User Guide to ECMWF Products

Designed, edited and printed by ECMWF

1. The European Centre for Medium-Range Weather Forecasts

Historical background to Numerical Weather Prediction (NWP)

From von Helmholtz to Richardson

In 1888 the hydrodynamist H. von Helmholtz made it possible to formulate mathematically the fundamental laws of atmospheric motion with the aid of the complete set of hydrodynamic and thermodynamic equations. At the turn of the century, another hydrodynamist V. Bjerknes suggested that the weather could be quantitatively predicted by applying these physical laws to a carefully analysed initial atmospheric state. Bjerknes vision inspired a young mathematician and meteorologist, L.F.Richardson, to endeavour to compute weather forecasts along these purely mathematical lines. Expressed in today's terms, and very much ahead of his time, Richardson defined a primitive equation model with a 300 kilometre grid and five layers in the vertical in which he set out to integrate the basic atmospheric equations.

The result, published in 1922, was a disappointment. Not only did the flow pattern forecast appear to be a total failure[1]: it would need 64,000 individuals to perform the manual computations just to keep pace with the weather itself. The ways of weather forecasting took other directions during the 20's and 30's.

Lacking the theoretical and practical means to make any quantitative predictions, Bjerknes around 1919 initiated the qualitative approach that has been known as the "Bergen School" model of air masses, fronts and cyclones. This conceptual model made it possible for the forecasters to analyse the current atmospheric situation even from a few observations. It allowed him to extrapolate the motion of important atmospheric flow patterns and to interpret the weather connected to this flow, qualitatively taking the effects of radiation, convection and turbulence into account.

Despite its considerable practical value as a forecasting tool, the Bergen school model also had serious limitations. It could only be used for one- or two-day forecasts and, more importantly, could not give any guidance in predicting rainfall amounts or the onset of a blocking.

After the end of the Second World War the renewed exchange of meteorological observations and the development of a hemispheric network of upper-air stations made daily analyses of the general circulation possible. At the same time the first electronic computer was constructed and made complex mathematical calculations feasible. The time was ripe for a new onslaught on the problem of "computing the weather".

1. The last decade of deeper understanding of NWP has shown that Richardson's computations were actually correct: the westward drift of the flow pattern in the analytical forecast was due to the barotropic assumption. The unrealistic pressure changes were due to spurious gravity waves (associated to the absence of an initialisation process).

The first barotropic NWP model

In 1946 the physicist and mathematician John von Neumann suggested that numerical forecasting start from the simplest of all models, the barotropic equations of atmospheric motion where the evolution of the flow is determined by the effect of the conservation of absolute vorticity of an air parcel. This was taken as too simplistic an approach by the meteorologists, who regarded it necessary to take account of the baroclinic nature of the atmospheric flow. In 1948 J. Charney and A. Eliassen derived quasi-geostrophic equations describing the large scale evolution of a baroclinic atmosphere, where sound and gravity waves were mathematically eliminated. Since this approach was too technically demanding for the computers of the time the first numerical meteorological forecast, run in 1950, had to use the simple barotropic model, as originally suggested by von Neumann.

The first experiments were surprisingly successful: the general mid-tropospheric flow pattern was forecast 2-3 days in advance with greater skill than previous subjective methods. Even evolutions which looked baroclinic often turned out to be mainly barotropic in nature. From the mid 50's, with improved computers, some countries started operational NWP at 500 hPa three days ahead using this simple barotropic model.

Objective analysis

In the early years of NWP initial conditions for the simulations were obtained from manually analyzed meteorological charts, laboriously interpolated to pre-defined grid points. Though the need of an automatic data handling and analysis system was realized already in the late 40's, it was not until the mid 50's that the current concept of fitting observations to a prognostic first-guess field was suggested and successfully tried. The impetus came from both mathematicians and meteorologists: the mathematicians were inspired by newly derived estimation theories, the meteorologists by their experience of analysing synoptic weather charts over data-sparse areas by looking at the likely evolution from previous analyses.

Baroclinic models

Though the barotropic model produced useful forecasts at 500 hPa up to three days ahead, its disadvantages were its restriction to the middle atmosphere and inability to create baroclinic developments. The 50's saw intense efforts in several countries to explore the baroclinic nature of the atmosphere. Several quasi-geostrophic models were designed where the computations were, in principle, made for the geopotential height fields, the winds and temperatures being derived as spatial derivatives. This allowed simple modelling of heating from below, friction and orography. The increased complexity introduced new problems and it was not until the 60's that the baroclinic quasi-geostrophic models began to show operational utility, and then only for one or two days; longer forecasts were still made by barotropic models. By that time, work was already under way, with the introduction, or rather re-introduction, of the primitive-equation model, Richardson's old invention, though now refined and enlarged.

The primitive equation (PE) model

In the PE model the changes in wind and geopotential fields are not restricted by any geostrophic linkage, but are allowed to interact freely. Physical parametrizations such as convection, which are difficult to handle in the quasi- geostrophic model, are realistically incorporated, so that the tropical regions, essential for forecasts over Europe beyond two or three days, can be included.

The first global PE model began operating in 1966, with 300 km grid and six-layer vertical resolution. During the 70's several other PE models were implemented, either hemispheric or global, or as Limited Area Models, which ran on a higher resolution over a smaller area and took boundary values from a larger hemispheric or global model.

The general connection between increased skill and model development, better use of an increasing amount of observations and improved analysis systems, is seen in the verification history (fig. 1). The present day 3 forecasts of ECMWF are of the same quality as the 36 hour forecasts made subjectively in the mid-50's.

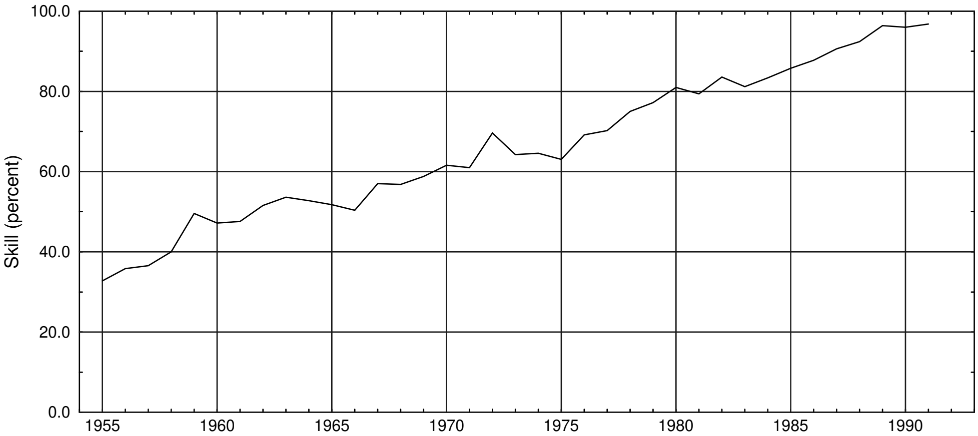


Figure 1 : The S1 skill score for the operational 36 hour NMC forecast from 1955-92. The S1 score is a measure of normalized error in horizontal pressure gradients. The normalization used here is 2 x (70-S1), yielding 0 for a worthless and 100 for a perfect forecast.

