assimilation model is used. The assimilation model is usually similar to, or identical to, the model used to create the forecasts from the initial analysis. Data assimilation therefore consists of a continuous blending of the observations with the numerical fields provided by the model. The numerical integration of the model enables information contained in past observations to be carried forward in time and space before being blended with information from later observations. For example, the analysed fields over the Atlantic are derived not only from the information contained in the observations in the local area, but also from the information in past observations over North America spread eastwards by the model as it is integrated over several hours or even days. Model fields are constrained to preserve a realistic atmospheric structure and maintain balance between various parameters, and by using a model within the data assimilation system this information is passed on to the analysis or initial state.

All data assimilation systems in operational use today follow the general principles described above, however, the means of blending model and observational information differs from system to system. Two quite different approaches are described below.

3.3.1 Statistical interpolation

Many centres, such as WAFC Washington and ECMWF, use the method of intermittent assimilation and blend observations with model fields by statistical interpolation. In this method assimilation is a cyclical process illustrated in Figure 3 and consists of 4 steps:

1. A 6-hour forecast is performed from the analysis at hour H-6 to produce a background field valid at hour H.

2. Observations falling within the time window H-3 to H+3 are selected and quality control is performed.

3. The observations and the background field are blended by an optimal statistical means to provide an analyis at time H.

4. The analysis fields are initialized to improve their self-consistency producing the final balanced analysis valid at hour H.

Steps 1 to 4 are repeated cyclically to produce analyses at successive synoptic hours 00, 06, 12 and 18 UTC every day. Each cycle of the data assimilation process uses all the data available within the time window; data valid between 0900 and 1459 UTC are used to create the 12 UTC analysis and so on. It is clear that all observations are used irrespective of their observation time. Forecasts are usually only run from 00 and 12 UTC analyses, nevertheless, the observations valid around the intermediate synoptic hours 06 and 18 UTC play an essential part in NWP by providing information which is passed forward in time through the assimilation process.

A form of statistical interpolation is used to combine the observations and the background to give the analysed value of each variable at each grid point. The method is based on the principle of minimising the error in some statistical sense and is often called optimal interpolation. The weights given to each observation at each grid point are then the solutions of a set of linear equations. Several characteristics of the equations are worth noting:

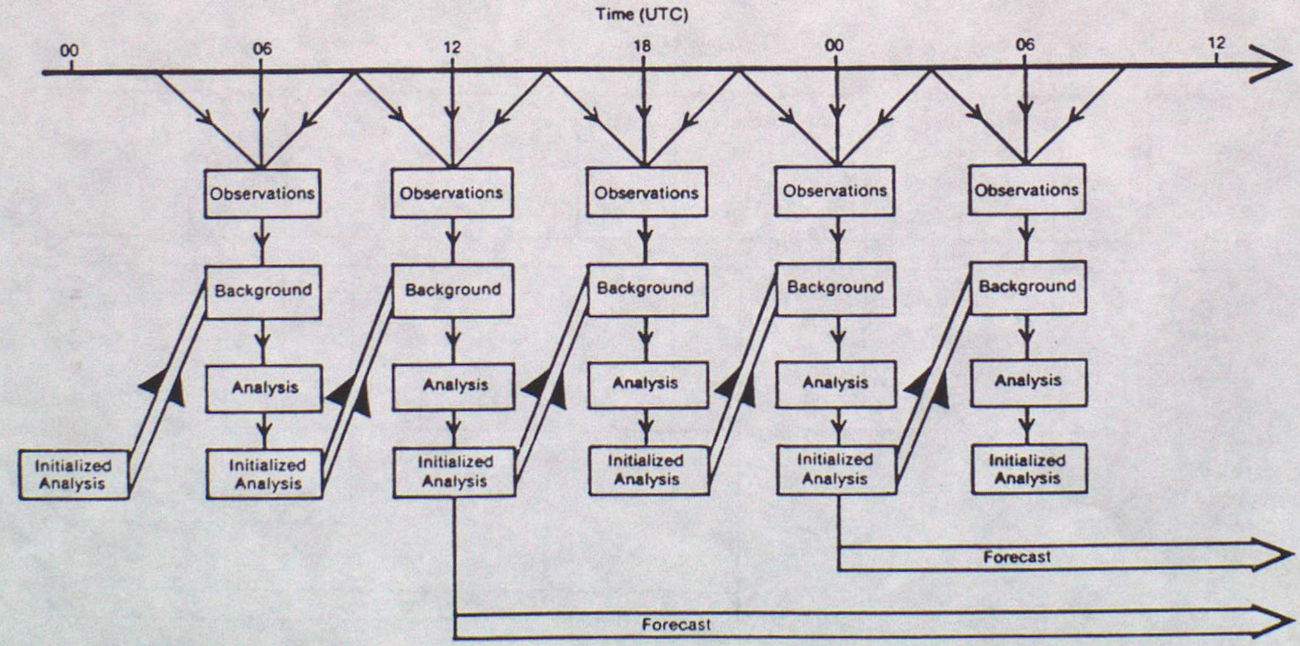

Figure 3. Intermittent data assimilation.

a) The solution of the equations requires considerable time on a powerful computer. If N observations are allowed to influence the analysis at a grid point then an N x N matrix must be inverted, and the process must be repeated for every grid point in the model. For this reason a number of simplifications are often made, for example, only a limited number of observations may be allowed to influence any grid point.

b) Estimates of the error of the observations and the background at any location enter the equations in such a way that observations are given high weight if their assigned error is small or the background error is large. Similarly they are given low weight if their assigned error is large or the background error is small.

c) The equations may be multivariate; that is the observations used to derive the analysed value of a particular variable need not be restricted to observations of that variable. Observations of geopotential height may be used to calculate the analysed value of wind and so on.

d) Because the equations are optimal, realistic sets of weights are assigned to observations, and this is important where they are very unevenly distributed in space. For example, high weight is given to isolated observations and low weight to observations in clusters to allow for data redundancy.

e) The equations take into account known correlations between observations and thereby eliminate redundant information. For instance, some of the information in a satellite temperature sounding is correlated with the information in neighbouring soundings.

3.3.2 Repeated insertion

The bunching of observations into 6-hour time windows is clearly an approximation to what should really be a continuous process. In the system described above observations at 0900 and 1459 UTC are treated as if they are valid at 1200 UTC though they are in fact separated by 6 hours. Meteorological fields can change greatly in 6 hours and sometimes this approximation will be

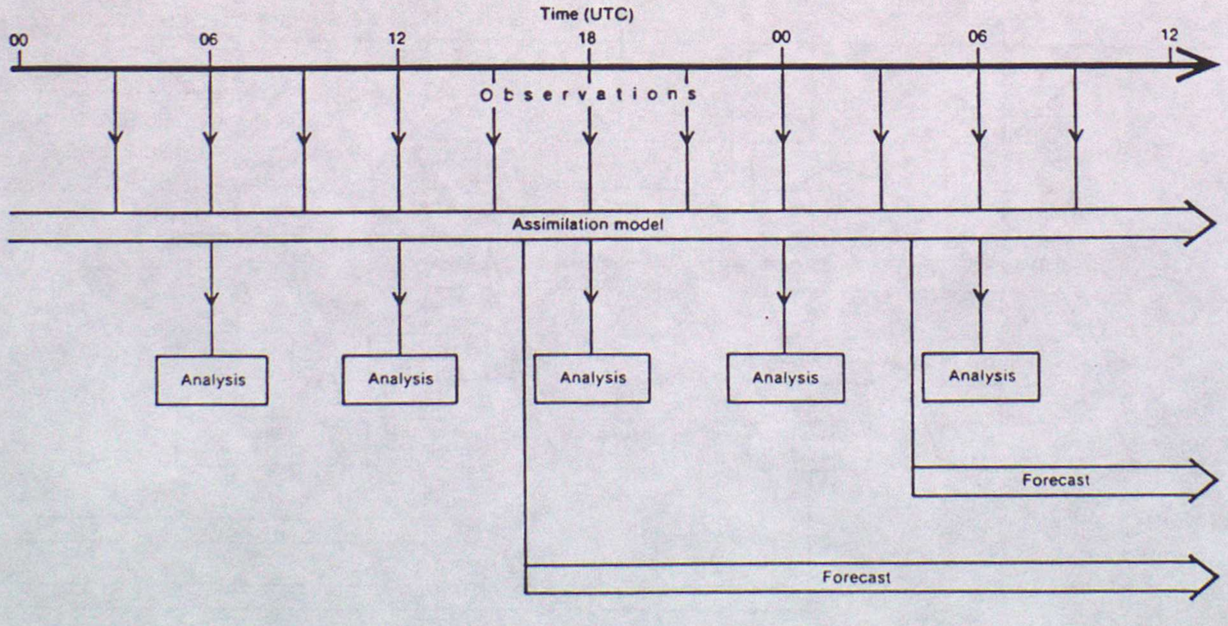

Figure 4. Continuous data assimilation.

inaccurate. The method of continuous assimilation (shown in Figure 4) used at Bracknell differs at steps 3 and 4 of the description in the previous section, and attempts to treat more accurately asynoptic data such as those from aircraft and satellites. A continuous integration of the numerical model is performed, and at each time step the fields are adjusted to give a better fit to the observations. Because the adjustment process cannot be achieved instantaneously, the changes required are applied in small amounts over a period of 6 hours. The weight given to an observation varies over the 6-hour period from zero at the beginning, to a maximum at the observation time, before falling to zero again at the period end. The manipulation of large matrices required in the method of statistical interpolation is avoided, and there is no need to limit the number of observations used. Although the method of repeated insertion is not strictly optimal, the characteristics of the statistical method listed under b) to e) above still hold in general.

By continuously "nudging" the model fields towards the observations in small amounts, balance is approximately maintained by the model and a final initialization step is not necessary. In fact the distinction between where data assimilation ends and forecasting begins becomes rather blurred in this system. Observations are allowed to influence the model even if they are valid after the nominal analysis hour; as the model integration proceeds fewer observations are left for assimilation and the system gradually turns to forecast mode. For example, in the current operational system observations are assimilated up to 4 hours after the nominal analysis hour providing greater accuracy in the earlier periods of the forecast.

3.4 Initialization

The primitive equations, on which numerical models are based, generally admit high-frequency gravity-wave solutions as well as the slower moving Rossby-wave modes. Both types of wave are found in the real atmosphere, but gravity waves, being readily dissipated, are not of major meteorological importance and the atmosphere is close to geostrophic balance. If the analyses produced by schemes based on statistical interpolation are used directly as initial conditions for a forecast, imbalances between the mass and wind fields will cause the forecast to be contaminated by spurious high-frequency oscillations of much larger amplitude than those observed in the atmosphere. Although the damping terms, which are part of a numerical model, will tend to dissipate these oscillations, they make the short-period forecasts noisy and may be detrimental to the quality control and the assimilation cycle. For this reason an initialization step is performed after the analysis with the object of eliminating these spurious oscillations. Analyses produced by schemes based on repeated insertion do not require a separate initialization step since balance is generally achieved during the assimilation process.

4. NWP PRODUCTS FOR AVIATION

World Area Forecast Centres are required to distribute grid-point data of wind and temperature at various levels as well as information on the tropopause and the maximum wind. Suitably dispayed in graphical or chart form, these data alone are of great value to aviation forecasters, however, a wide range of ancillary fields and derived data may be generated from an NWP system which provide a more complete picture of the numerical forecast. The range of products which can be generated from a numerical system will be illustrated using T+24 forecasts from the UK operational models. Most are used regularly at Bracknell in its role as a Regional Area Forecast Centre. Some may be derived from fields issued routinely on the GTS, but many require data at present only available at the centre. A mixture of charts from the UK global and regional models is shown here, but all products could equally well have been derived from a high-resolution global model. In all cases the model products have been projected onto a uniform grid (about 100 km grid spacing) for output purposes, which is considerably finer than the resolution of data available on the GTS in 1990. The output resolution, both in the horizontal and vertical, of course greatly affects the detail that can be identified.

The products presented here relate to a case of explosive cyclogenesis in the North Atlantic, and all are from the same data time 12 UTC 7 January 1990.

1. Mean sea-level pressure, 500 hPa height, 1000-500 hPa thickness and 250 hPa wind isotachs are shown for the initial analysis (Figure 5) and for the T+24 forecasts (Figure 6). Interest centres on the developing low at about 45N 45W at 12 UTC on the 7th which is forecast to deepen by 46 hPa in 24 hours and move rapidly northeast to a position southwest of Iceland. The fields depict the development of a southerly jet as the upper trough sharpens, and the amplification of the thermal ridge ahead of the low with a wide tongue of warm air spiraling into a warm core over the centre itself. Clearly a classical frontal structure can be associated with this pattern, though the position of a warm front is not entirely clear.

2. Maximum wind and height of maximum wind are derived by finding the maximum value of a quartic fitted to the wind speed at the 5 model levels adjacent to the jet. In this way a better estimate of the maximum wind is obtained than by taking the maximum value at any model level. In this case (Figure 7) the jet is around flight level 310 to 330.

3. Tropopause height and temperature are estimated by identifying the point above 500 hPa where the lapse rate rises above the critical value of -0.002° K/m over a 2 km layer of the atmosphere. This is the WMO criterion applied to observations and works well in most cases with the model's representation of the atmosphere as the relatively smooth contours of tropopause height (Figure 8) demonstrate. However, there are occasions where this criterion picks an unrealistic level at one or two grid points and bull's-eyes appear on the chart. This often occurs where there may be a double tropopause, and more specialized output modelling is required to obtain a consistent field.

The fields presented so far have included some of those traditionally used by aviation forecasters to analyse synoptic development in middle latitudes. However, a much wider range of fields can be generated from a model to give a broader insight into the evolution and to help in the interpretation, particularly where (unlike in this case) the meteorological development may not be clearly defined. Examples of some of these charts follow.

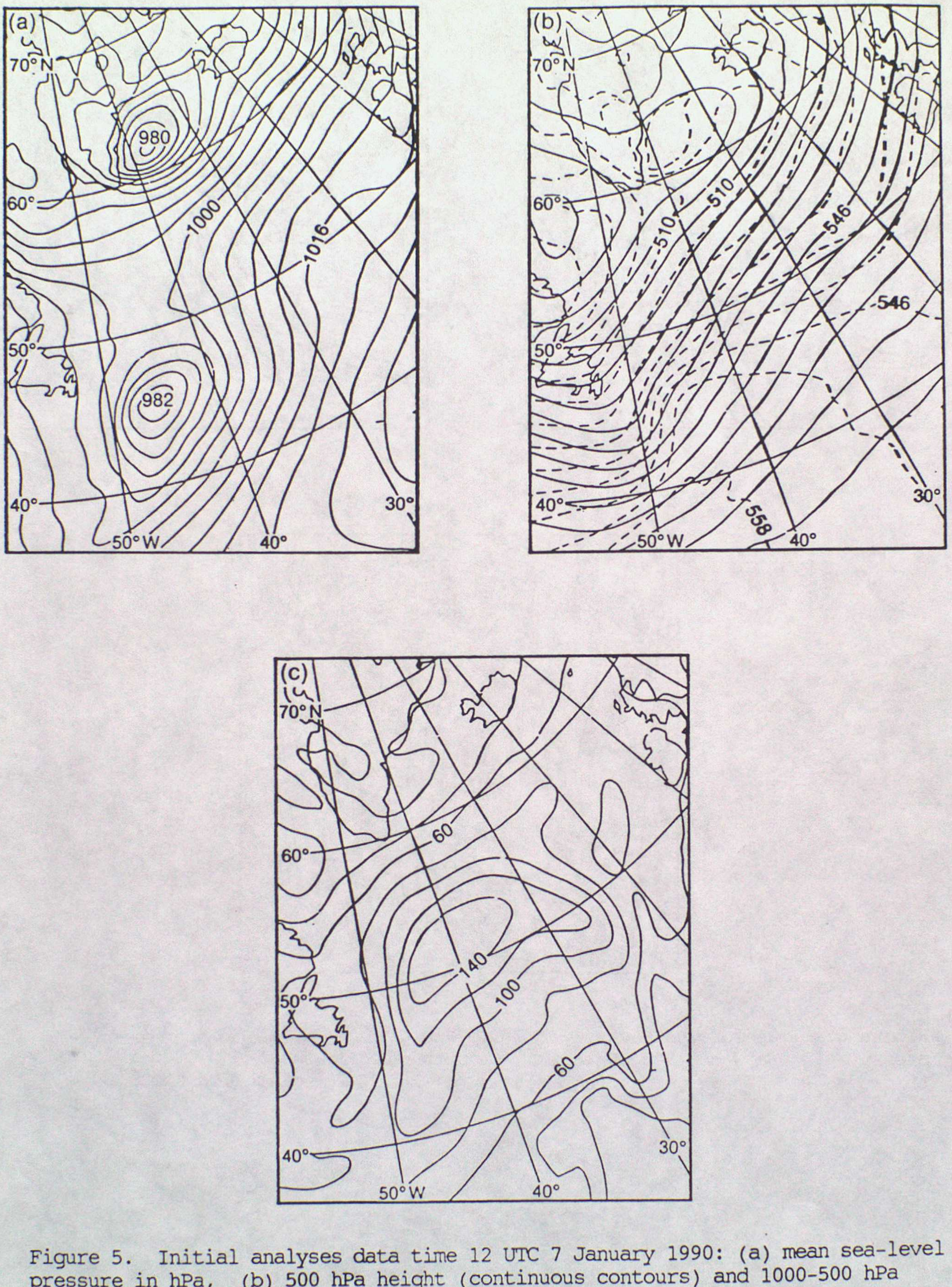

Figure 5. Initial analyses data time 12 UTC 7 January 1990: (a) mean sea-level pressure in hPa, (b) 500 hPa height (continuous contours) and 1000-500 hPa thickness (dashed contours) in dam, and (c) 250 hPa isotachs in knots.