Table 1: Summary of the development in large scale NWP, 1950-1990

	Type of Model	Computer performance (MIPS)	Dynamic skill (days)	Numerical technique	Resolution	Parametrization	Model output
1950	Barotropic, regional	0.01	1-2 (barotropic develop-ments)	Finite difference	300 km, 1 level		500 hPa height
1960	Baroclinic, quasi-geos-trophic, hemispheric	1	2-3 (baroclinic develop-ments)		150-300 km, 2-5 levels	Simple topog-raphy, land/ sea, moisture	1000 & 500 hPa height and thick-ness
1970		10	4-5 (blockings)	Semi-implicit, Finite difference Spectral methods Semi-Lagrang-ian	100-150 km, 6-10 levels	Convection, cloud, radia-tion, friction, diffusion	Most atmospheric parameters, incl. 2m T, 10m wind, clouds, rain, snow, showers
1980	Primitive equations	50-100	5-6		50-100 km, 20-30 levels		
1990		> 500	6-7				

The history of ECMWF

Towards medium range and global models

In 1955 J. von Neumann had outlined an overall strategy in atmospheric modelling and prediction. Between short- range predictions of motions, determined mainly by the initial state of the atmosphere, and climate simulations with longer-term predictions that are largely independent of the initial state, he identified an intermediate medium-range category for which it was necessary to consider the details of both the initial state and the external forcing.

From the experience gathered with short-range and climatological simulations, there was in the late 60’s enough know-how in both these fields to attack the medium-range forecast problem defined as the interval from three to ten days ahead. The scientific and technical problems were still formidable, and only few countries had enough expertise to tackle them. This made medium-range forecasting an ideal candidate for multi-national co-operation. When a PE model began operating in the USA in 1966, there were moves in Europe to build up a similar system to provide weather forecasts for up to 10 days ahead.

The creation of ECMWF

In October 1967 the Council of Ministers of the European Communities adopted a resolution to implement a programme to promote joint scientific and technical research. A proposal for a “European Meteorological Computer Centre for Research and Operations" occupied the first place on a list of meteorological projects submitted by an expert group in April 1969. The proposal was accepted and other European nations were invited to participate. In April 1970 an expanded expert group initiated two study groups to look into the economic and scientific motivations for the project.

The reports from the two groups were completed in August 1971, and at the conference of ministers in the same year it was decided to create the European Centre for Medium-Range Weather Forecasts. The ambition, laid out in the plans, was to produce five-day forecasts with the same accuracy as subjective two-day forecasts in the 50's.

The ECMWF convention was signed in October 1973. ECMWF was established by eighteen European States, and cooperation agreements have been concluded with Iceland, Hungary, WMO, EUMETSAT and ACMAD. The objectives of the Centre were laid down as follows:

- To develop dynamic models of the atmosphere with a view to preparing medium-range weather forecasts by means of numerical methods;
- To prepare, on a regular basis, the data necessary for the production of medium-range weather forecasts;
- To carry out scientific and technical research directed towards the improvement of these forecasts;
- To collect and store appropriate meteorological data;
- To make available to the meteorological offices of the Member States, in the most appropriate form, the results of the studies and research provided for in the first and third objectives above and the data referred to in the second and fourth objectives;
- To make available a sufficient proportion of its computing capacity to the meteorological offices of the Member States for their research, priority being given to the field of numerical forecasting. The allocation of the proportions would be determined by Council;
- To assist in implementing the programmes of the World Meteorological Organization;
- To assist in advanced training for the scientific staff of the meteorological offices of the Member States in the field of numerical weather forecasting.

The first operational forecast was produced on 1 August 1979.

The ECMWF forecasting system since 1979 - an overview

The ECMWF forecasting system consists of two components: a general circulation model and a data assimilation system. Every day ECMWF makes a forecast to ten days ahead, and distributes it from its computer system to the systems of the national meteorological services of its Member States via a dedicated telecommunication network.

The first ECMWF numerical model was a grid-point model with 15 levels in the vertical and a horizontal resolution of 1.875 degrees of latitude and longitude, corresponding to a grid length of 200 km on a great circle. In April 1983 the grid-point model was replaced by a T63 spectral model (i.e. a spectral representation in the horizontal with a triangular truncation at wave-number 63). The spectral technique was found to be more accurate than the grid point model for the same computational cost. The number of levels in the vertical was increased to 16.

In May 1985 the spectral truncation was extended to wave-number 106; the number of levels was increased to 19 in 1986. Finally, in September 1991, a much higher resolution spectral model was put into operations, whereby the spectral truncation was extended to wave-number 213 and the number of levels was increased to 31. The shortest half-wavelength resolved is 90 km. The model uses a computational grid with a resolution of about 60 km. The global grid contains 4,154,868 points in all three dimensions. At each of these grid points, the meteorological variables are re-calculated every 15 minutes out to ten days ahead. The total number of computations amounts to about 20,000,000,000,000. With the current Cray C90 this takes approximately 2 hours.

The end use of the ECMWF medium-range weather forecasts

The ECMWF forecasts are used for a wide range of social and economic activities. The following list is not exhaustive:

- agriculture (harvesting, protection, frost warnings)
- energy (generation, oil refining, consumption)
- construction (heavy engineering, general building)
- transport and marine (ship routeing, off-shore activities, road, ice breaking, fishing)
- environmental (pollution, forest fires, water distribution, sea level estimations)
- public (tourism and leisure, health, marketing, emergencies, protection and safety)

2. The ECMWF global atmospheric model

The model formulation

The model characteristics can be summarized by six basic physical equations, the resolution in time and space and the way the numerical computations are carried out.

The basic equations

Of the six equations governing the ECMWF primitive equation atmospheric model, two are diagnostic and tell us about the static relation between different parameters:

- The GAS LAW gives the relation between pressure, density and temperature,
- The HYDROSTATIC EQUATION shows the relationship between the density of the air and the change of pressure with height,

The other four equations are prognostic and describe the changes with time of the horizontal wind components, temperature and water vapour content of an air parcel, and of the surface pressure.

- The EQUATION OF CONTINUITY ensures that the mass is conserved and makes it possible to determine the vertical velocity and change in the surface pressure.
- The EQUATION OF MOTION describes how changes in the wind velocity are caused by the pressure gradient and the Coriolis force and what the effects of friction are near the earth's surface.
- The THERMODYNAMIC EQUATION expresses how a change in an air parcel temperature is brought about by adiabatic cooling or warming due to vertical displacements, latent heat release, radiation from the sun and the earth's surface and frictional or turbulent processes (diffusion).
- The CONTINUITY EQUATION FOR MOISTURE assumes that the moisture content of an air parcel is constant, except for losses due to precipitation and condensation or gains by evaporation from clouds and rain or from the oceans and continents.

As in the quasi-geostrophic models, the hydrostatic assumption makes vertically propagating sound waves impossible. Geostrophy itself, which would also have excluded horizontal sound waves, cannot be assumed, as it would have deleted all gravity waves, which play a vital role as messengers or mediators in the adjustment process between the wind and geopotential fields.

The resolutions in time and space

- Temporal resolution: The computational time step has to be chosen with care in order to avoid numerical instabilities and ensure enough accuracy. The present system uses a time step of 15 minutes.
- Vertical resolution: The atmosphere is divided into 31 layers. The resolution (measured in geometric height) is highest in the planetary boundary layer, where the levels follow the earth's

surface, lowest in the stratosphere where they coincide with the pressure surfaces. In between a smooth transition is applied.