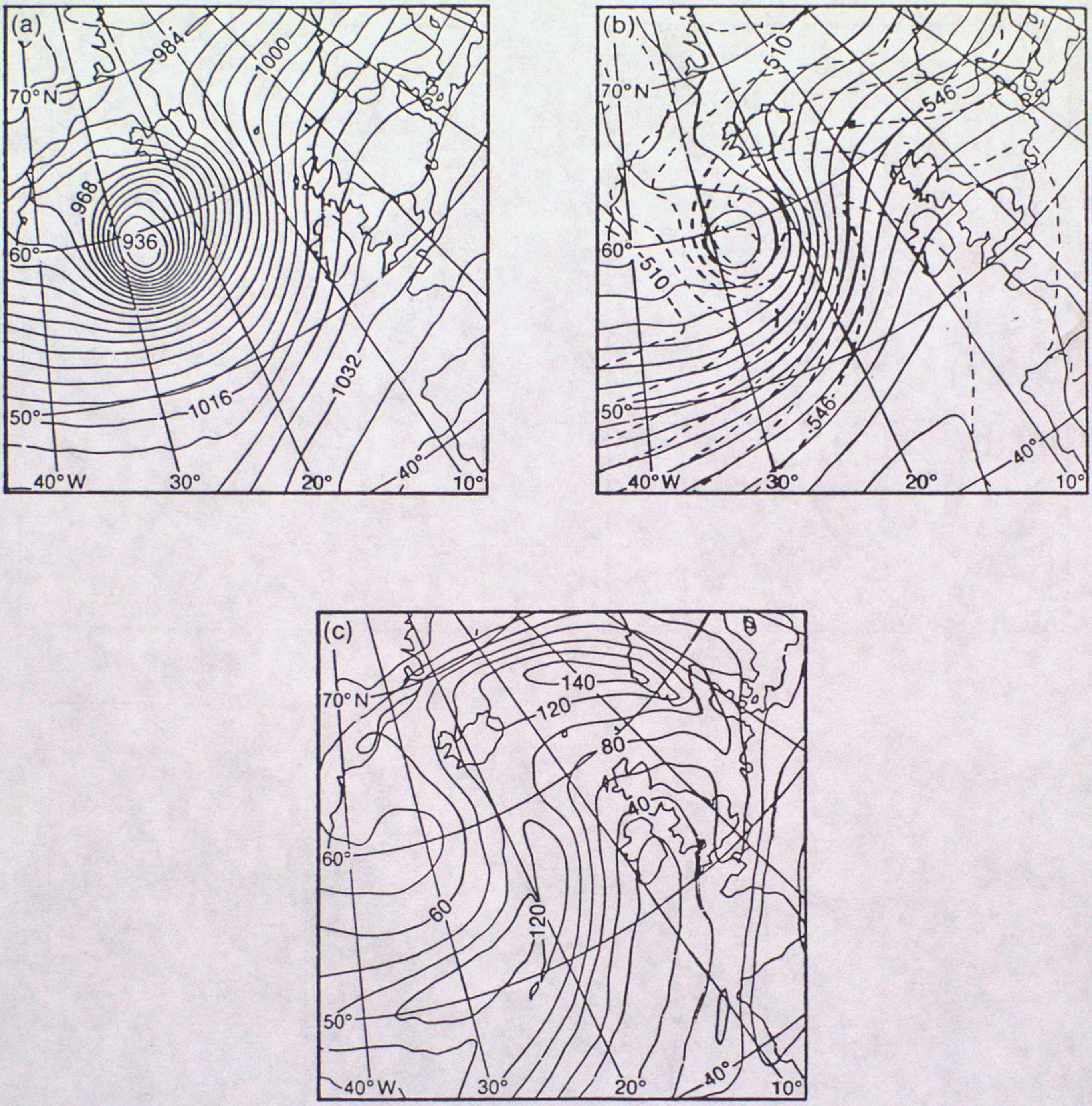

Figure 6. T+24 forecasts valid 12 UTC 8 January 1990: (a) mean sea-level pressure in hPa, (b) 500 hPa height (continuous contours) and 1000-500 hPa thickness (dashed contours) in dam, and (c) 250 hPa isotachs in knots.

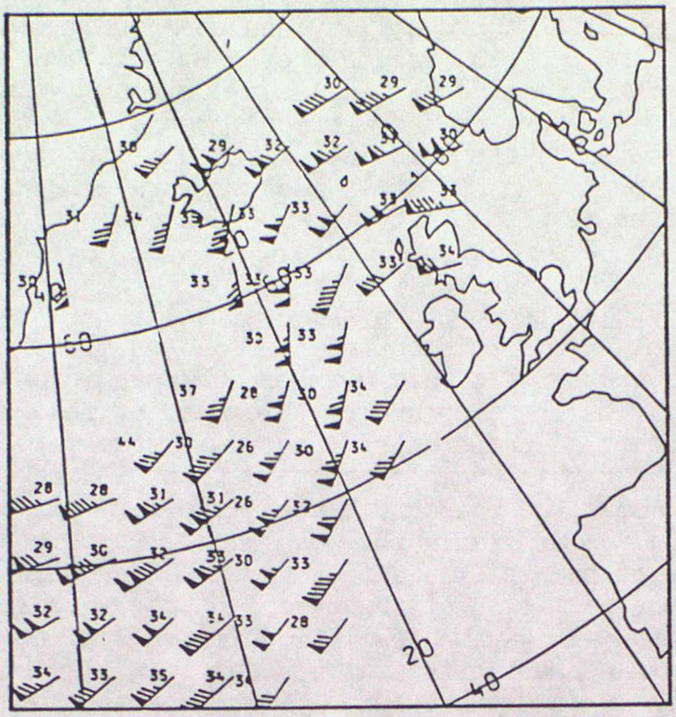

Figure 7. T+24 forecasts valid 12 UTC 8 January 1990: maximum wind in knots (values greater than 70 knots plotted), and height of maximum wind in 1000's of feet.

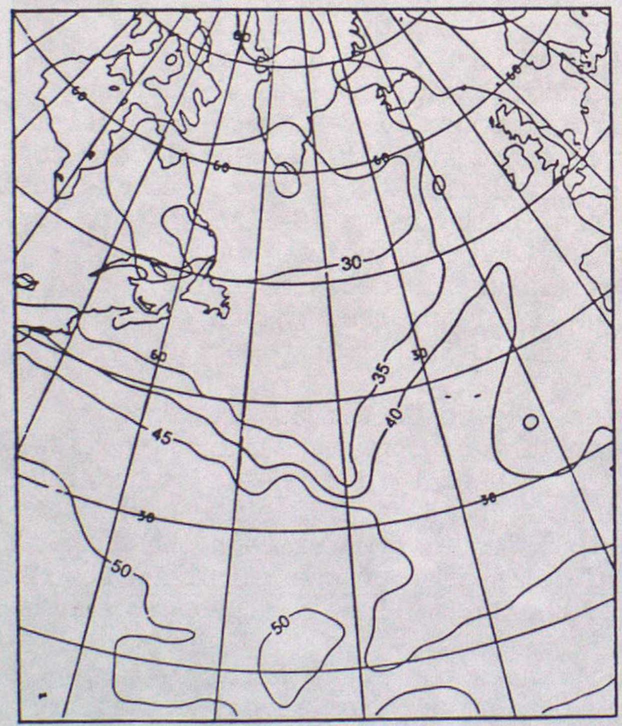

Figure 8. T+24 forecast valid 12 UTC 8 January 1990: tropopause height in 1000's of feet.

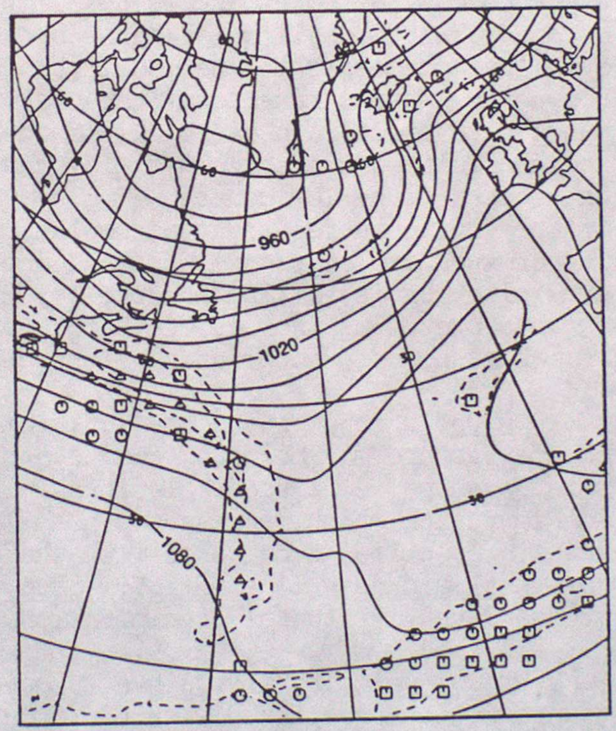

Figure 9. T+24 forecast valid 12 UTC 8 January 1990: 250 hPa height in dam (continuous contours), and percent probability of encountering CAT of moderate intensity per 100 km of flight path (dashed contours). The level of maximum CAT is given by the symbols: squares=300 hPa, circles=250 hPa, and triangles=200 hPa.

4. Clear air turbulence (CAT) probability has been estimated by a number of empirically-derived indices. The values presented here (Figure 9) are based on a simple function of the model's vertical and horizontal wind shear (Dutton, 1980), and have been averaged in the vertical over 3 layers. The level of the maximum CAT is indicated by the symbols. Forecasts are presented as probabilities of encountering CAT of at least moderate intensity per 100 km of flight path. The average probability is around 2 percent and dashed contours of 4 and 6 percent are shown in the Figure.

5. 850 wet-bulb potential temperature (Figure 10a) is a very valuable tool for identifying low-level thermal discontinuities and enables fronts and other air-mass boundaries to be positioned with greater precision than can be achieved by using fields of temperature, thickness or mean sea-level pressure alone. Wet-bulb potential temperature (theta-w) is conserved in all moist adiabatic processes. In this example the cold front is close to the 10°C line at about 20W which marks the boundary between the warm air to the east and the colder air to the west. Similarly the warm front, which could not be easily placed by reference to the thickness field, can be associated with the 8°C line across Ireland on the warm side of the strong theta-w gradient. The occluded tongue of high theta-w air can be easily identified curling back towards the centre of the low. A weakening frontal boundary can also be identified across northern France, Denmark and the Baltic. Most forecasts of the thermal structure of fronts show similar sharp theta-w gradients, even where the front may be quite weak and other numerical fields are of little help.

6. Precipitation rate and accumulation direct from the model have immediate forecasting applications. The precipitation rate (Figure 10b) is usually averaged over a few timesteps to eliminate high-frequency changes, and it is often useful to distinguish between the precipitation deriving from the dynamical processes in the model (the o's) and that deriving from the convective parametrizations (the v's). In this example the model develops bands of dynamic rain along all of the frontal boundaries already identified in the analysis of the theta-w field, and widespread showers in the cold air to the south of the low centre. The heaviest precipitation is mostly to the north of the centre where 6-hour accumulations are in the range 10-12mm (Figure 10c). The crosses and stars over Iceland and Norway are grid points where precipitation is falling and the 1.5 m temperature is below freezing; this may be interpreted as snow at the height of the model surface, though a more reliable snow predictor at sea level is described in the next section.

7. 1000-850 thickness (Figure 10d) is often used to determine rain/snow boundaries and may be converted to a probability of snow by various empirical relationships. One such relationship has been used to derive the dashed lines in Figure 10b which represent probabilities of 20, 50 and 80 percent at sea level. Practical experience with the regional model over Britain shows that a forecast thickness line of 1300m is a good delineator of the rain/snow boundary at sea level in frontal precipitation, and the 1285m line in a showery airmass.

8. Vertical velocity at 700 hPa (Figure 11) shows the areas of large-scale upward motion associated with the frontal boundaries. The largest values lie just ahead of the intense low centre. The field may contain much grid-scale noise, particuarly in the tropics, and some averaging in the horizontal and vertical may be desirable. In the tropics vertical velocity can greatly help to identify the structure of synoptic-scale systems forecast by the model.