Table 2: Pressure of model levels when the surface pressure is 1015 hPa

	(hPa)		(hPa)		(hPa)
1	10	11	238	21	634
2	30	12	270	22	681
3	50	13	304	23	727
4	70	14	340	24	773
5	90	15	378	25	819
6	110	16	417	26	863
7	132	17	458	27	904
8	156	18	501	28	942
9	181	19	544	29	973
10	209	20	589	30	997
				31	1011

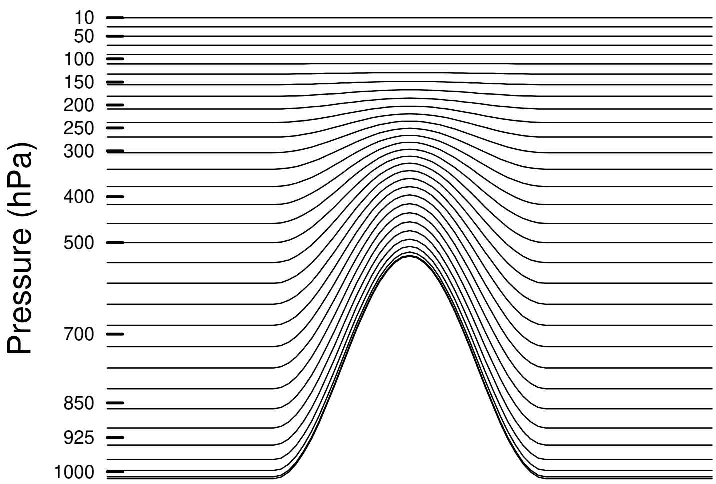


Figure 2 : The 31-level vertical resolution

- Horizontal resolution: The ECMWF model uses two different horizontal numerical representations:

  a spectral representation, based on 213 wave numbers, for the representation of upper air fields and the computation of the horizontal derivatives,

  a grid point representation used for computing non-linear adiabatic terms and the diabatic physical parametrization.

The spectral technique, where the wave-like atmospheric features are represented by trigonometrical functions, is more efficient than the grid-point technique[1]. Though the grid can describe features with half a wavelength down to 0.6 degrees, due to numerical reasons the waves would have to be twice as long to be properly advected by a finite difference scheme. In this sense the grid point representation is coarser than the spectral representation, which has an effective resolution of about 0.8 degrees.

It is convenient to integrate spectral models by carrying out much of the computation on a so-called Gaussian grid, which is regular in longitude and almost regular in latitude. Due to the convergence of the longitudes toward the poles, the east-west distance between the grid points decreases poleward. At 60° latitude it is half that of the equator, in the polar region north of 80° latitude it is less than 1/20 compared to the equator. This very dense east-west resolution, not matched by a similar resolution along the north-south direction, takes more computer time than is necessary for accuracy. To save computer time, a reduction of the Gaussian grid was introduced in 1991. The reduced Gaussian grid is defined as a stepwise reduction of the number of grid points along a latitude line, to keep the east-west separation almost constant. Between 20N and 20S the grid is identical to a regular Gaussian longitude-latitude grid. By doing this the computational time has been reduced by about 25 to 30%.

The numerical formulation

The choice of a numerical scheme is the result of a compromise between the need to preserve numerical accuracy, and the need to save computer time and speed up the forecast. When the T213L31 model was implemented in 1991, the traditional Eulerian scheme would have been too expensive, and a semi-Lagrangian scheme was introduced to reduce the computer cost.

The basic difference between an Eulerian and a Lagrangian representation can be seen from the equation (in a one-dimensional space):

$$\frac{dQ}{dt} = \frac{\partial Q}{\partial t} + U\frac{\partial Q}{\partial x} = 0$$

which in an Eulerian way expresses that the local changes in Q are due to the advection of Q by the wind U:

$$\frac{\partial Q}{\partial t} = -U\frac{\partial Q}{\partial x}$$

or in a Lagrangian way that Q is conserved for a given parcel:

$$\frac{dQ}{dt} = 0$$

Whereas most Eulerian schemes require small time steps to avoid numerical instability, (the quantity Q must not be advected by more than one grid length per time step), the Lagrangian scheme

1. When the spectral technique was introduced with lower resolution models in the early 80's, the purpose was also to improve the accuracy in computing advective terms, which was crucial for correct phase speed estimation.