9. Forecast tephigrams (Figure 12) have immediate application where forecasts for particular sites are required, though they can also be useful for giving an indication of airmass characteristics. In this example the warm air aloft ahead of the surface warm front can be seen at Stornoway (58N, 6W). In all

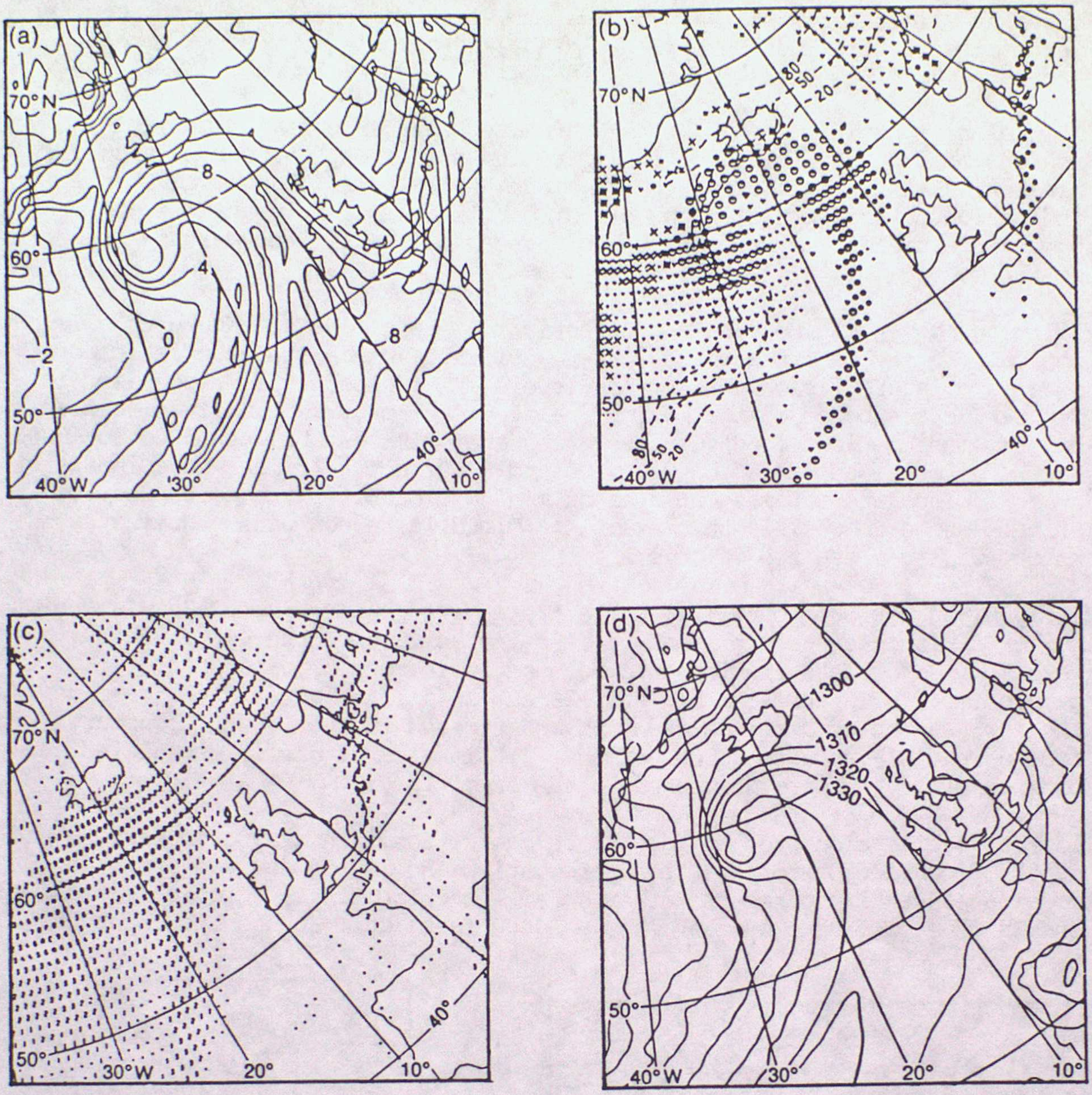

Figure 10. T+24 forecasts valid 12 UTC 8 January 1990: (a) wet-bulb potential temperature in °C, (b) snow probability (dashed lines) in percent, and precipitation rate (o's dynamic, v's convective, and x's snow), (c) 6-hour accumulation of precipitation in mm (A=10, B=11 etc.), and (d) 1000-850 hPa thickness in dam.

cases the limitations of the numerical model in accurately representing the vertical structure must be borne in mind, and this is covered in more detail in section 6.5.

10. Relative humidity at 700 or 500 hPa are useful fields for delineating regions of frontal cloud, and in Figure 13a cold fronts appear particularly clearly. Relative humidity at 950 or 850 hPa (Figure 13b) may give some indication of the spread of low cloud, but if it is fairly shallow and capped by an inversion it may be poorly represented by the limited vertical resolution of the model.

11. Cloud cover may be obtained directly from some models. Where this is not the case it may be represented in terms of the average characteristics of the model's moisture field over several levels. Two cloud types recognised in Figure 13c are based on the maximum relative humidity within given vertical bands; medium cloud (open circles) lies approximately between 5000 to 15000 feet and low cloud (dots) between 100 and 5000 feet. It is a good indicator of frontal cloud and the leading area of medium cloud over the north west of Britain shows up well in this example. Cloud where convection dominates is seldom well represented in this way.

12. 500-850 wet-bulb potential temperature difference (Figure 13d) is one of a number of indices used to identify deep instability in the extratropics. Values of 2K or less are found to be good indicators of widespread cumulonimbus. In this example at T+24 sub 2K air is found in the warm core of the low, in the cold air between 55N and 60N and in the frontal boundary lying from northern France to North Germany. It is a particularly useful indicator of instability in warm airmasses in summer months.

13. Convective cloud top and depth are useful for identifying the extent and depth of convection for aviation forecasting and may be derived from the model's convective parametrization scheme (section 2.3.4). Figures 13e and 13f show high significant weather (above 20000 feet) at T+36 and highlight the

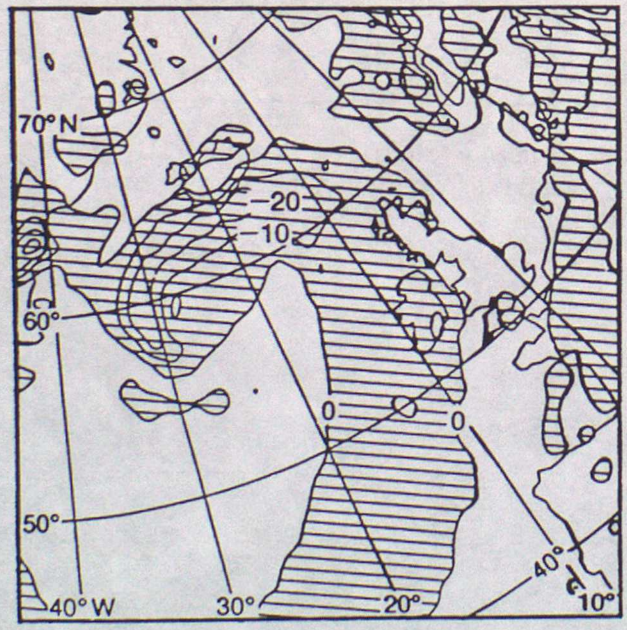

Figure 11. T+24 forecast valid 12 UTC 8 January 1990: 700 hPa vertical velocity in hPa/hr (upward motion is shaded).

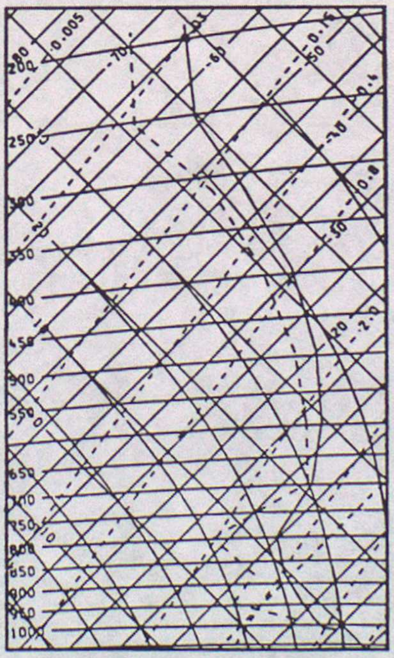

Figure 12. T+24 forecast valid 12 UTC 8 January 1990: tephigram showing the vertical profiles of temperature and dewpoint at Stornaway (58N, 6W).

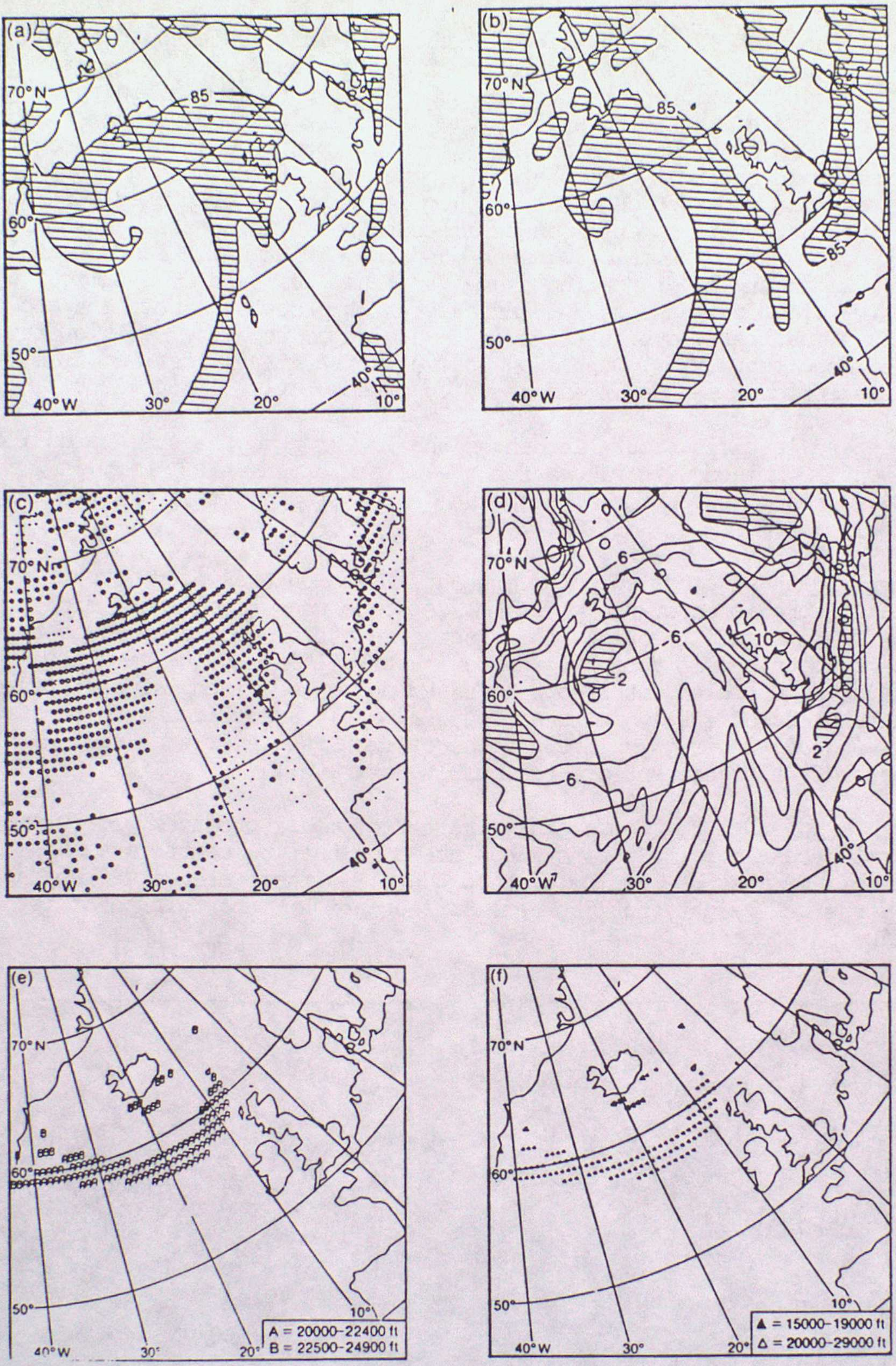

Figure 13. T+24 forecasts valid 12 UTC 8 January 1990: (a) area of 500 hPa relative humidity greater than 85 percent (shaded), (b) area of 950 hPa relative humidity greater than 85 percent (shaded), (c) parametrized medium cloud (open circles) and low cloud (dots), and (d) 500-850 hPa wet-bulb potential temperature difference in °C (less than 2°C shaded). T+36 forecasts of high significant weather (above 20000 feet) valid 00 UTC 9 January 1990: (e) convective cloud top in 1000's of feet, and (f) convective cloud depth in 1000's of feet.

band of cloud tops (20-22,000 feet) in the cold air to the south of the low centre. Cloud is one of the parameters forecast least well by numerical models, and systematic errors are often evident; for example, in the Bracknell model excessive amounts of shallow cloud are found just below the tropopause representing moist convective adjustment in the model, which is probably not taking place in the real atmosphere. In general it is best to use values of predicted cloud tops and depth in conjunction with the predicted vertical temperature structure to check on the meteorological processes taking place. It is important to distiguish between deep convection which is essentially driven by boundary-layer heating alone, and that assisted by dynamical uplift. Convective cloud output does not indicate which process in dominant and the forecaster must carry out this type of exercise to separate cellular from embedded deep convection. Other convective indices may be derived from model output to indicate the depth and severity of convective instability.

14. <u>Freezing level</u> in Figure 14a shows the lowering to the surface behind the cold front. Combined with values for the height of the -20°C isotherm, the typical region of severe icing associated with deep convective cloud can be obtained.

15. <u>Significant supercooled water content</u>, based on the water content and temperature predicted by the model, may also be used to give an idication of icing. Where a model provides no direct forecast of liquid water content it may be parametrized in terms of the forecast humidity and temperature. An example of supercooled water content based on parametrized values (Figure 14b) shows the areas of likely icing at 700 hPa mostly associated with frontal cloud. Indeed, it is only likely to be of much use in frontal regions where forecasts of water content are reasonably accurate.

16. <u>10 m wind and 1.5 m temperature</u> are direct model products widely used for surface forecasting. The strong winds ahead of the low centre are shown in Figure 15. It must be remembered that over land these are values at the model's surface height, not the real surface height, and this point is amplified in section 6.4.

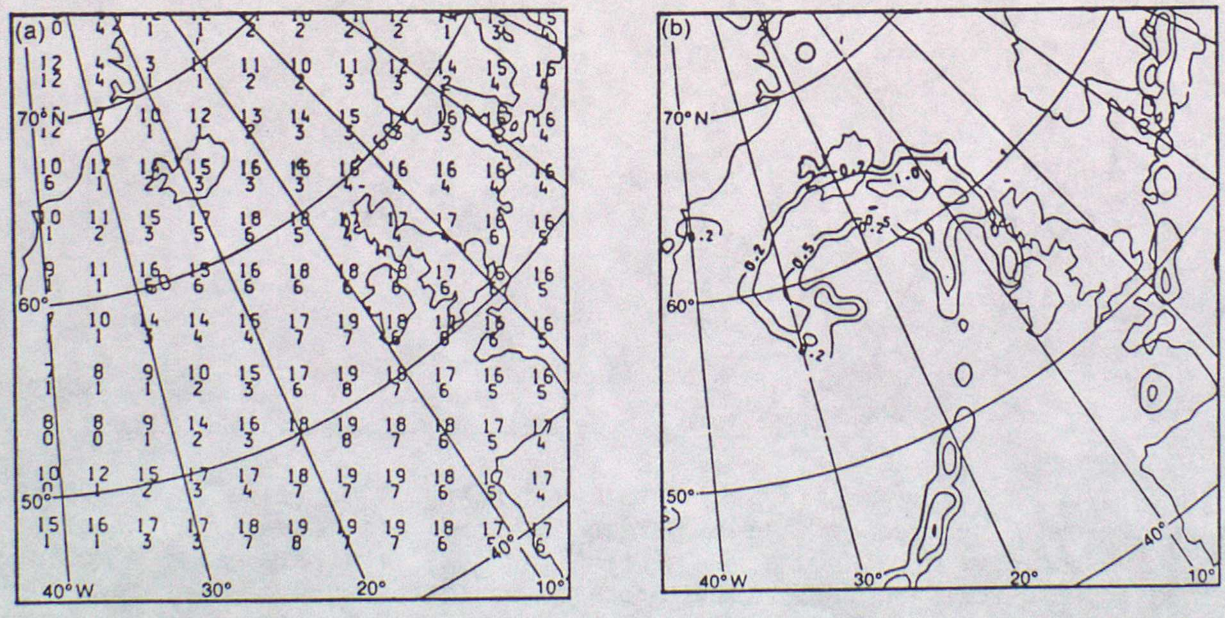

Figure 14. T+24 forecasts valid 12 UTC 8 January 1990: (a) height of -20°C isotherm (upper figure) and freezing level (lower figure) in 1000's of feet, and (b) 700 hPa significant supercooled cloud water content in g m^{-3}.

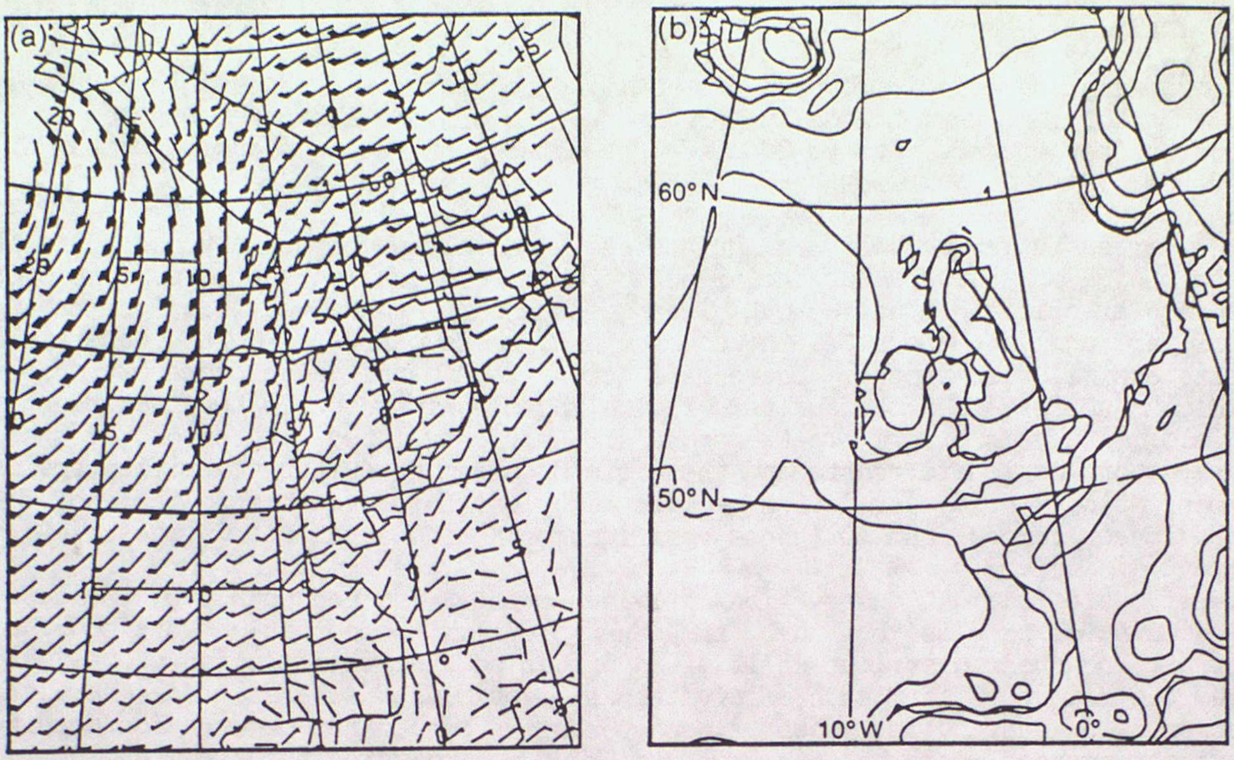

Figure 15. T+24 forecasts valid 12 UTC 8 January 1990: (a) 10m wind in knots, and (b) 1.5m temperature in °C.

5. VERIFICATION

Operational numerical products are verified routinely for three main purposes; to monitor long-term trends in performance, to provide absolute measures of current performance, and to identify the effects of recent changes to the NWP system.

The forecasts may be verified against analysed values, or against observations. The choice of analyses has the advantage that verification can be performed on a regular grid and equal weight given to each part of the verification area. However, analyses are not without error and, where derived from the numerical data assimilation process, there is a strong dependence on the forecast model. In data-sparse areas the analysis fields may closely resemble the background field; analysis errors are therefore strongly correlated with errors of the very short-period forecasts and these fields are most suitably verified against observations. The correlation becomes much less for forecasts in the medium and longer ranges, and for these verification against analyses is ideal.

Verification against observations provides greater independence from the data assimilation process, but there are other problems: observations are prone to error, and their distribution is often uneven so that verification scores which sum the departure from each observation will be biased towards areas where the observation density is highest. Moreover areas of highest observation density are often areas where the analyses and short-period forecasts are most accurate, which introduces another undesirable bias. For this reason observations are best used for local verification performed against a selection of reliable stations providing a uniform distribution over a limited area. There is one further difference between the results from the two verification methods: observations will contain information on scales that the model's analyses cannot resolve; the strong temperature gradients around inversions, local mesoscale effects or the strong wind shear associated with jets may all be observed at a point, but even in a perfect model will be smoothed to the resolution of the grid of perhaps 100km. Verification against observations contains a component representing the contribution from sub-grid scale processes and values of forecast error are generally larger than where analyses are used.

In the sections which follow a selection of verification results is presented from the operational global model used at Bracknell. The medium-range systematic errors in section 5.2 vary a good deal from model to model; otherwise the magnitude of the errors and the characteristics of numerical forecasts demonstrated here are not greatly different from those of other global models in operational use in 1990.

5.1 Long-term trends in performance

Figure 16 shows values of annual rms errors in forecasts of mean sea-level pressure from 1966 to 1989. The forecasts for an area covering much of the North Atlantic and Europe have been verified against analyses. Although restricted to a single variable and a limited part of the globe, this source of verification data is valuable for comparing recent performance with that of previous years. It quantifies the advantage to be gained by the transition from a 3-level quasigeostrophic regional model (1966-1972), to a 10-level primitive-equation model covering the extratropical northern hemisphere (1972-1982), and to a 15-level global model (1982-1989). The trend of improving performance results not only from the two major upgrades to the model specification in 1972 and 1982, but also from the cumulative effect of a multitude of smaller changes made over the 24-year period.

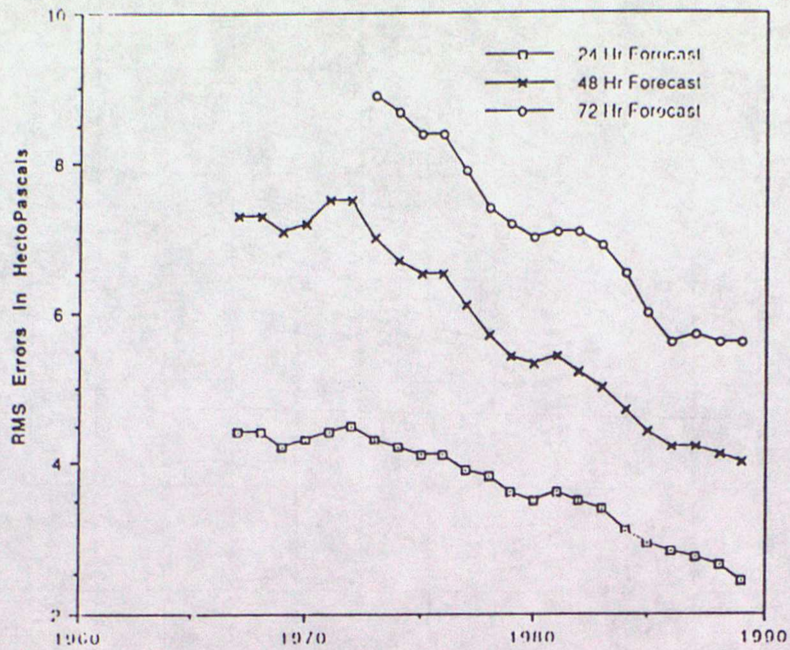

Figure 16. RMS error in hPa of forecasts of mean sea-level pressure, 1967-1989. Verification against analyses in an area covering much of the North Atlantic and Europe.

It is interesting to note that the rms errors at T+48 in 1989 are less than the errors at T+24 in 1966 representing a gain in over 24 hours in forecast lead time before a given error level is reached. At T+72 the gain is even greater.

5.2 Distribution of errors

The global distribution of errors is demonstrated for the 3-month period January to March 1990. Figure 17 shows the mean speed at 250 hPa of the starting analysis and of the T+72 forecasts. The two fields are very similar from which it follows that the growth of systematic errors in the first 72 hours of the forecast is not very large. The mean jet speeds are similar in both cases except the jet to the south of Japan which is 10 knots lighter.

Figure 18 shows the mean T+72 forecast of mean-sea level pressure with the areas marked where the mean errors are greater than +2 hPa (+'s) and less than -2 hPa (-'s). The errors, almost everywhere smaller in magnitude than 4 hPa, are positive in the sub-tropical anticyclones and negative in the high-latitude lows. This indicates that the model forecasts are too zonal. A similar characteristic is noticed in the mean errors in the 500 hPa height field (Figure 19) where the greatest negative values are found at high latitudes and the westerly gradient is excessive.

The distribution of the rms errors is shown in Figure 20 for T+24 forecasts of the vector wind. Errors are largest in the sub-tropical jet in the northern (winter) hemisphere where the atmospheric variability is greatest. At high latitudes values are somewhat larger over the North Atlantic and North Pacific than over the centre of the continental land areas, reflecting that forecast quality is lowest near or downwind of areas with fewest observations. The relatively small magnitude of this land/sea contrast in error levels results from the success of the data assimilation scheme in spreading information from the data-rich to the data-sparse areas.

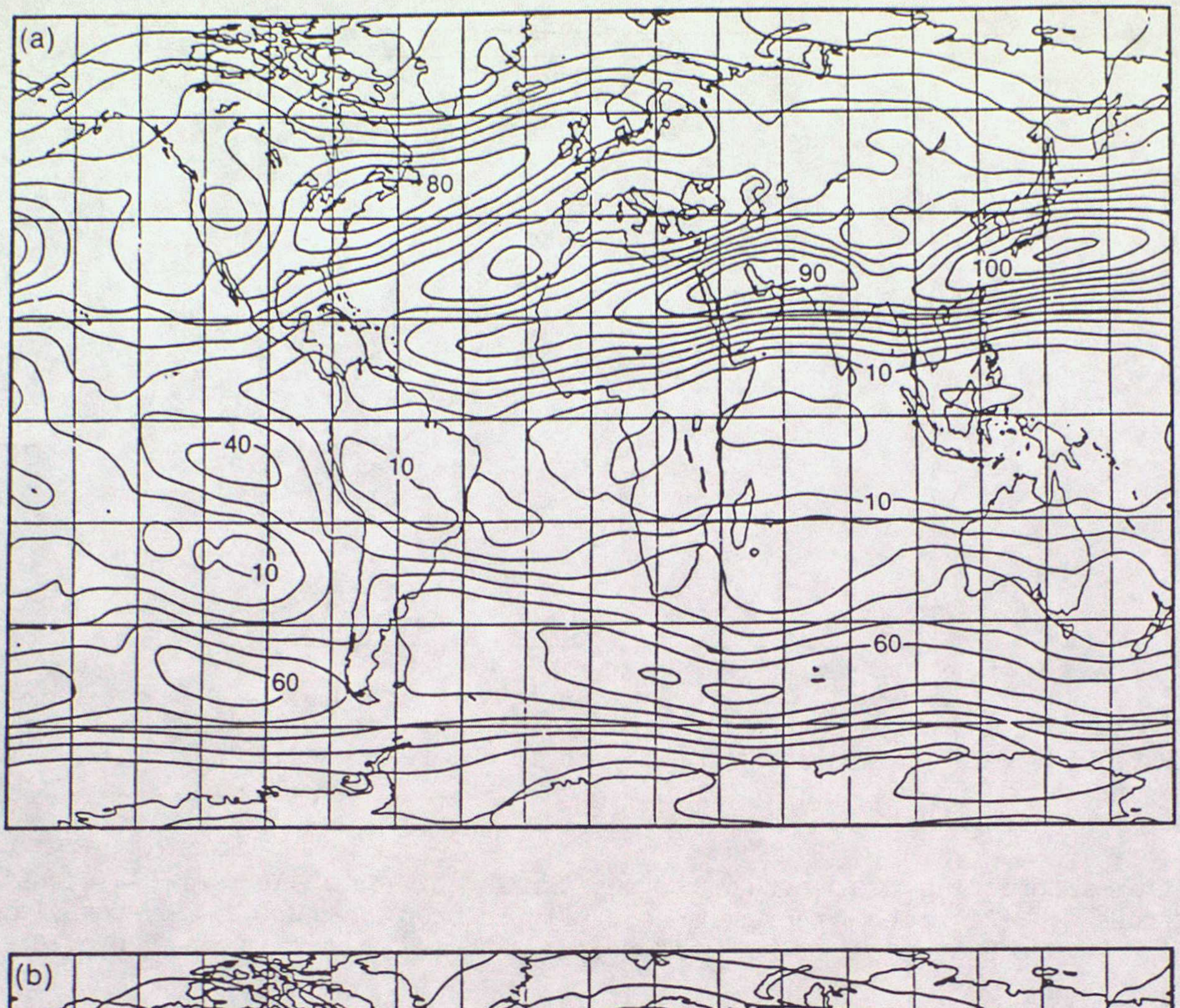

Figure 17. Speed of the mean wind in knots at 250 hPa, January to March 1990: (a) initial analyses, and (b) T+72 forecasts.

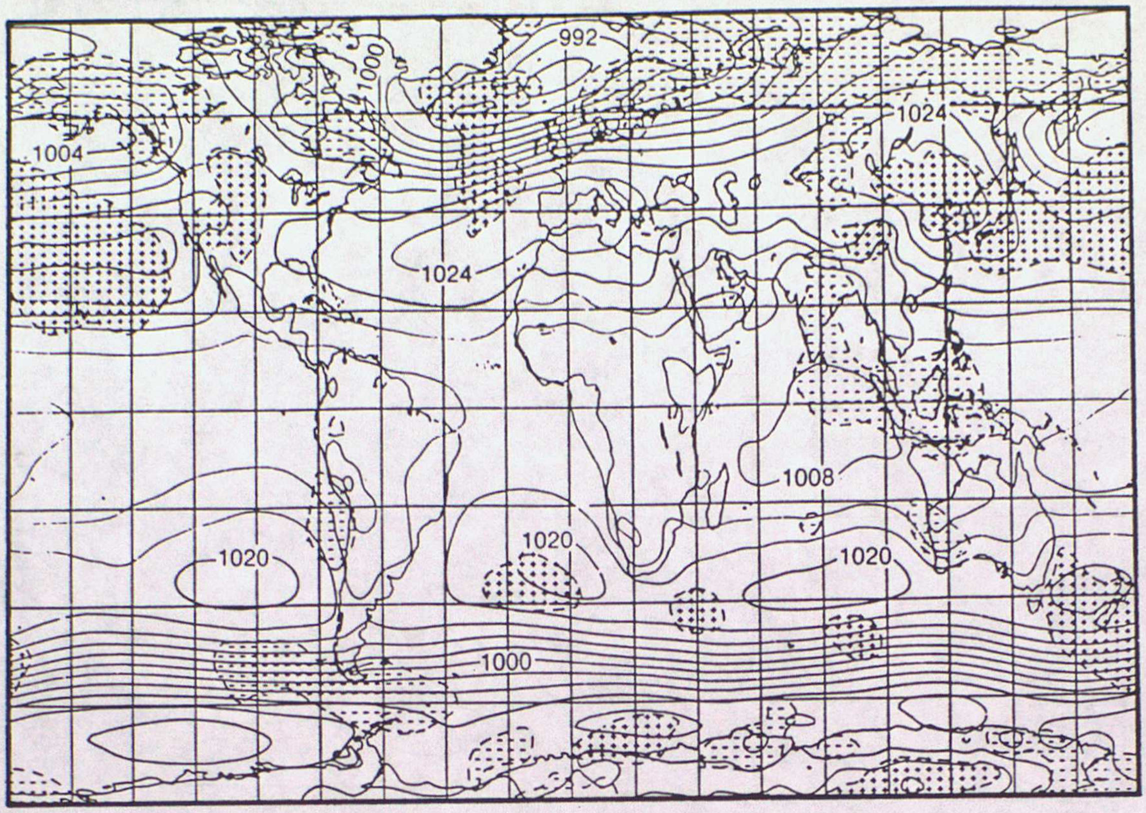

Figure 18. Mean T+72 forecast of mean sea-level pressure, January to March 1990
+ indicates mean errors greater than 2 hPa and - mean errors less than -2 hPa.