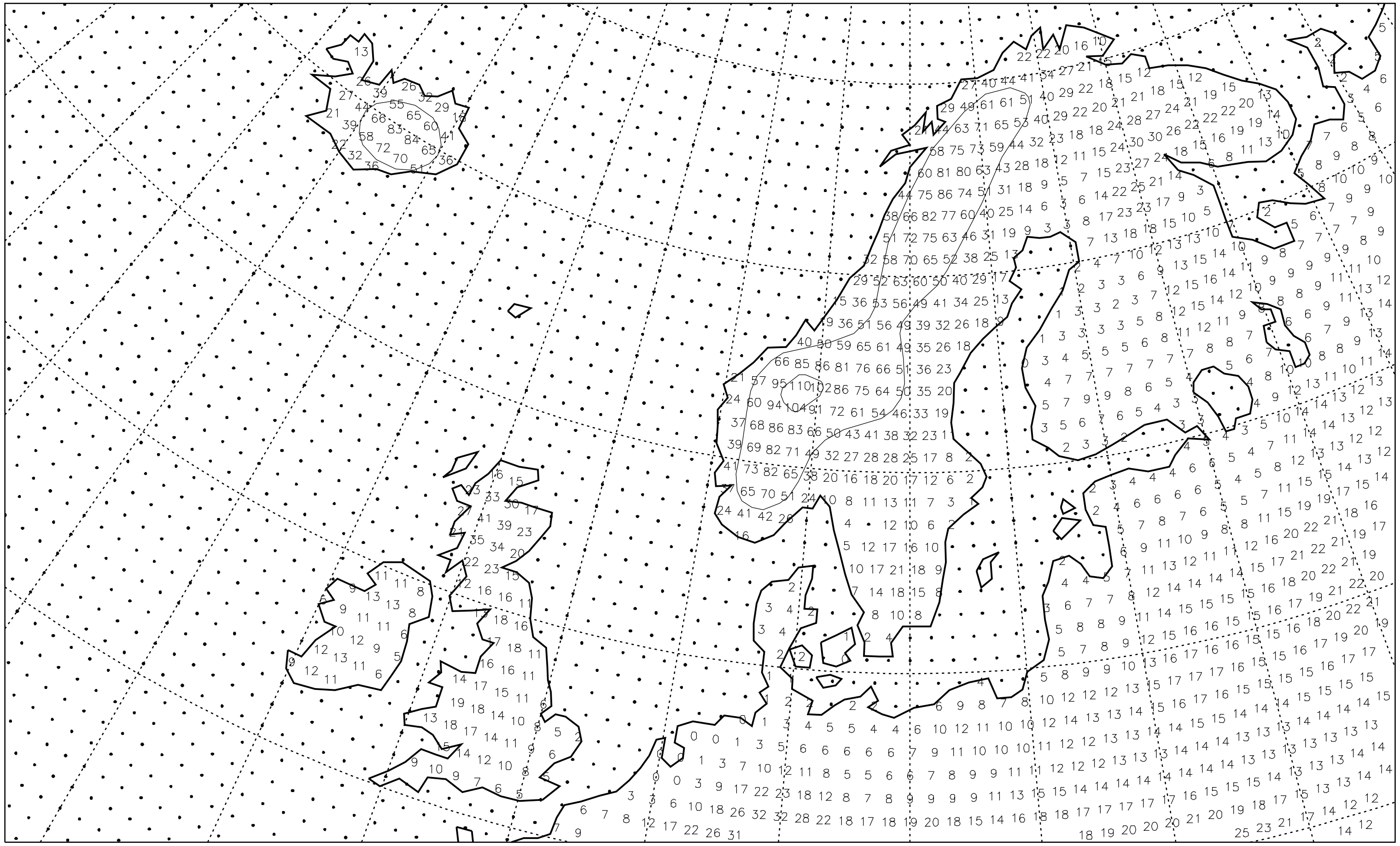
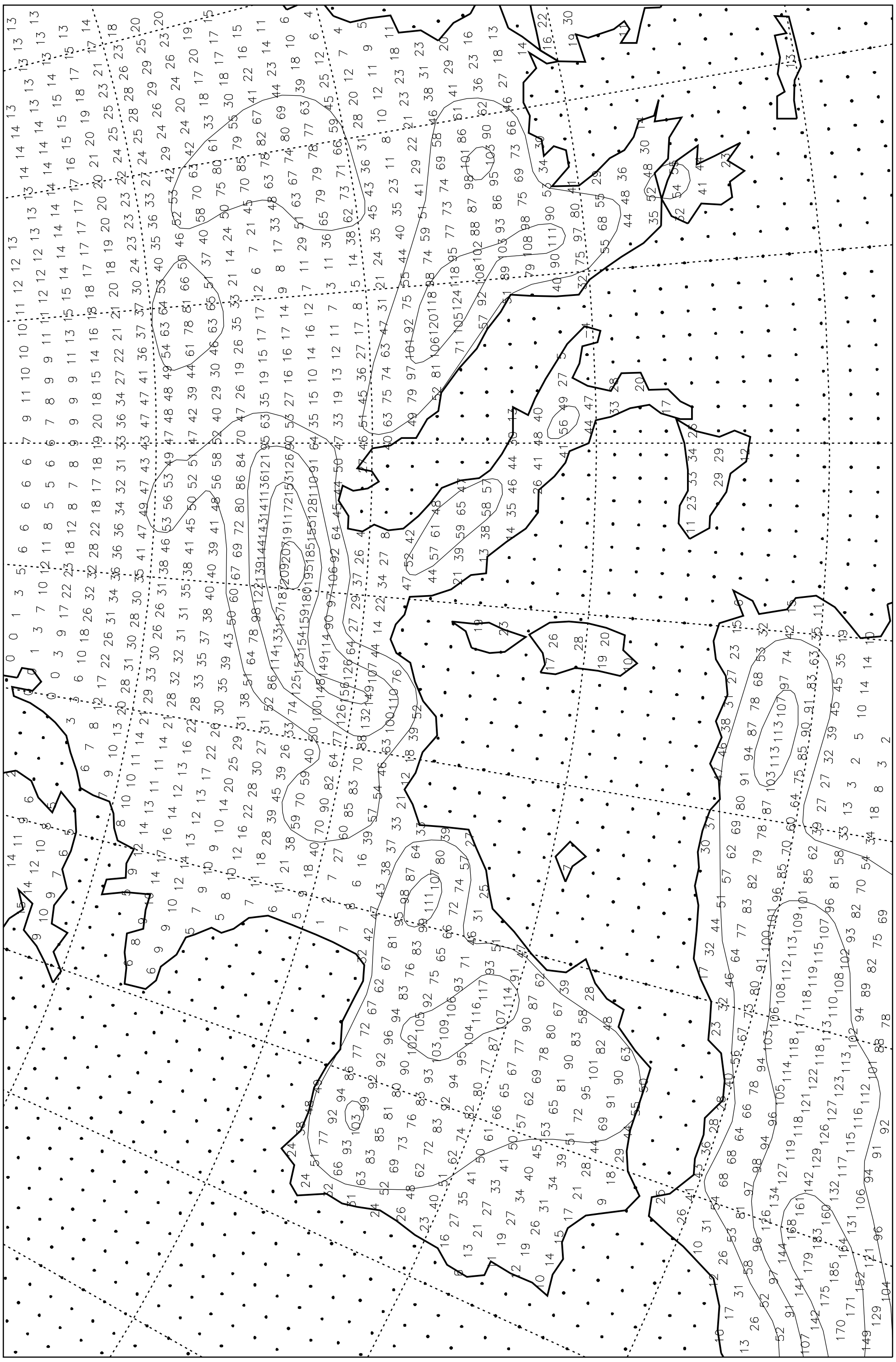
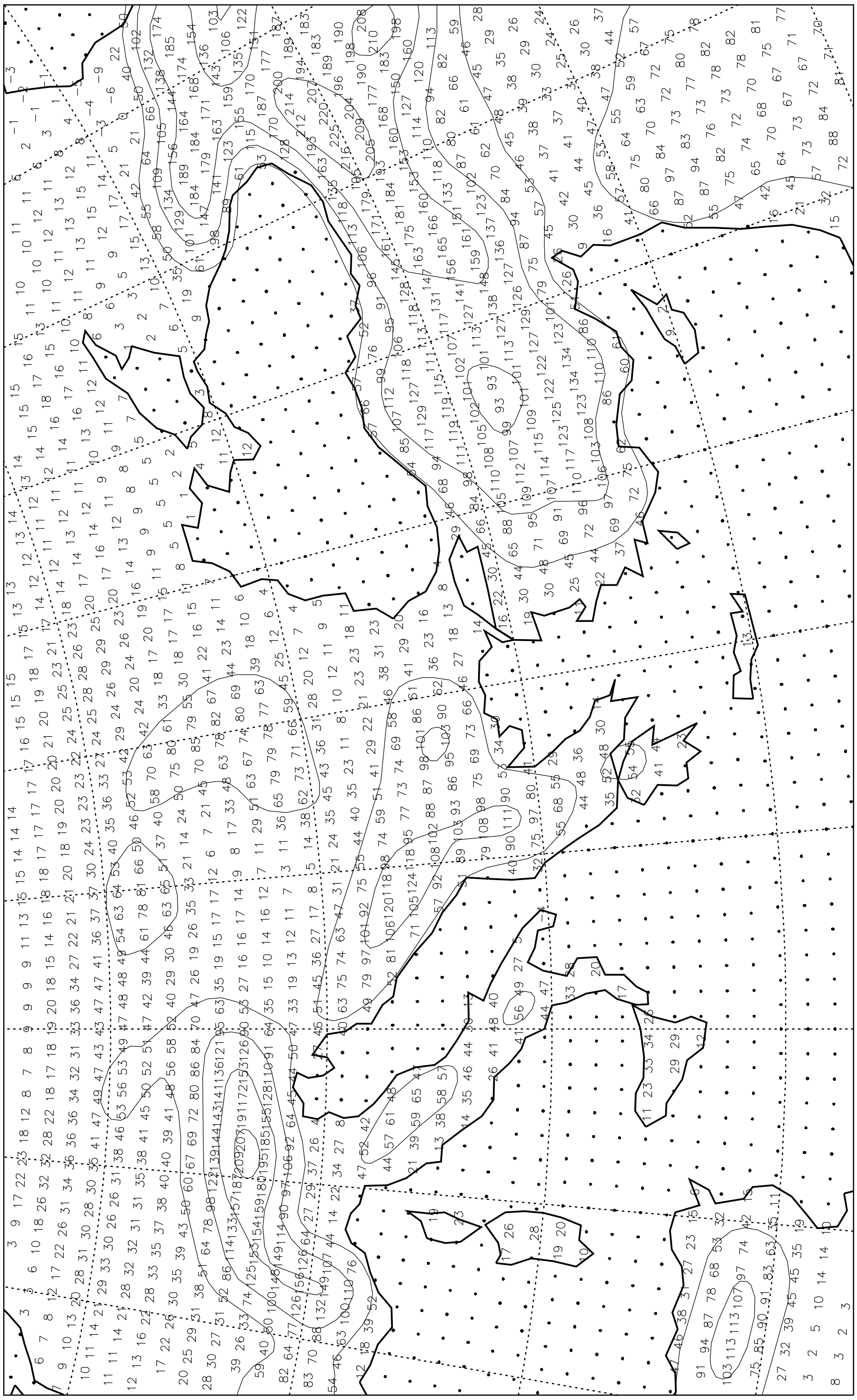


Figure 3 : The model Gaussian grid over Europe (heights in decametres; dots indicate sea points)



The model Gaussian grid over Europe (cont.)