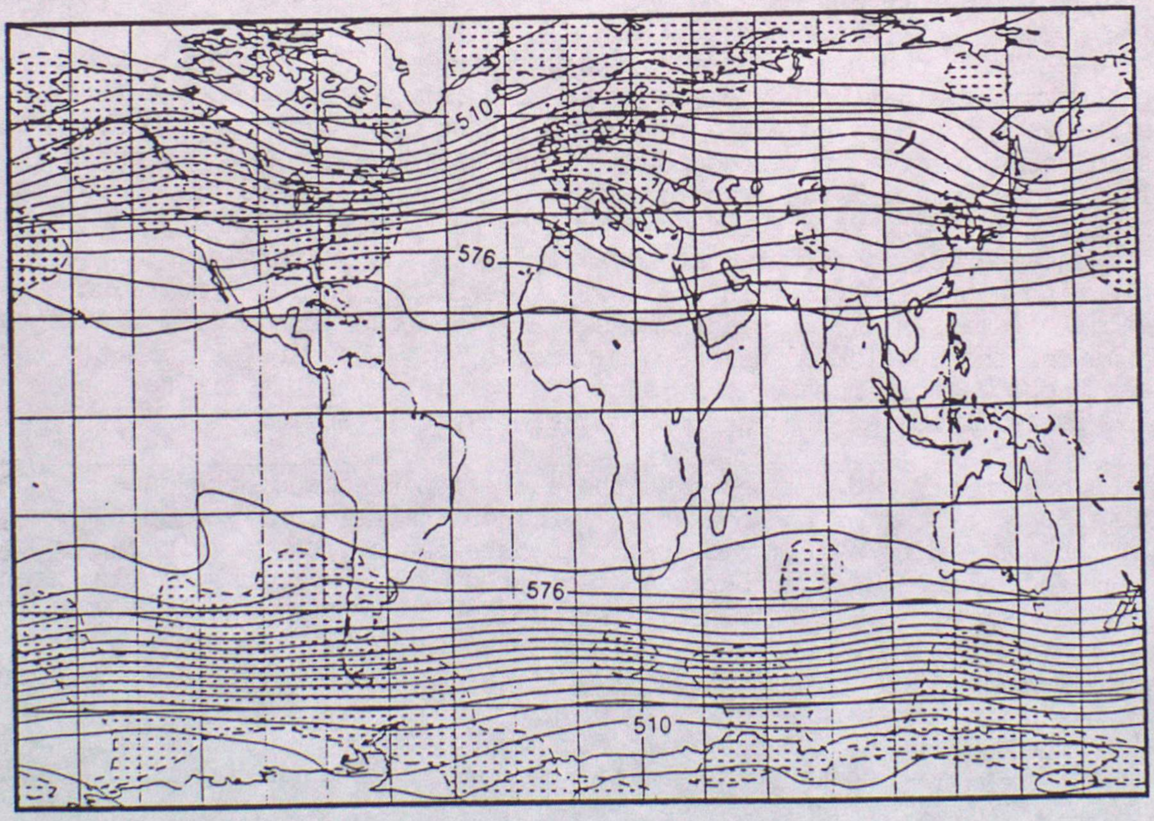

Figure 19. Mean T+72 forecast of 500 hPa height, January to March 1990.
+ indicates mean errors greater than 2 dam and - mean errors less than -2 dam.

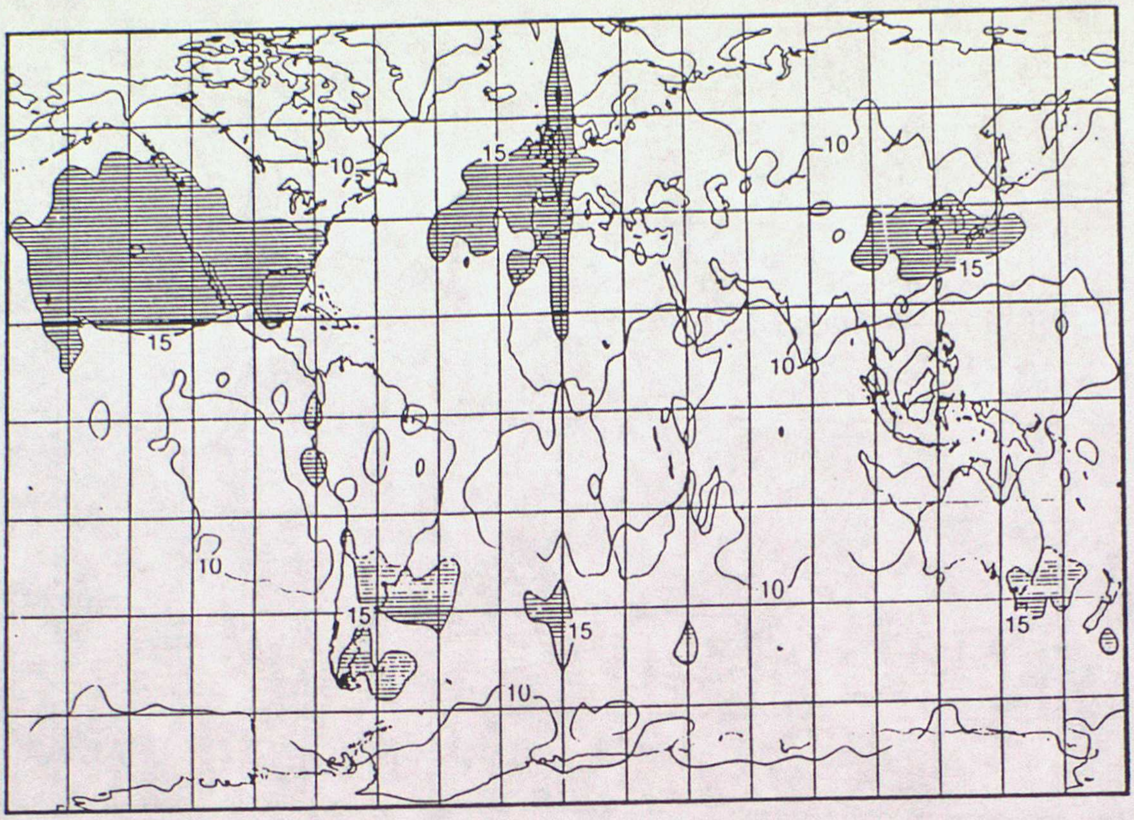

Figure 20. RMS vector error in knots of T+24 forecast wind at 250 hPa, January to March 1990 (greater than 15 knots shaded).

5.3 Initial errors and error growth

Figure 21 shows the growth of error in the wind at 250 hPa during the forecast together with values of the error obtained using persistence as a forecast. The rms vector errors have been evaluated using observations from radiosondes within the same area, referred to in Figure 16, covering much of the North Atlantic and Europe. The error growth over the whole period is approximately linear and the gain relative to persistence is greatest around T+48. The rms difference between observations and analysis is significantly larger than zero, reflecting not only errors in the analyses and observations, but also the effects of small-scale structure measured by the radiosonde wind-finding system but beyond the resolution of the numerical grid. The data assimilation system takes these factors into account and as a result a perfect fit to the observed value is never achieved by any optimal statistical method.

It has been mentioned earlier that the close dependence of the data assimilation system on the operational forecast model can lead to the numerical analyses containing systematic errors in data-sparse regions similar to those in the forecasts at longer periods. Compared with the mean analysis, mean jets at T+72 (Figure 17) are only a little too light, and the discrepancy is even less if the T+24 forecasts are considered (not shown). To obtain a more accurate picture of the magnitude of this systematic error and its dependence on wind speed, very short-period forecasts (T+6) have been verified against aircraft observations. The results for various 10-degree latitude bands stratified by wind speed (the mean of the observed and the forecast) are shown in the Table opposite.

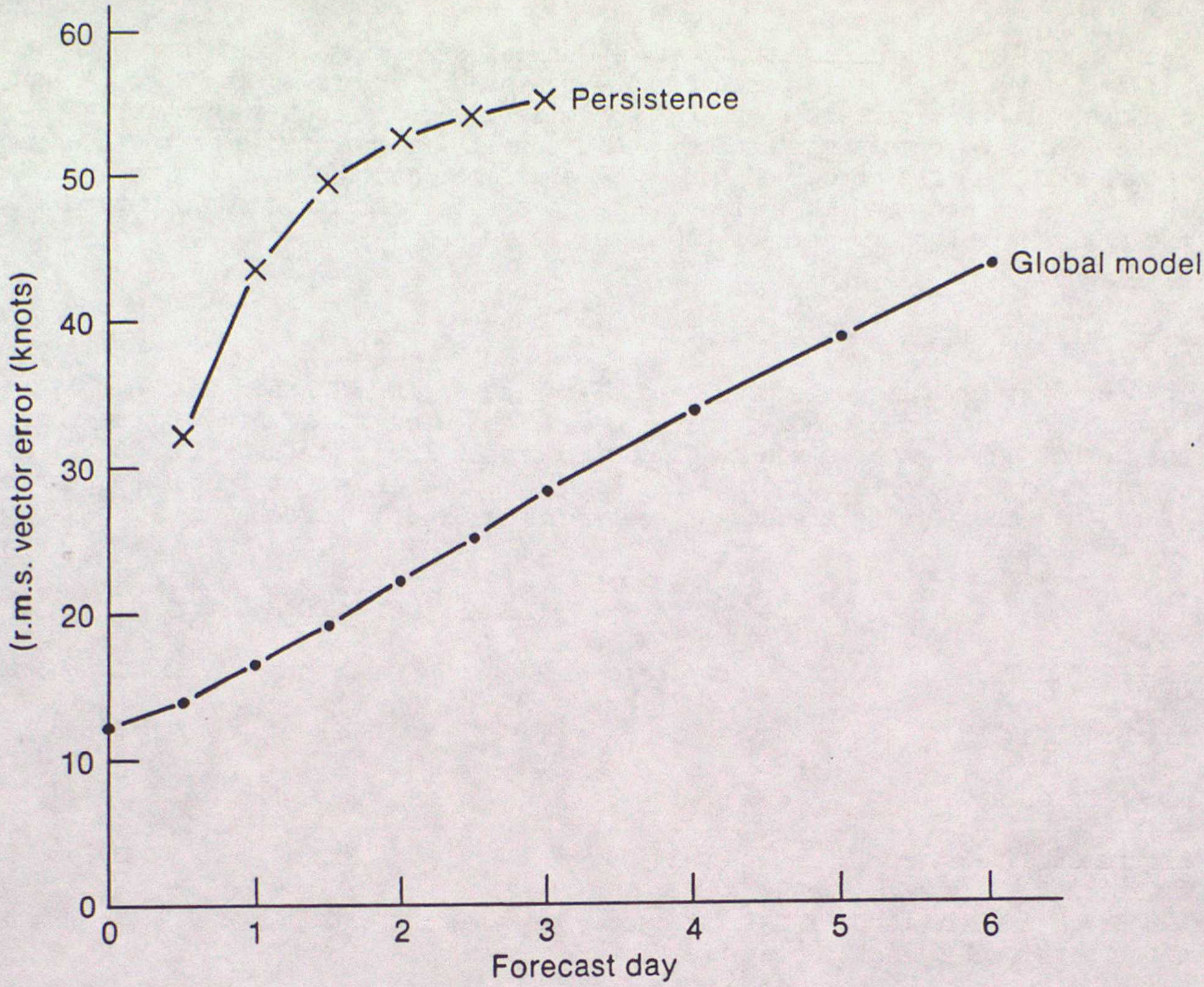

Figure 21. RMS vector error in knots for global-model forecasts and persistence forecasts of wind at 250 hPa. Verification against radiosondes in an area covering much of the North Atlantic and Europe in 1989.

Latitude band	5-20	20-40	40-60	60-80	80-100	100-120	120-140	140-60	>160
80-90 N	-1.6	-3.5	-8.2	-11.5	-	-	-	-	-
70-80 N	-1.7	-4.1	-8.0	-10.7	-12.4	-17.9	-	-	-
60-70 N	-1.2	-2.9	-5.2	-8.0	-11.1	-13.6	-14.6	-18.3	-
50-60 N	-0.8	-1.7	-3.1	-4.9	-7.2	-10.1	-12.0	-15.3	-17.7
40-50 N	-0.8	-1.4	-2.7	-4.7	-6.8	-9.9	-12.2	-15.3	-17.1
30-40 N	-1.2	-1.9	-2.9	-3.9	-5.4	-7.2	-8.9	-11.5	-12.8
20-30 N	-1.6	-2.7	-4.3	-5.8	-7.6	-9.3	-12.0	-14.0	-
10-20 N	-2.5	-5.2	-7.6	-9.5	-12.0	-15.9	-	-	-
0-10 N	-1.9	-5.2	-9.1	-10.3	-12.4	-	-	-	-
0-10 S	-3.1	-7.6	-11.5	-16.3	-	-	-	-	-
10-20 S	-2.5	-5.2	-6.2	-7.8	-6.8	-	-	-	-
20-30 S	-2.1	-3.5	-5.0	-6.0	-7.6	-8.5	-9.7	-10.9	-
30-40 S	-0.6	-2.1	-4.9	-7.4	-9.9	-13.0	-13.6	-14.0	-
40-50 S	-2.1	-3.1	-6.6	-8.0	-11.5	-15.3	-	-	-

TABLE 2 Mean errors in very-short term forecasts (T+6) of wind speed in knots verified against aircraft reports in the period February 1989 to February 1990. Stratification by 10-degree latitude band and 20-knot speed categories. "-" indicates fewer than 50 observations.

The picture which emerges is of uniform underforecasting of wind strength at all latitudes by about 10 percent. The systematic errors in the North Atlantic and the North Pacific are found to be similar, and are consistent with the biases found by comparison against radiosondes. The magnitude of these errors is greater than the perceived growth of error between the starting analysis and the T+72 forecast, and it is reasonable to assume that it is representative of the analysis errors in some of the data-sparse areas.

5.4 Verification of CAT forecasts

In section 4 examples were presented of forecasts of CAT based on a simple function of the model's horizontal and vertical wind shear. The accuracy of the method has been assessed by comparing probability forecasts for 584 flights over the North Atlantic with the CAT logged by the pilots on route (Forrester 1986), and the results are summarised in Table 3 below. Each count refers to a 100 km segment of flight.

	FORECAST CAT PROBABILITY		
REPORTED CAT	0-4 percent	>4 percent	all forecasts
nil or light	33450	3088	36538
moderate or severe	473	244	717
all reports	33923	3332	37255

TABLE 3. Verification of CAT: frequency of forecast categories of CAT against reports from 584 flights over the North Atlantic.

The figures show that the frequency of encountering moderate or severe CAT in regions of low-predicted probability was 0.014, while in regions of relatively high forecast probability (greater than 4 percent) the frequency increased to 0.073. The background frequency, defined as the overall proportion of reports with moderate or severe CAT, was 0.019.

5.5 Verification of precipitation

Quantitative forecasts of precipitation are strongly dependent on the type of parametrization scheme used for convective processes and also the resolution of the numerical model. Greatest success is usually achieved by high-resolution regional or mesoscale models, which are able to represent frontal structure and some of the influences of orography with greater accuracy than global models. Verification of forecasts from the UK regional model (horizontal resolution approximately 75 km) is performed for the following precipitation categories: Nil (less than 0.1 mm), Light (less than 2.0 mm), Moderate (less than 10.0 mm), and Heavy (greater than or equal to 10.0 mm). Results for forecasts of accumulation between T+18 and T+24 are given in Table 4 below. Verification has been performed against observed 6-hour accumulations over the whole of 1989 from some 400 stations spread over Western Europe.

Forecast	Observed category O	L	M	H	
O	67.8	4.7	1.1	0.1	73.8
L	12.4	5.9	2.1	0.2	20.6
M	1.9	1.7	1.4	0.3	5.4
H	0.1	0.1	0.1	0.1	0.3
	82.2	12.4	4.6	0.7	100.0

TABLE 4. Verification of precipitation: forecasts of accumulation between T+18 and T+24 against stations in Europe for 1989. The numbers are the percent of cases in each category (zero, light, moderate, and heavy).

There is an apparent overestimation of light precipitation and underestimation of heavy precipitation, however, in part this may be a consequence of the verification method. Observed values at a point location have been compared with model values which represent at best a grid-box mean; where the distribution of precipitation is patchy the incidence of light precipitation in a grid box will be greater than at a single station, and the incidence of heavy precipitation less. Various scores have been devised to quantify forecast accuracy relative to some threashold of precipitation and Threat Score (TS) and Hanssen and Kuipers Score (HK) are probably the most widely used. They are defined as

$$TS = C/(M+F+C)$$

$$HK = C/(M+C) - F/(N+F)$$

Where C is the number of correct forecasts of the event to occur, F the number of false alarms, M the number of misses, and N the number of correct forecasts of the event not to occur. An equivalent definition of the Hanssen and Kuipers score is the hit rate minus the false-alarm rate. These scores have been evaluated where the event is the occurrence of measurable precipitation (greater than 0.1 mm). The dependence on the forecast period is given in Table 4 below:

	TS	HK
0 - 6 hours	0.40	0.52
6 - 12 hours	0.39	0.52
12 - 18 hours	0.39	0.51
18 - 24 hours	0.37	0.49
24 - 30 hours	0.35	0.46
30 - 36 hours	0.34	0.44

TABLE 4. Values of Threat Score and Hanssen and Kuipers Score for forecast accumulations greater than 0.1 mm. Verification against stations over Europe in 1989.

There is little difference between 0-6 and 6-12 values of either of the scores listed, showing that the model does not appear to have a spin-up problem. Pecipitation forecasts in the early stages of integration are very sensitive to imbalances in the model fields; large changes in forecast amounts in the first 6 to 12 hours are indicative of shortcomings of the initialization procedures.

5.6 Verification of low centres

Studies of the accuracy of forecasts relative to some synoptic feature have greatest relevance to the users of numerical products. The position of a centre of low pressure is of major interest and has been verified in many models. Comparison against verifying analyses yields values for the error in the depth, the position error, the timing error, and the amount by which a forecast track deviates to the left or right of the observed track. The most notable results from the verification of forecasts from the Bracknell regional model are summarised here. Figure 22 shows the geographical distribution of the mean error in T+24 forecasts of central pressure of lows. Errors are no more than 1 hPa over the regions of the Atlantic where most lows develop, but there are larger negative values over land indicating either some deficiencies in the parametrization of physical exchanges over land, or a more general failure to model the filling process. Mean timing errors are found to be generally less than 1 hour and there is no systematic deviation to either side of the observed track.

The forecast deepening rates were studied in more detail for cases of extreme cyclogenesis. During the period January 1986 to June 1988, 94 forecasts from the model were verified; the cases related to all 43 different low-pressure systems where explosive cyclogenesis (central pressure falling by at least 24 hPa in 24 hours) was either observed or forecast to occur. The relationship between observed and forecast change in central pressure of the low is shown in Figure 23 for the 94 forecasts verified. In general the magnitude of the errors is relatively small, being in most cases less than 10 hPa. There is little bias apparent in the forecasts, even where deepening in excess of 50 hPa occurs over a 24-hour period. The few occasions where errors are much larger than 10 hPa are instances of the underforecasting of the intensity of cyclonic development.

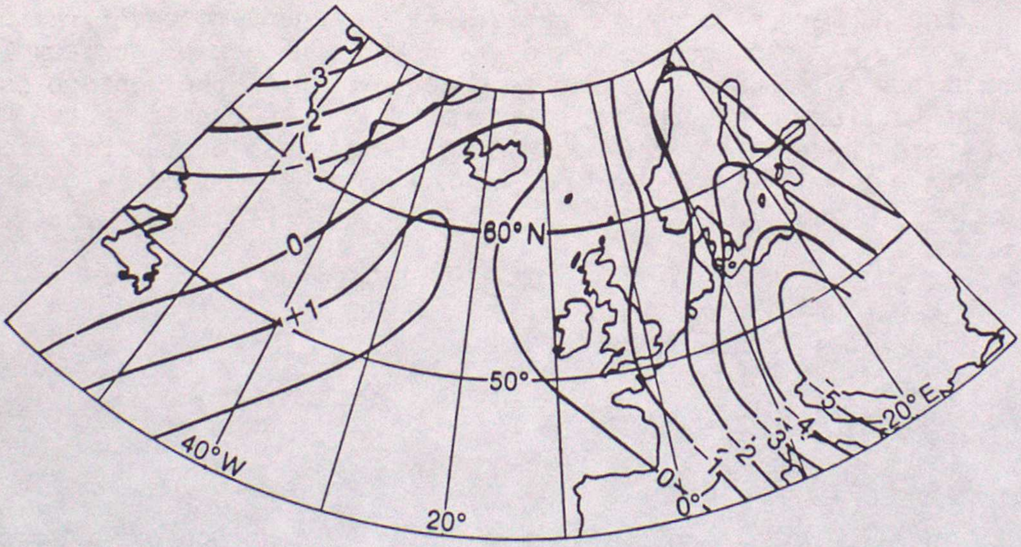

Figure 22. Mean error in hPa of T+24 forecasts of the central pressure of lows, September 1987 to August 1988.

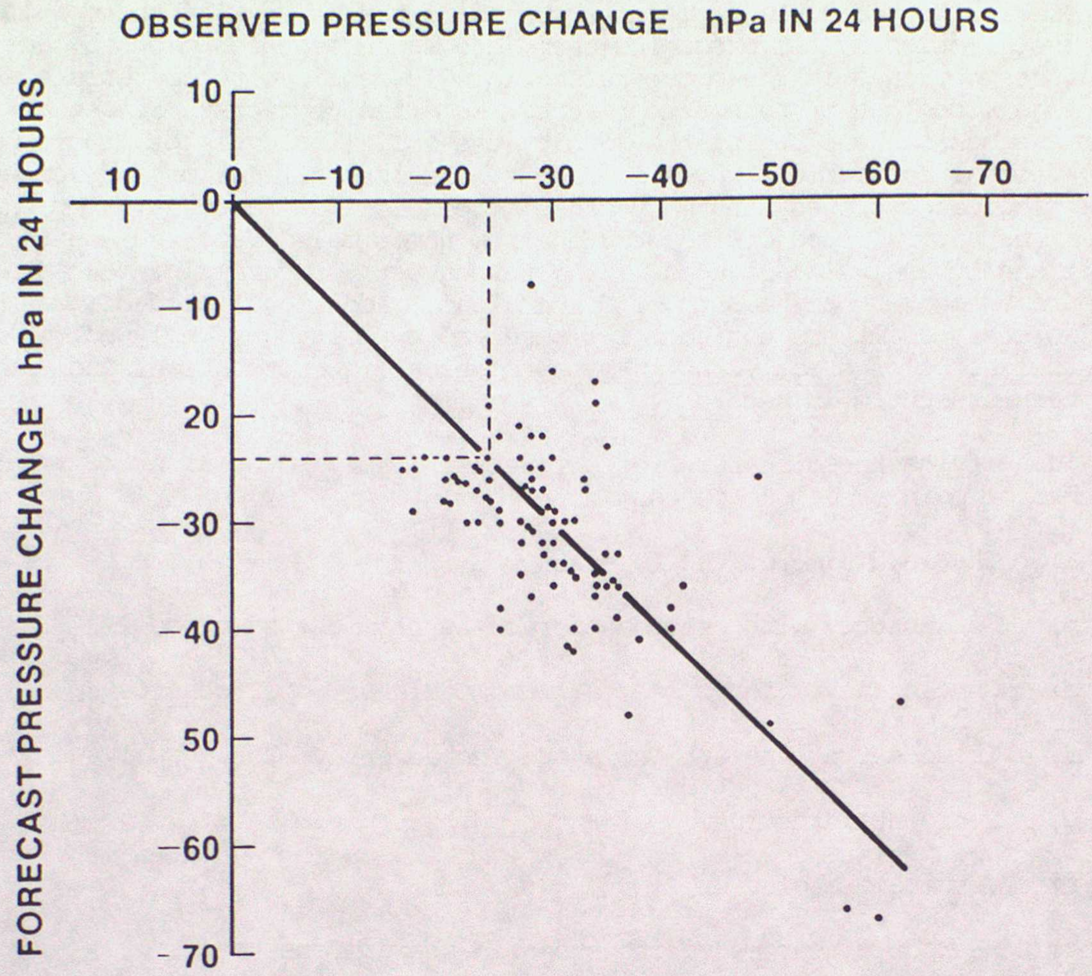

Figure 23. Observed 24-hour change in central pressure in hPa of rapidly deepening lows in the North Atlantic against forecast values, January 1986 to June 1988. Only cases where the observed or forecast pressure change is less than -24 hPa have been plotted.

6. INTERPRETATION TECHNIQUES AND THE LIMITATIONS OF MODEL PRODUCTS

All numerical forecasts must be interpreted in the context of the model and the data assimilation system producing them, and an understanding of the basic principles outlined in the previous sections is required to appreciate what aspects a model can or cannot represent. Numerical forecasts almost always offer a plausible evolution; they depict the full life cycle of middle-latitude lows, frontal boundaries, waves on fronts, the intensification and weakening of jets, tropical cyclones, and many other meteorological features. For this reason the natural products to provide from numerical models include those traditionally analysed and used by the forecaster: for example, mean-sea level pressure, geopotential height, wind and cloud. Additional products can be made available of parameters not normally observed or routinely analysed, which may nevertheless be of great value in meteorological interpretation, and examples have been presented in section 4.

When identifying those features of a forecast likely to be accurately handled, a number of points need to be considered:

a) The lead time of the forecast

b) Consistency with previous forecasts from the same model

c) Consistency with forecasts from models of other centres

d) The observations available and the accuracy of the analyses

e) Horizontal resolution

f) Vertical resolution

g) Methods of parametrizing sub-grid-scale processes

h) Known systematic errors of the model in the region

i) Characteristics of the post processing

6.1 Lead time of the forecast

It is axiomatic that on average forecasts with shorter lead times are more accurate than those with long lead times; Figure 21 shows a near linear increase in forecast error over the forecast period. However, the use of this fact to the application of numerical products requires some background knowledge of the typical error associated with a given synoptic system at different lead times. Figure 24 shows forecasts with various lead times all verifying at 00 UTC 12 May 1986 together with the verifying analysis. At T+144 the forecast low is poorly defined, but the centre is only misplaced by some 600 km. The low is too shallow, and in particular the strong winds to the west of the British Isles are not predicted. At T+96 greater accuracy is achieved in the forecast synoptic evolution; the strong winds to the south west of the British Isles are better predicted, but the centre of the low is still poorly represented. At T+48 there is much closer agreement with the truth; the forecast low is well positioned and is now defined by two closed isobars, though it is still not deep enough. As a result the surface flow in the vicinity of the UK is not much in error.

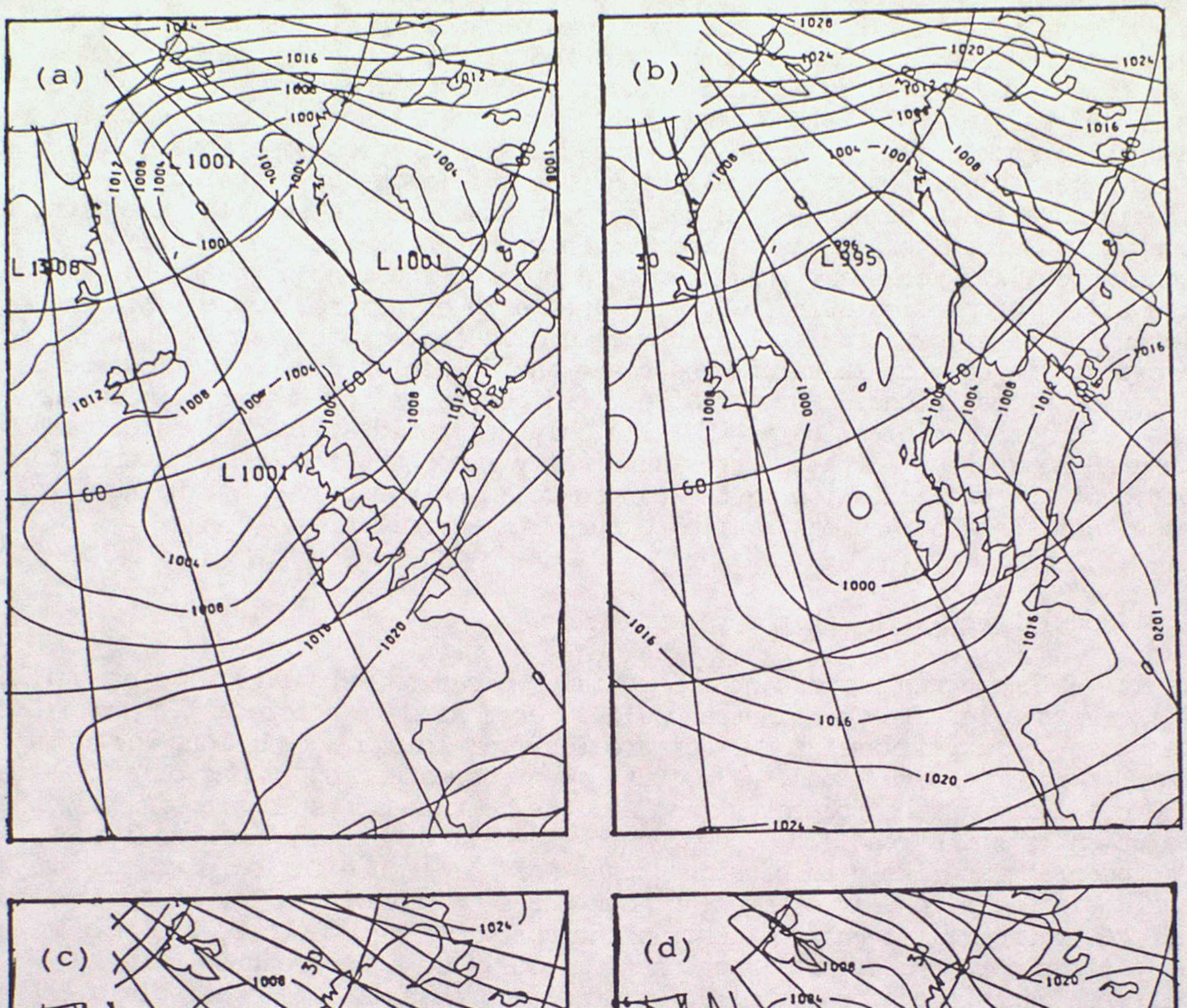

Figure 24. Forecasts of mean sea-level pressure verifying at 00 UTC 12 May 1986: (a) T+144, (b) T+96, (c) T+48, and (d) verifying analysis.

The forecasts for this low system are probably quite typical of the quality to be expected from current high-resolution global models. The accumulation of experience gained by forecasters over long periods of time enables them to estimate the range of errors to be expected with a given synoptic system in a way that is more meaningful than objective scores based on rms error. The point of this example is to demonstrate what useful information can be extracted from numerical forecasts with different forecats periods. At longest lead times only the most general aspects of the large-scale evolution are likely to be handled with any accuracy; in this example at T+144 the pattern over the UK can be forecast to be cyclonic, but there can be little confidence in forecasts which attempt to predict the wind strength let alone the timing of precipitation. By T+48 the range of errors in the track and intensity of a low of this size is much smaller and greater confidence can be expressed in the forecasts of wind speed and direction around the low and in the frontal positions. More detailed predictions of the extent, timing and intensity of precipitation are usually only attempted at lead times of less than 48 hours, but in these cases an equally important factor is whether the scale of the precipitation system can be reasonably resolved by the numerical model and the observations available for data assimilation.