The model Gaussian grid over Europe (cont.)

allows longer time steps, where a limitation is the need to approximate curved trajectories by straight lines (or great circles on the globe) during each time step.

Although it would be possible in theory to carry out predictions in a Lagrangian framework by following a set of marked fluid parcels, in practice shear and stretching deformations tend to concentrate parcels inhomogeneously, so that it is difficult to maintain uniform resolution over the forecast region. A semi-Lagrangian scheme is used to overcome this difficulty.

In this version, the grid points are stationary. At each time step the scheme computes a backward trajectory from every grid point. The point reached defines where the air parcel was at the beginning of the time step. The value of the variable in that point is then carried forward to the grid point, applying the various physical processes.

Tests have shown that a semi-Lagrangian timestep can be around four times longer than the Eulerian without significant difference in accuracy.

Parametrization of physical processes

Introduction

While good operational use can be made of the forecast weather parameters in the ECMWF model, their primary function lies in their impact on the overall atmospheric flow. A ten-day integration makes it absolutely necessary to include effects with relatively long time scale, even as subtle as the evaporation by vegetation, in order to handle the flow pattern more accurately. The different time scales and feed-back mechanisms between the various processes makes the computations extremely complex and expensive.

The mechanisms for these processes are mainly related to small scale disturbances in space and time, smaller than the scales explicitly resolved by the model, from convective clouds down to molecular processes. The effect that these subgrid scale processes have on the larger scales can be computed only by parametrization, i.e. formulating indirectly their overall effect in terms of known grid scale variables.

The Planetary Boundary Layer

The treatment of the planetary boundary layer (PBL), the lowest part of the troposphere, plays a fundamental role for the whole atmosphere-earth system. It is through the surface exchanges of momentum, heat and moisture that the atmosphere “feels” that it moves over a rough land surface or a wet smooth sea.

In the ECMWF model the lowest six levels are at around 30, 140, 340, 600, 900 and 1200 m above the model surface. Even with this fairly high resolution the vertical gradients of temperature, wind, moisture etc. in the PBL cannot be described very accurately, let alone the turbulent transports of momentum, heat and moisture. For the estimation of these parameters the model uses the larger scale variables such as wind, temperature and specific humidity, with the assumption that the transports are proportional to the vertical gradients. At the earth’s surface, the turbulent transports of momentum, heat and moisture are computed as a function of air-surface differences and surface characteristics.

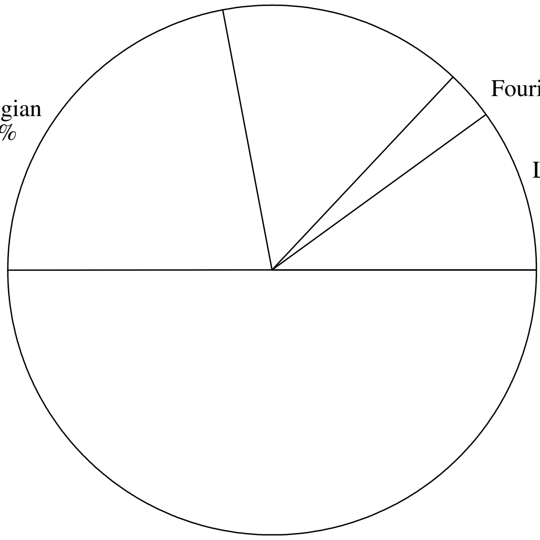


Figure 4 : The computational time devoted for the different parts in the forecast computation.

The surface

The model orography determines the relief of the lower model boundary, but other characteristics such as vegetation, snow cover, sea ice distribution, albedo etc. strongly influence the surface processes in the model.

To have a realistic simulation in the PBL, the knowledge of such factors as the heat and moisture content in the surface soil is essential. The degree to which convective clouds are created in the model depends on the stored heat and moisture in the soil. Over land areas, snowdepth, soil temperature and wetness are forecast variables, calculated by a model of the soil with 4 layers at depths 7, 21, 72 and 189 cm.

The orography

The representation of the orography used in the ECMWF model was changed in April 1995. Since 1983 an envelop orography had been used, whereby the grid square mean height was enhanced by an amount proportional to the standard deviation of the sub-grid scale orographic heights. This had a positive impact on the forecast dynamics, but was detrimental in particular with respect to the physical processes.

The new representation uses the mean orography and four additional fields describing the height, orientation, anisotropy and slope of the sub-grid orography. This allows a more realistic representation of the mountain drag. A novel and important part of the scheme is that, depending on dynamical criteria, it can block the low level flow rather than make the air going over the orography.

The new orography, together with the new physical parametrization, produces more realistic precipitation in mountainous regions; whereas in the old version the largest rainfall tended to fall on the tops of mountain ranges, it now falls on the slopes.

The land-sea mask

The model surface is logically divided into sea and land points. A grid point is defined as a land point if more than 50% of the actual surface of the grid is land (calculated from a 1/6˚ x 1/6˚ reference field). With a T213 resolution, islands like Corsica, Crete and Cyprus are represented by two grid points, Mallorca by only one. The Faroe Islands, Rhodos, Gotland and several Danish Islands are not represented by any land point.

Sea surface temperature

The sea surface temperature (SST) is based on analyses received daily from NMC, Washington. It is based on ship, buoy and satellite observations. It is generally of high quality, but in small waters like the Baltic where rapid changes in SST can take place during the cold season, the real SST can sometimes differ by as much as 5˚ from the analysis. Also in areas where there are few data, such as Hudson Bay, there can be large differences between real and assumed SST. The SST over ice-free water is kept constant during the forecast.

Albedo

A background yearly climate field is used, according to which the albedo is set to 0.55 over sea ice and 0.07 over open water. Over land the albedo has a minimum value of 0.07 and cannot exceed 0.80. The model is able to alter it during the run according to changes in snow cover.

Ice

The sea-ice distribution corresponds to the region of SST values below -1.8˚C. The temperature at the surface of the ice is variable, according to a simple energy balance/heat budget scheme. The distribution of sea and sea-ice points is kept constant during the forecast; no freezing of the water or melting of the ice is allowed.

The soil representation

The parametrization of the surface processes over land takes into account the distribution between bare land and vegetation (based on geographical data) at each grid point. The soil is represented by a four-layer model described earlier. The soil hydrology is simulated in the same four layers. A skin (or brightness) temperature, characteristic of a layer with no heat capacity at the soil-atmosphere interface, represents the balance between radiative fluxes, sensible and latent heat fluxes and a flux into the ground. Temperature in the four soil layers changes due to the combined effect of ground heat flux and snow melting, where appropriate.