6.2 Consistency with other forecasts

If it was known that errors on a particular occasion were likely to be smaller than average, greater confidence could be expressed in a forecast. Monte Carlo methods, whereby several forecasts are run from initial conditions differing by small random perturbations, have often been suggested as a means of addressing the problem; if the forecasts from all the perturbed states are similar, the solution is not strongly dependent on the detail of the initial conditions, and the accuracy is likely to be higher than normal. Monte Carlo forecasts are not available operationally at present, but the same principles can be applied to forecasts from different sources: either previous forecasts of the same model at earlier data times, or forecasts from models of other centres. The differences in the model formulation or in the observations available will lead to differences in the forecasts which can be very large on occasions. In general consistency between the various numerical forecasts valid at any time is found to be a useful indicator of accuracy.

A related subject is the accuracy of forecasts in different synoptic situations. Some types of synopic development are found to be regularly well forecast, while for others, particularly those involving non-linear interactions between systems of different scales, the forecast errors are considerably larger. Several statistical predictors of forecast skill, which use model output to characterise the type of flow, have been developed and their reliability is being assessed.

6.3 Observations available to the analysis

In areas where observations of good quality are plentiful at all levels of the atmosphere, the analyses are likely to be accurate. Unfortunately this is seldom the case and forecast errors can frequently be traced back to areas where data are lacking and the analysis is uncertain. The use of an assimilation model to provide background fields for the analysis ensures that information contained in observations for earlier hours is carried forward in time. In the absence of many observations in a given area the analysis will closely resemble the background; moreover, the forecasts in this region will often resemble the forecast from the previous run of the model, until the influence of systems on the larger scale begin to dominate. It follows that consistency between forecasts from successive model runs, rather than implying increased confidence in the forecasts, may just reflect that no new observations have been received in those regions critical for meteorological development. This is an important consideration when assessing the consistency between successive forecasts from the same model in the data-sparse regions of the tropics or the southern hemisphere.

Limited-area models require values at their lateral boundaries, which can only be provided by another model covering a larger domain (typically a global model). Since timely forecasts are required from limited-area models, the global-model run providing the boundary conditions frequently has an earlier data time and lacks the benefit of many of the latest observations. This will have minimal impact on the quality of short-period forecasts, but at longer periods the inferior quality of the global model run will contaminate the interior of the limited-area model domain. Such error propagation can be quite rapid where the flow across the boundary is strong.

It is often the case that the skilled human analyst is able to identify errors in the model analyses either by a careful interpretation of isolated observations, or by having available extra information, such as satellite imagery, not used by the numerical scheme. Satellite imagery often provides accurate information on the centre of a circulation, the position of a front, the existence of a frontal wave, or the areas of large-scale convergence. Where an analysis error is identified it may persist into the forecast in a linear non-amplifying mode, in which case successful modifications to the short-term forecasts may be made by the forecaster. For example, a low or a front which is too far advanced in the analysis is usually too far advanced in the T+12 or even T+24 forecasts; similarly the model's position of a front may be modified to take into account a wave absent or wrongly positioned in its analysis. Unfortunately many analysis errors amplify in a non-linear fashion and the relationship between analysis error and forecast error is far more complex and unpredictable. Few rules exist which predict the likely effect of such errors on the subsequent forecasts.

6.4 Horizontal resolution

Clearly the horizontal resolution is an essential factor in determining what features can or cannot be resolved by a model. In terms of physical representation in global models, land-sea boundaries are greatly simplified and many mountain ranges and valleys are smoothed out even using the highest resolution available. Figure 25 shows an example of the representation of a mountain range (the Alps along longitude 10E) at different resolutions by mean and enhanced (envelope) versions of the surface height of the ECMWF model (Simmons 1986). At T106, or equivalently 100km resolution, there can be very large differences between reality and the model's representation of a mountain range or valley; differences between model surface height and station height of some hundreds of metres are common, even in regions not considered to be particularly mountainous. Differences greater than 1000m are not infrequent in mountainous regions even at highest resolution. The differences will be particuarly large if the model surface height is spatially averaged to provide a smoother lower boundary, or artifically enhanced to improve the forecasting of blocking processes. As a result near-surface fields must be interpreted as valid on the level of the model, not at the height of the station for which the forecasts are used. Orographic enhancement of precipitation will typically be underforecast, while detail in the wind or temperature field will at best be smoothed to the model's level. The simplification of the surface type will affect regions where land-sea boundaries are important. A sea of limited extent or narrow channels will be poorly represented and important meteorological

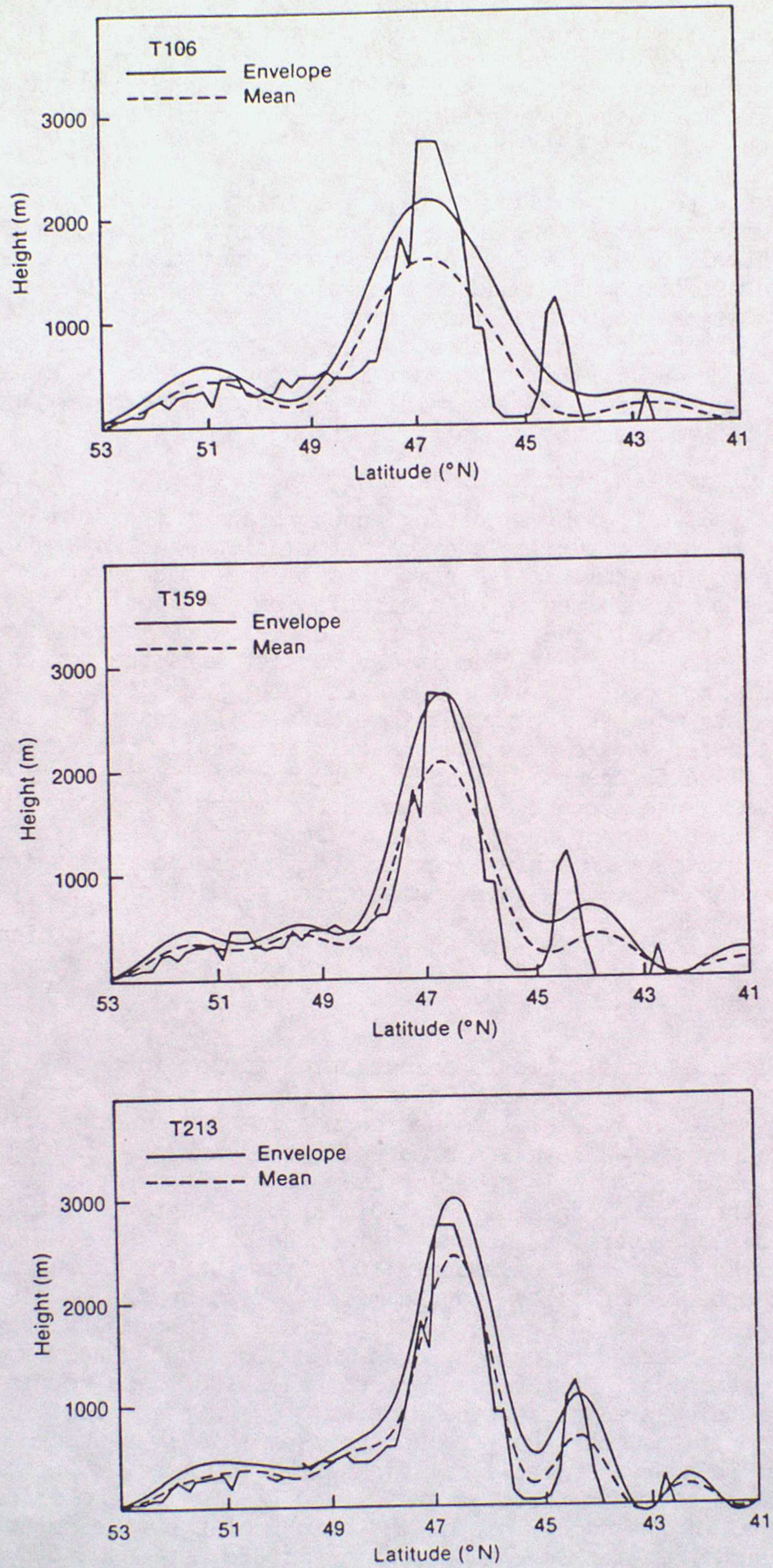

Figure 25. Representation of the Alps along longitude 10E at different spectral resolutions by mean and enhanced (envelope) model surface height. Reference values are obtained from US Navy 10-minute data.

effects associated with them will be missing from the numerical forecasts. Model values interpolated to a location near a land-sea boundary may have the characteristics of a model land point, a model sea point, or more likely a combination of the two. For instance a model surface wind over sea, but within one model grid length of land will include a contribution from land frictional effects.

In terms of what the model dynamics will resolve the issue is more complicated. Mesoscale structure on scales below the separation of the model grid points cannot be resolved, but the parametrization schemes can represent quite well the different physical processes occurring at each grid point. A simple wave perturbation may be represented by just two points per wavelength, but such features close to the grid scale of the model are handled with little accuracy by the numerical methods used to approximate the equations of motion; they are immediately lost within the numerical noise which is an inevitable by-product of mathematical approximations. It requires 3 or 4 grid points to handle a simple perturbation with any success, which, in the case of a 100km grid-point model, is a scale of 300-400 km. Such arguments are based on a very simple 1-dimensional analysis of forecast errors and though similar considerations apply in the full 3-dimensional case, not all grid-length aspects of the forecast fields are inaccurate. For example, the sharp gradients across a front are generally well represented in models, and the frontal position is forecast with considerable skill in spite of being a 1-dimensional discontinuity.

The case considered in section 4 provides a good example of the effect of model resolution on forecast detail. The T+24 forecast of mean sea-level pressure obtained from the global model with horizontal resolution 150 km (Figure 26) may be compared with the forecast from the regional model with exactly half the grid spacing (Figure 6a). The general evolution predicted by both models is almost identical, but there is a difference in 14 hPa in the central pressure of the low, and both are not as intense as the verifying analysis (central pressure 928 hPa). The fine-mesh version has a better representation of the depth and also the exceptionally strong gradient on the southwestern flank. Such differences are typical of the advantages to be gained from higher horizontal resolution.

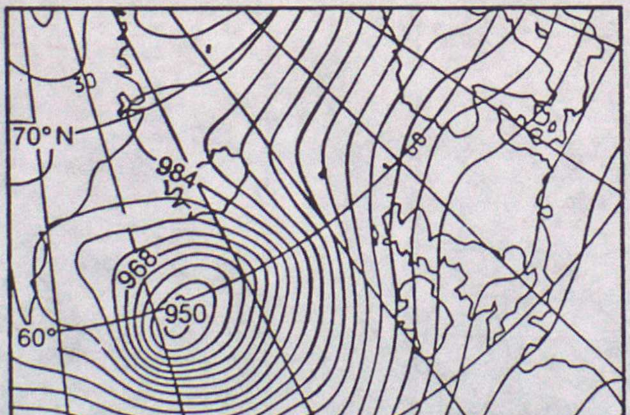

Figure 26. T+24 forecast valid 12 UTC 8 January 1990: mean sea-level pressure in hPa from the Bracknell global model.

6.5 Vertical resolution

The 15 to 20 levels of the global models in use in 1990 offer only very limited resolution of some of the vertical structure in the atmosphere of great importance to aviation. Inversions are often only represented as an isothermal between two layers, and as a result the depth of convection beneath the inversion is frequently underestimated as is demonstrated in the following example. The observed temperature profile in Figure 27a is typical for an anticyclonic northeasterly flow over the UK, and shows a cloud-capped inversion around 800 hPa below which the air is unstable to sea-surface temperatures. All detail is lost in the T+12 forecast from the regional model (Figure 27b); the warm nose of the inversion is completely missing, the depth of instability is negligible, and no sub-inversion cloud layer is indicated. All failings of the model forecast are related to the lack of resolution in the boundary layer; the shallow cloud and inversion layers cannot be well represented in a model with levels 70 hPa apart. Lacking cloud, and therefore long-wave cooling at the cloud top, the model cannot maintain the low temperatures just below the inversion. In this example the tropopause is also somewhat smoothed out.

In the wind field important detail may also be lost, especially at jet-stream levels in the extratropical regions where strong vertical wind shears can occur. An example is shown in Figure 28 of the observed wind speed at a station in Southern England and the layer-mean values (the open circles) presented for data assimilation. The limited resolution provided by the 15 model levels

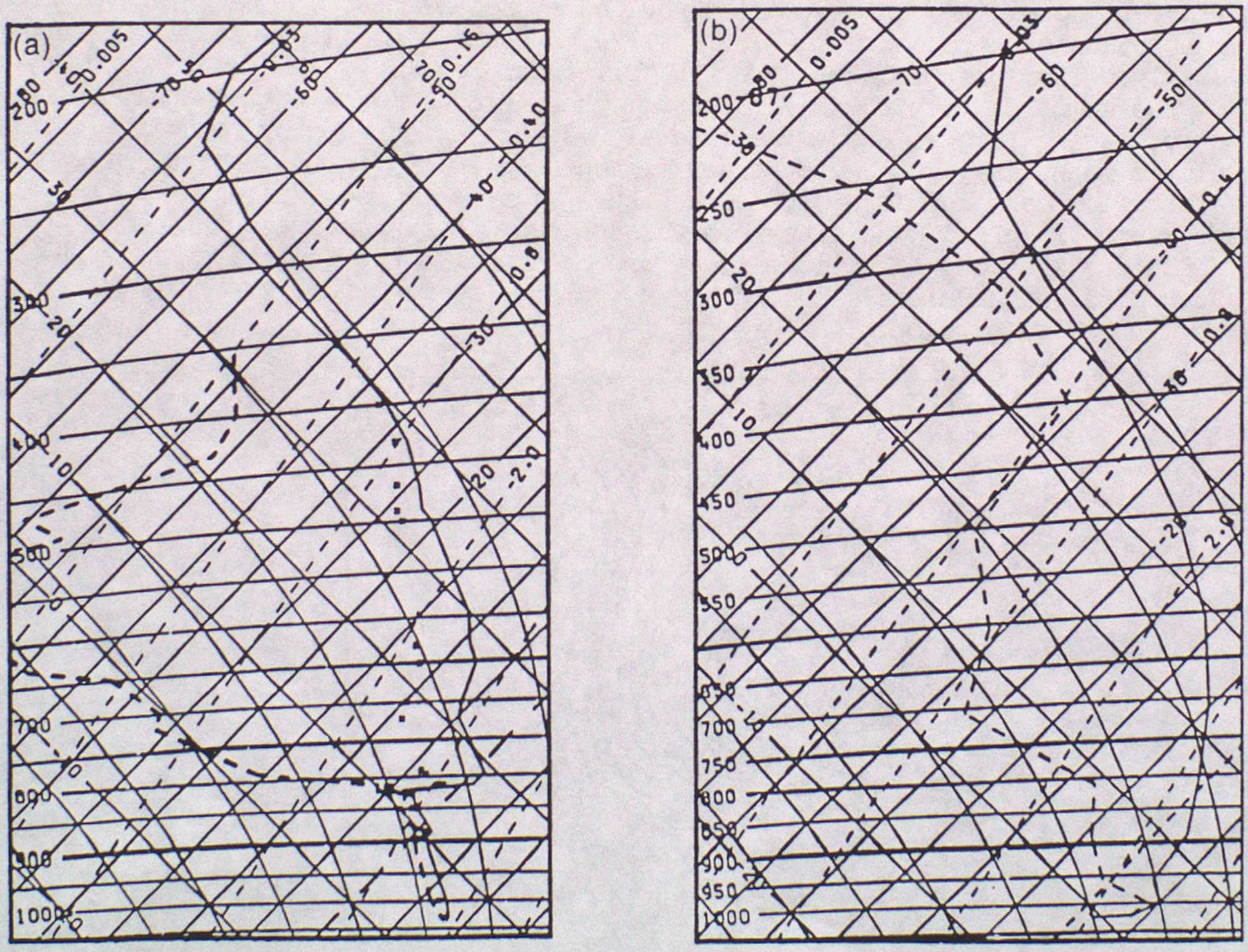

Figure 27. Tephigram showing the vertical profiles of temperature and dewpoint at Aughton (54N, 3W) valid 00 UTC 5 December 1989: (a) observed, and (b) T+12 forecast.

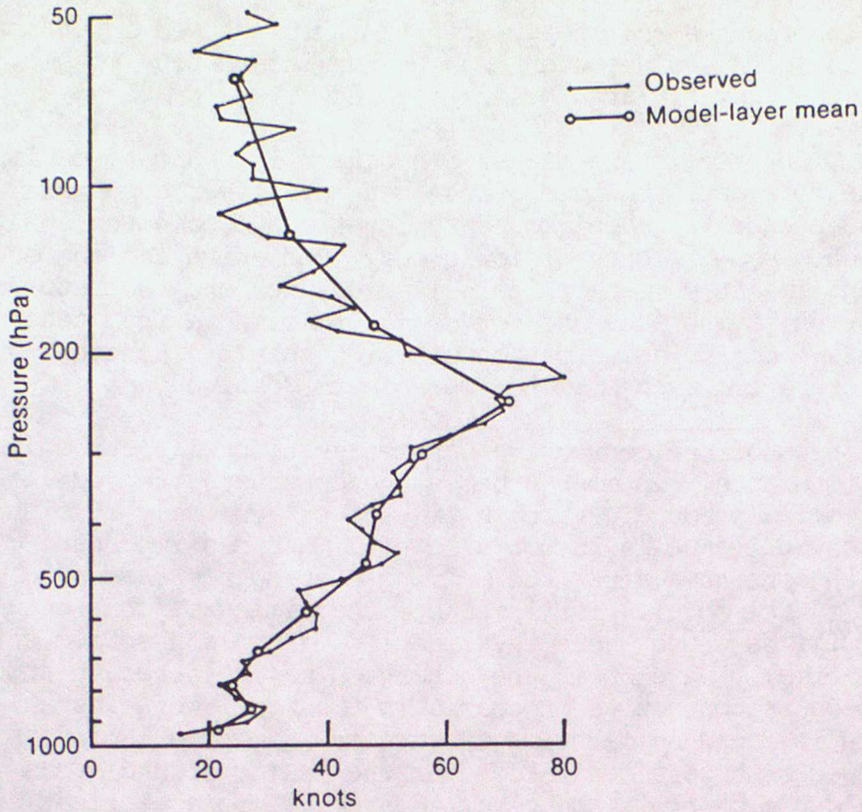

Figure 28. Observed vertical profile of wind speed in knots at Crawley (51N, 0W) based on 1-minute averages. The layer-mean values used in the Bracknell model are shown by the open circles.

gives a fit to the observed profile which is quite close in the troposphere, except at the jet core where the reported winds in excess of 80 knots occur over a very narrow band. A similar problem will occur in data assimilation systems which perform analysis at standard levels using just the standard-level observations. This is an important consideration when using a model to forecast maximum winds; in some cases the model may analyse winds 10-20 knots too light in areas of dense observation coverage, merely through having insufficient vertical resolution. The problem may be partially overcome by suitable post processing using a high-order spline fit to wind speed at jet-stream levels, but no amount of output modelling will pick up the fine detail found in this example.

6.6 Limitations of the parametrization schemes

The accuracy and representativeness of the model forecasts of near-surface parameters is very dependent on the parametrization of the sub-grid-scale processes. Forecasts of screen-level temperature depend, for example, on whether a detailed soil model is used and whether the radiation scheme takes into account the forecast cloud cover or the diurnal cycle. Very much better temperature forecasts were obtained from the Bracknell regional model once a single-layer soil parametrization was replaced by a 4-layer scheme. The specification of soil moisture is very important for accurate temperature and rainfall forecasts. Schemes for specifying soil moisture based on climatological fields will lead to overforecasting of rain in anomalously dry periods and vice versa. On the other hand, values of soil moisture determined by an interactive hydrological cycle can become unrealistic if rainfall forecasts are in error. Snow and sea-ice cover has a large impact on forecast screen-level temperatures and where this is misrepresented in the model (because climatological values are taken or the interactive scheme has predicted the wrong cover) large errors may occur.

The parametrization of moisture-driven convection is found to be important in determining the forecast structure of the boundary layer especially over the oceans. In its absence the model boundary layer can become too shallow and dry, and forecasts show a deficiency of low cloud. Radiative cooling due to clouds has an important impact on meteorological structure, and accurate forecasts depend not only on having accurate forecasts of moisture from the model, but also on having a good radiative parametrizarion scheme. Schemes which simplify the cloud structure too much will not be able to resolve much vertical detail.

The characteristics of the convective parametrization will strongly influence precipitation forecasts. In most schemes the conditions for convection to take place are tested independently at each time step (typically 15 minutes) and the advection of convective cells is not allowed. This has important consequences; convection which continues after the driving heat source ceases to operate will not be handled by the model. For instance, the timing of convective precipitation will be wrong where the lifetime of the convective cells is long. Showers which normally develop in the afternoon may be forecast around the local midday because convective processes in the model work instantaneously. Another example is found in maritime airstreams in middle latitudes where a strong flow advects showers generated over the sea to inland areas where convection would not otherwise develop. Convective parameterization schemes are seldom able to handle the situation where showers develop in a scattered fashion and in such cases precipitation amounts forecast by the model are usually nil.

6.7 <u>Other systematic errors</u>

Any trend shown by model forecasts must be interpreted in the light of knowledge of the systematic errors of the model. Jet cores in numerical models are frequently too weak and the type of speed-dependent errors quantified in Table 2 provide the basis of successful modifications made by forecasters to numerical products. Typically jets in the global model are found to be on average 10-15 knots too light both in the analysis and the short-term forecasts, and maximum winds issued on significant weather charts from Bracknell are usually modified to take this into account. Systematic errors may be particularly large in the tropics where in places they may approach the magnitude of the day to day changes.

6.8 <u>Characteristics of the post processing</u>

Most products issued on the GTS are derived using bilinear horizontal interpolations from the model grid points. In many cases the output resolution is substantially coarser than that of the original product and as a result important detail may be lost. The means of interpolating vertically can have a major impact on wind strengths around jet levels where vertical shear is particually strong. Significantly better representation of jet strength will be obtained if some quadratic or higher-order fit is applied to the data. Over high ground some standard-level data (for example 850 hPa winds) will represent values near the surface. To make meaningful use of the product it is necessary to know the exact model surface height at each grid point and what procedure is followed where it is greater than the height of the standard level. Spot values of precipitation are best derived from the nearest model grid point, rather than by interpolation which greatly increases the incidence of non-zero values.

7. NWP IN THE 1990s

There has been a widespread adoption of global forecast models in the 1980s and the steady reduction of forecast errors at all lead times. For aviation the greatest benefit has been the availability of grid-point wind and temperature forecasts of accuracy and resolution not previously achieved. The parallel development of regional models has resulted in successful treatment of detail beyond the resolution of a global model; precipitation and surface parameters such as temperature and wind are now often well forecast. It seems reasonable to expect the trend towards modelling meteorological systems on smaller and smaller scales to continue into the 1990s. Cloud amount, cloud base and visibility have not surprisingly proved to be some of the meteorological parameters hardest to forecast accurately, and mesoscale models having sufficient resolution in both the horizontal and vertical to tackle this problem are still in the development stage at the beginning of the decade. Advances in numerical forecasting are likely to come on two fronts: improvements to the numerical prediction models as a result of increased computer power, and the availability of more observations arising principally from advances in satellite technology.

7.1 Future NWP systems

Computer power has increased exponentially since the early 1950s, there being a 10-fold increase approximately every 5 years. Though this rate of increase may not be maintained through the 1990s, substantially more powerful machines will continue to be developed. Highest resolution global models in operational use at the beginning of the decade are around 100 km (or T106 in spectral resolution) and 20 levels; a halving of resolution to around 50 km (or T200) and 40 levels should be achieved at many major centres by the mid to late 1990s. A concentration of the extra levels in the upper troposphere for aviation purposes is quite likely in some models. These high resolution global models should be at least as accurate as the best regional models in 1990, providing reasonably accurate forecasts of precipation and large-scale cloud systems. Indeed the role of regional models is likely to diminish, and the requirement for timely runs for local forecasting may be met by preliminary runs of a global model. Automated significant weather products based on numerical output are likely to become widely available.

A major area of development is expected in mesoscale modelling, where much higher resolution in the boundary layer will be achieved. Coupled with very detailed parametrizations of the meteorological processes, the means will be available for the first time to tackle realistically the operational forecasting of such elements as cloud base and visibility. Some of the improved parametrizations developed for mesoscale modelling may well filter down into future regional and global models, and in particular improved modelling of cloud processes are expected from these models.

Improved methods of data assimilation will be required to make best use of the observations available. Much hope is placed on adjoint techniques to make use of the power of numerical models to descibe how meteorological variables change in time. The initial state is derived using an iterative procedure which ensures not only a good fit to the current observations, but also to observations at earlier times. If such methods are found to work well, it will be possible to make better use of asynoptic observations such as aircraft reports and satellite data. In mesoscale models the successful assimilation of data from radar and satellite imagery may also be possible.

7.2 Future observation systems

As the resolution of numerical models becomes higher and higher, a denser distribution of observations is required to provide accurate starting conditions closer to the scale of the model grid. This is unlikely to be achieved from the current land-based systems, for reasons of cost, and advances in remote sensing are likely to be the only means to provide the detail required in the future.

There have been steady improvements in the quality of satellite temperature soundings during the 1980s, but most studies show that they provide no great benefit to NWP in the northern hemisphere. A major reduction in observation error from these systems is still a number of years off. Estimates of surface wind from a satellite-borne scatterometer were made in the late 1970s and will be available again from a satellite due to be launched in the early 1990s. They should greatly help surface analysis over the oceans, but the benefit to NWP in general is as yet unclear. The use of lidar to measure the vertical profile of wind at a land station has been demonstated to give accurate values of particular use to mesoscale models, and space-based systems have been proposed. They have the potential of providing a massive increase in valuable data for NWP, but their implementation date is still quite distant. A major improvement in the availability of observations for NWP in the shorter term may be provided by commercial aircraft. Improved air-to-ground communication links on new aircraft will allow the rapid transmission of valuable information to the main meteorological centres. If an efficient system can be implemented, a greatly improved cover of observations will be available at levels and in areas of greatest use to aviation itself.

REFERENCES AND BIBLIOGRAPHY

1. History of NWP and operational systems

Bushby, F.H., and M.S. Timpson, 1967: A 10-level atmospheric model and frontal rain. Quart. J. Roy. Met. Soc., 93, 1-17.

Charney, J.G., R. Fjortoft and J. von Neumann, 1950: Numerical integration of the barotropic vorticity equation. Tellus, 2, 237-254.

Corfidi, S.F. and K.E. Comba, 1989: The Meteorological Operations Division of the National Meteorological Center. Weather and Forecasting, 4, 343-366.

ECMWF, 1987: Workshop on meteorological operational systems. Available from ECMWF, Reading, UK.

Petersen, R.A. and Stackpole, J.D., 1989: Overview of the National Meteorological Center production suite. Weather and Forecasting, 4, 313-322.

Richardson, L.F., 1922: Weather prediction by numerical process. Published by Cambridge University Press, 236pp.

2. Forecast models

Bell, R.S. and A. Dickinson, 1987: The Meteorological Office operational numerical weather prediction system. Meteorological Office Scientific Paper No. 41, published by HMSO.

ECMWF, 1985: Seminar on physical parametrization for numerical models of the atmosphere. 2 Vols.; available from ECMWF, Reading, UK.

Haltiner, G.J. and Williams, R.T.: Numerical prediction and dynamic meteorology. Published by J. Wiley.

Hoke, J.E., N.A. Phillips, G.J. DiMego, J.J. Tuccillo and J.G. Sela, 1989: The regional analysis and forecast system of the National Meteorological Center. Weather and Forecasting, 4, 323-334.

Simmons, A.J., 1986: Orography and the development of the ECMWF forecast model. ECMWF Seminar/Workshop on observation, theory and modelling of orographic effects, Vol 2, 129-164; available from ECMWF, Reading, UK.

3. Data assimilation

Barwell, B.R. and A.C. Lorenc, 1985: A study of the impact of aircraft wind observations on a large-scale analysis and numerical weather prediction system. Quart. J. Roy. Met. Soc., 111, 103-130.

Hollingsworth, A., 1986: Objective analysis for numerical weather prediction. J. Met. Soc. Japan, special volume containing papers presented at WMO/IUGG Symposium, Tokyo, 4-8 August 1986, 11-60.

Kanamitsu, M., 1989: Description of the NMC global data assimilation and forecast system. Weather and Forecasting, 4, 335-342.

Lorenc, A.C., R.S. Bell and B Macpherson, 1991: The Meteorological Office analysis correction data assimilation scheme. To appear in Quart. J. Roy. Met. Soc.

Pailleux, J., 1986: Use of meteorological observations in numerical weather prediction. WMO/WWW TD-No. 105.

WMO/ECMWF, 1989: Workshop on data quality control procedures. Available from ECMWF, Reading, UK.

4. NWP products

Dutton, M.J.O., 1980: Probability forecasts of clear-air turbulence based on numerical model output. Met. Mag., 109, 293-310.

Dutton, M.J.O., 1988: Specialized products for aviation forecasting using the Meteorological Office NWP global and limited area models. WMO PSMP Rep. Ser. No. 27, 49-54.

Forrester, D.A. and D.W.G. Dancey, 1989: Automation of significant weather forecasts for civil aviation. 3rd Int. Conf. on the Aviation Weather System, Am. Met. Soc. 284-289.

Gustafsson, N., 1990: Sensitivity of limited area model data assimilation to lateral boundary condition fields. Tellus, 42A, 109-115.

Marks, D.G., 1989: Current progress at the National Meteorological Center in automated clear-air turbulence forecasting. 3rd Int. Conf. on the Aviation Weather System, Am. Met. Soc. 244-248.

Quarterly report on numerical products from Bracknell. Available from the Meteorological Office, Bracknell, UK.

5. Verification

Arpe, K. and E. Klinker, 1986: Systematic errors of the ECMWF operational forecasting model in mid-latitudes. Quart. J. Roy. Met. Soc. 112, 181-202.

Forrester, D.A., 1986: Automated clear-air turbulence forecasting. Met. Mag., 115, 269-277.

Gadd, A.J., C.D. Hall and R.E. Kruze: Operational numerical prediction of rapid cyclogenesis over the North Atlantic. Tellus, 42A, 116-121.

Heckley, W.A., 1985: Systematic errors of the ECMWF operational forecasting model in the tropics. Quart. J. Roy. Met. Soc., 111, 709-738.

Junker, N.W., J.E. Hoke and R.H. Grumm, 1989: Performance of NMC's regional models. Weather and Forecasting, 4, 343-366.

Lange, A.A., 1988: Results of the WMO/CAS NWP data study and intercomparison project for forecasts for the northern hemisphere in 1988. WWW Tech. Rep. No. 7.

NMC monthly performance summary. Available from US Dept. of Commerce.

Puri, K. and D.J. Gauntlett, 1985: Numerical weather prediction in the tropics. J. Met. Soc. Japan, special volume containing papers presented at WMO/IUGG Symposium, Tokyo, 4-8 August 1986, 605-632.

Trenberth, K.E. and J.G. Olson, 1988: An evaluation and intercomparison of global analyses from NMC and ECMWF. Bull. Am. Met. Soc., 69, 1047-1057.