- Snow cover: the thermal properties of snow covered ground depend only on the depth of the snow cover (actually the amount of water in the snow). No considerations are made for the age of the snow, i.e. the model will treat old dark snow as if it was white.
- Soil moisture: the soil moisture is divided into skin and soil reservoirs. The skin reservoir (which mainly is moisture on vegetation) evolves under the action of its own evaporation and its ability to collect dew and intercept precipitation. The soil reservoir takes into account contributions from precipitation and snow melt, as well as losses due to deep penetration (gravity), evaporation over bare ground and root uptake by vegetation (i.e. to the transpiration).
- Further climatological fields: the vegetation ratio is specified in each grid point and used by the model to estimate the roughness and the evaporation.

Gravity wave drag

When stably stratified air flow crosses a mountain ridge, gravity waves are excited into the flow. Depending on the static stability and vertical wind shear, these gravity waves can propagate vertically until they have sufficiently large amplitude to break. This process has a certain impact on the large scale flow; it makes it slightly less zonal and contributes to the formation of blocking highs and cut-off lows. In 1986, this previously unrepresented physical process was incorporated into the model as the gravity wave drag (GWD) scheme. It represents the momentum transport due to sub-grid gravity waves. Some of the wave drag occurs in the stratosphere, and there is also significant low-level drag. The dependence on static stability and wind speed implies a maximum in winter and a minimum in summer.

Radiation

In view of the importance of cloud-radiation interaction in both long and short term processes, ECMWF has placed high emphasis on the treatment of the absorption and scattering by clouds of solar and terrestrial radiation. About 1/5 of the overall computational time is devoted to the radiation scheme, as much as for the dynamics.

The radiation spectrum is divided into eight frequency bands: two in the short wave spectrum (direct and diffuse radiation from the sun), and six in the long wave spectrum (from the earth and within the atmosphere). The upward and downward diffused radiation is computed for each of the eight spectral bands. The parameters influencing the emission and absorption are pressure, moisture, cloud cover and cloud water content. Assumed parameters are the ground albedo (modified according to the snow cover), the solar constant and the concentration of CO_2, O_3 and aerosols.

The radiation scheme is designed to take the cloud-radiation interactions into account, in considerable detail. It allows partial cloud cover in any layer of the model. For cloudy grid points, computations are made both for clear and overcast conditions, and the total amount weighted together according to the forecast cloud amount.

Provision is made to have the radiative effects of various types of aerosols (oceanic, desert, stratospheric and background) taken into account. The carbon dioxide has a constant mass mixing ratio over the whole globe corresponding to a volume concentration of 345 ppmv. The ozone distribution depends on height, latitude, longitude and season, based on analyses from the 1970’s.

Convection

The convection schemes in the model fulfils five objectives:

- create a cloud amount to be used by the radiation scheme,
- compute the precipitation,
- compute the vertical transport of moisture,
- compute the vertical momentum fluxes,
- compute temperature changes in the atmosphere due to release of latent heat or cooling in connection with evaporation.

In the general convection scheme, sub-grid vertical fluxes of mass, heat, water vapour and momentum are computed at each model level with the help of a simple cloud model interacting with its environment. The scheme is applied to penetrative convection, shallow convection and mid-level convection. They are mutually exclusive, so only when the scheme fails to create cloud of one type, does it try the next.

Deep convection predominantly occurs in disturbed situations with a deep layer of conditional instability and large-scale moisture convergence. The downdraught mass flux is assumed proportional to the updraught mass flux.

Shallow convection predominantly occurs in undisturbed flow, in the absence of large scale convergent flow. For example trade wind cumuli under a subsidence inversion, convection occurring in the ridge region of tropical easterly waves or day time convection over land. The moisture supply is from surface evaporation. It does not normally produce precipitation.

Mid-level convection describes convective cells which originate at levels above the boundary layer. A well known example is Altocumulus castellanus floccus. Less clearly visible, but frequent, are rain bands connected to extratropical cyclones.

Clouds

Although in general the forecast cloud cover gives useful guidance, the main purpose of the cloud scheme is to provide input to the radiation computations. There have been documented cases when errors in the radiation fluxes have triggered bad forecasts.

Until 1995 the ECMWF model did not contain any explicit clouds, only interpretations from other fields like relative humidity, precipitation, vertical motion and vertical temperature gradients. The clouds could only affect the forecast through their effect on the radiation.

A new scheme was introduced in April 1995 with clouds as prognostic parameters, defined through the cloud fraction and the content of cloud liquid water and cloud ice. The cloud scheme is unique in treating the main cloud-related processes in a consistent way by forecasting both cloud fraction and cloud water/ice content with their own prognostic equations. In the new scheme the cloud processes are strongly coupled to other parametrized processes.

Clouds are generated by large-scale ascent, cumulus convection, boundary layer turbulence and radiative cooling. They are dissipated through evaporation due to large-scale descent, cumulus-induced subsidence, radiative heating and turbulence at both cloud tops and sides, as through precipitation processes.

Convective clouds are computed in parallel with the convective scheme (see above). Moisture is carried upward and condenses into liquid water/ice or “condensate”. This condensate will either fall out as precipitation, be carried higher up in the cloud or be advected horizontally out of the cloud. In this latter case, and only then, the scheme will use this part of the condensate to create stratiform and cirrus clouds (altocumulus castellanus, anvils and other remains from convective processes).

Stratocumulus clouds are linked to the boundary layer moisture flux produced by the vertical diffusion scheme.

Stratiform clouds (e.g. low level stratus and medium level nimbostratus types) are determined by the rate at which the saturation specific humidity decreases due to upward vertical motion and radiative cooling.

Evaporation processes are accounted for in several ways: large-scale and cumulus-induced subsidence and radiative heating, evaporation at the cloud sides due to turbulent processes and turbulent motion at the cloud tops.

Precipitation processes do not only take into account the local water/ice content, but also different precipitation enhancement processes. The effect of evaporation of falling precipitation is also taken included.

The hydrological cycle

- Precipitation: two mechanisms to generate precipitation are included in the ECMWF model, for convective and for stratiform (frontal or dynamical) precipitation:

  convective precipitation: the condensation leading to precipitation is assumed to be liquid water or snow. No ice crystals or liquid water are assumed to be stored in clouds or floating in the air as cloud particles. The rain/snow partly moistens the atmospheric environment by detrainment, the rest falls out of the cloud as precipitation.

  stratiform precipitation: precipitation both as water and ice crystals (snow) are considered, depending on the temperature of the layer where condensation takes place. No condensation is stored as cloud drops or ice crystals. The transition from ice to water is supposed to occur when the precipitation passes through layers with temperatures warmer than +2˚C. Freezing water is not considered in the model except as snow.
- Evaporation: it is assumed that precipitation falling from a saturated layer saturates the first layer underneath before reaching the next layer below. This may substantially reduce the precipitation on the ground. Evaporation of the precipitation is not assumed to take place within the cloud, only between the cloud base and the ground. The layer below a precipitating, non-convective cloud is always almost saturated.
- Melting: melting of falling snow occurs in a thin layer of a few hundreds of metres below the freezing level. It is assumed the snow can melt in each layer whenever the temperature exceeds 2˚C. The melting is limited not only by the snow amount, but also by keeping the induced cooling of the layer such that the temperature of the layer after melting is not less than 2˚C.

The data assimilation

Data availability

In many areas of the globe, the density of available observations is far below what is needed to support the analysis with the required accuracy. In those areas, the assimilation relies mainly on satellite based observations: cloud cleared radiance data and temperature and humidity data from the NOAA satellites, and cloud motion wind data from geostationary satellites (between 50˚N and 50˚S).Typical coverages of non-satellite observations for one analysis cycle are shown in figure 5.

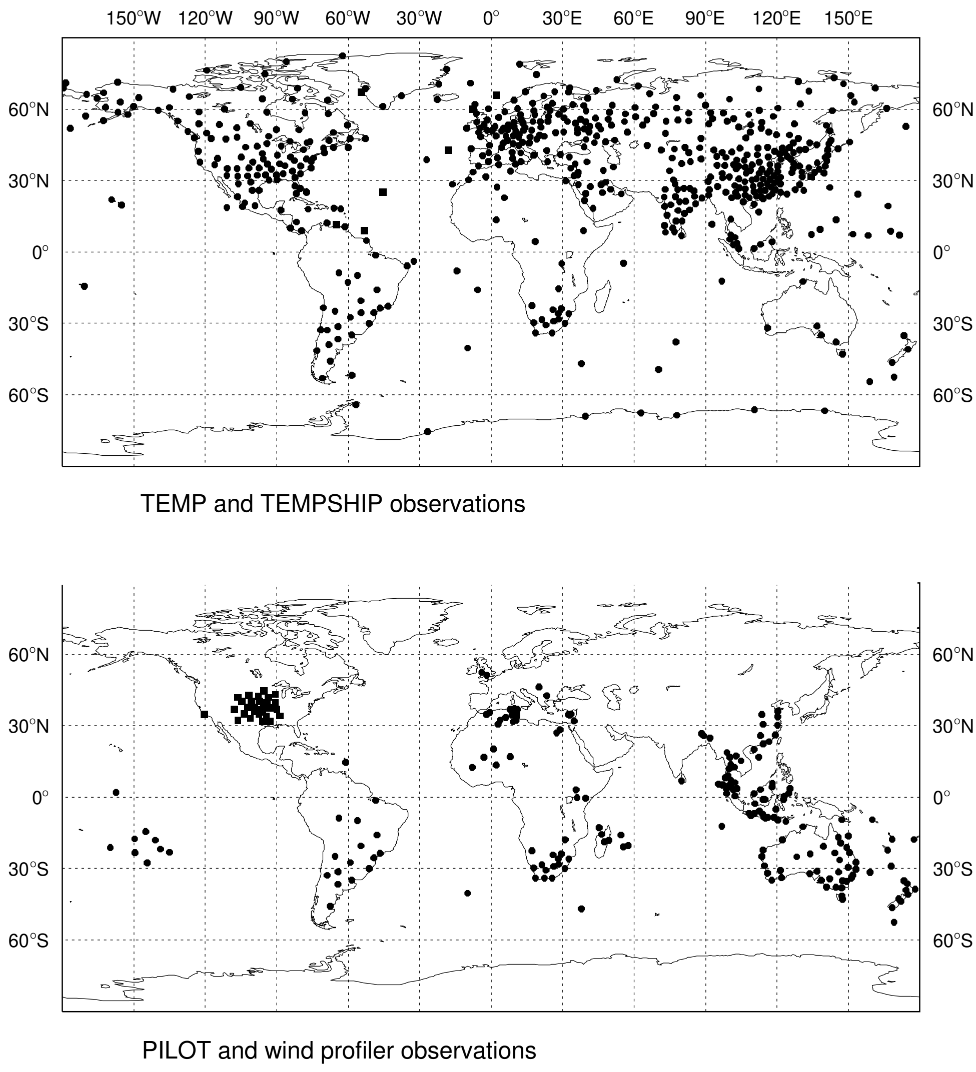
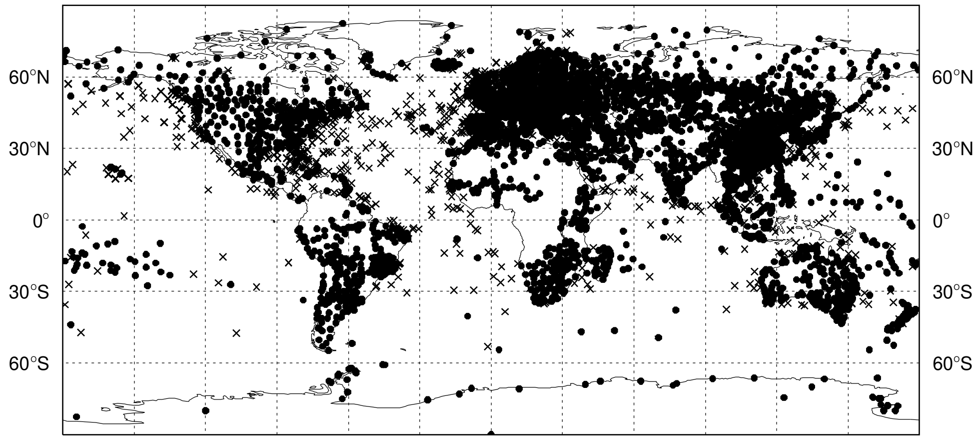
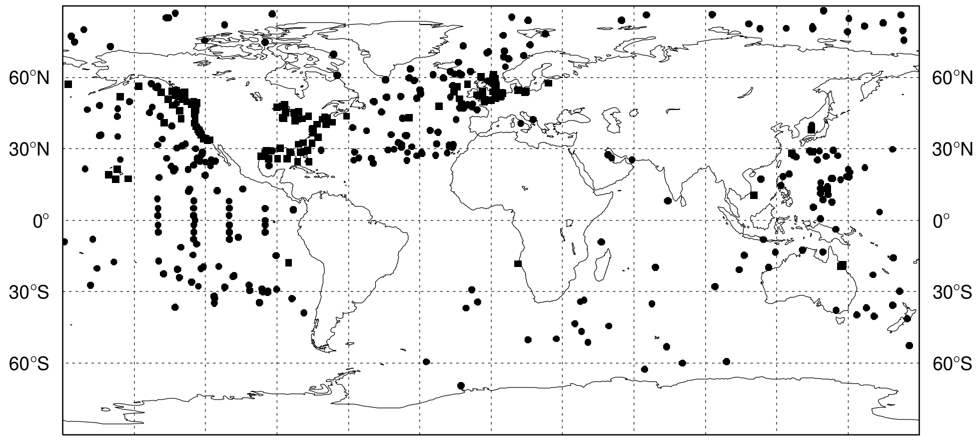


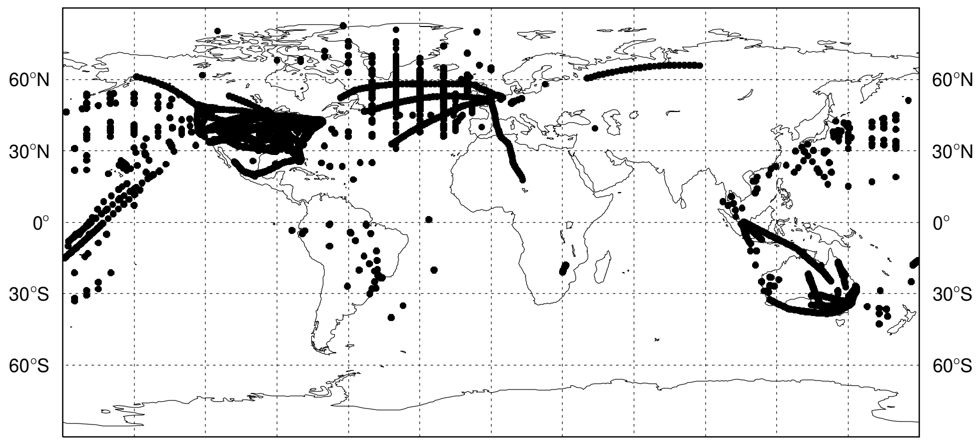
Figure 5 : Typical coverage of conventional observations, 1 July 1994 12UTC.



SYNOP and SHIP observations



Drifting and moored buoy observations



Aircraft observations

Data quality

In addition to the problem of data availability, serious difficulties arise from the highly varying quality of the data itself, from one station to another, and from one time period to another. ECMWF therefore undertakes regular monitoring of all observations used in the data assimilation, with emphasis on those from the global radiosonde network. Statistics on the differences between the observed values and the values given by the ECMWF first-guess field (6 hour forecast) are regularly accumulated. In principle, they can indicate problems either with the data or with the first-guess itself, i.e. the performance of the model in the region. However, large biases (mean differences) and large random differences are usually an indication of data problems. Comparisons with neighbouring observing platforms of the same type and collocation statistics from different data types are used to check the results.

The analysis and forecast parameters

The ECMWF forecasts are computed exclusively in five atmospheric variables: surface pressure, temperature, wind (u and v components) and specific humidity. The various weather parameters (precipitation, cloud cover, geopotential, etc...) are derived as by-products from the above mentioned four variables.

The data used for the height and wind analysis come from SYNOP, SHIP, TEMP, PILOT, DRIBU, aircraft data (AIREP, AMDAR and ACARS), SATOB, SATEM and TOVS (cloud-cleared radiance data). The analysis of humidity (up to 300 hPa) is based only on TEMP and satellite data.

Though temperature is one of the basic analysis and forecast parameters, in the current operational system it is not based on temperature observations from SYNOP, SHIP, TEMP and AIREP (but temperature from ACARS and AMDAR reports are used). The temperature analysis is derived through the hydrostatic equation from the analyzed fields of geopotential. Temperature observations from TEMPs are used only to check the reported geopotential heights. Surface observations of 2m temperature and dew point are used for the humidity analysis.

In addition, surface pressure data from PAOB received from the Bureau of Meteorology, Melbourne, are used. They are so-called “pseudo” observations covering the Southern Hemisphere, derived by experienced meteorologists on the basis of all available information, including satellite imagery.

Pre-processing

Before being passed to the analysis, the observations are decoded and go through a quality control procedure. The code format is checked, and the bulletins that do not follow a WMO code form (syntax errors) are displayed on a screen for manual correction by the meteorological assistant on duty, when possible. This is the only manual intervention in real time in the ECMWF analysis and forecast system. No attempts are made to perform corrections based on meteorological considerations.

The quality control checks that the reported values are realistic. It includes hydrostatic check of TEMP data, check of the displacement of ships and drifting buoys, etc... It conforms to WMO recommendations.

The data assimilation and quality control

Several quality checks are performed within the analysis itself.

- The observation is compared with the 3, 6 or 9-hour forecast (first-guess field) interpolated to the time of the observation.

SYNOP which report more than once during the 6 hour period or appear in duplicate form are reduced in number (the observation closest to analysis time is chosen). High density aircraft data and drifting buoy data are thinned when necessary.

- All observations (except super observations) are compared with surrounding observations and once again with the first-guess field. There is a specific check for multi-level data. A flag is set to serve as a quality indicator in the analysis scheme. The flag can have one of four values:

  0: observation is accepted as being correct

  1: observation is doubtful but will be used

  2: observation is very doubtful and will not be used

  3: observation will not be used.

An observation which has been rejected in the early stages cannot be considered in later checks. Observations accepted in the first test can in a later test have their flag changed to the better or to the worse, and possibly be rejected.

Preparation of the data for the analysis

In contrast to some other analysis schemes, grid points are not analyzed individually in the ECMWF system but are grouped together, in “boxes” of variable horizontal size depending on the data density. The boxes reach from the surface to 100 hPa and from 300 hPa to the model’s top level. The analysis for all the grid points in each box is carried out using the same data from the box and surrounding boxes, assuring consistency of the analysis between the grid points. The analysis is evaluated on the model levels, not on standard pressure levels.

Data from TEMPs are normally only taken from 15 standard levels. If any are missing the nearest significant level will be used. The heights to the significant levels have been computed during the hydrostatic check. If there is a significant difference between a reported standard level and the re-computed one, the former will be rejected and the latter used.

The analysis

Though the need of an automatic data handling and analysis was realized already in the late 40’s, it was not until the mid-50’s that the current concept of fitting observations to a prognostic first-guess (or preliminary) field was suggested and successfully tried.

Though this method was refined during the 60’s and early 70’s, the numerical forecast component was given greatest importance. From the outset ECMWF invested considerable resources in developing an assimilation system and a sophisticated analysis system, combined with the most advanced techniques and ideas.

The assimilation and analysis system has been further refined during the 80's and will during the 90's be further advanced by the so called variational analysis, which will make better use of satellite data and will also better account for the forecast model equations.

The assumed observation errors (σ_o)

In the ECMWF analysis system all observations of the same type are ascribed typical error variances (σ_o), computed from long series of observations compared with analysis. Except for TEMPs, there is generally no distinction between different platforms, all are assumed to be of equal quality.

The assumed typical wind errors are for SYNOP/SHIP: 3-4 m/s, DRIBU 5-6 m/s. TEMP and PILOT are assumed to have a typical error of 2-3 m/s in the lower troposphere, compared to 3 m/s for AIREP and SATOB. In the upper troposphere TEMP and PILOT are assumed to have errors around 3 m/s, AIREP 4 m/s and SATOB 6 m/s.

The assumed typical height errors are for SYNOP 7 m (1 hPa), SHIP and DRIBU 14 m (2 hPa) and PAOB 32 m (4 hPa). For TEMP there are three quality classes, defined according to the monitoring statistics. The typical 200 hPa geopotential error in the first group is 13 m, in the second 20 m and in the third 26 m.

Certain vertical error correlations are used to "spread out" the influence of e.g. an observation of an AIREP in the vertical. For example a wind report at 250 hPa is assumed to correlate 0.5 with the wind at 200 and 300 hPa, only 0.1 with 500 hPa and 100-150 hPa. In the same way a height observation at 500 hPa is assumed to correlate around 0.5 with the height at 700 and 350 hPa.

The assumed "First Guess" (FG) errors (σ_g)

The assumed uncertainty of an observation (σ_o) is combined with the assumed uncertainty of the FG (σ_g), resulting in an estimate of the total uncertainty in the analysis. For the following FG 6 hours later this uncertainty is increased by about 50%, a value roughly representative of a typical error growth over six hours.

In the present analysis system, neither the analysis error nor the FG error are flow dependent. They depend to a large extent on the typical data quality and coverage in the area, which in some areas may lead to occasional misfits.

Objective optimum interpolation analysis

If Z_g is the extrapolated geopotential (or FG) and Z_0 a single new observation and σ_g and σ_o are the assumed errors then the analysis Z_a takes the value

$$Z_a = Z_g + (Z_o - Z_g)\,\sigma_g^2 / (\sigma_o^2 + \sigma_g^2)$$

which means that when the observations are unreliable, σ_o is large and Z_a almost takes the value Z_g. Then there is little impact on the FG. On the other hand, when the observations are assumed fairly accurate, σ_o is small and Z_a almost takes the value Z_o. Then the observations will have a substantial impact on the analysis.

The normal mode initialisation

Though the wind and mass fields are balanced within the analysis “boxes”, on the larger scale, between the “boxes”, there appear minor imbalances, which set up fictitious, undesired gravity waves. In the normal mode initialisation process the model suppresses these gravity waves. During this process, the mass and wind fields become adjusted in such a way that no further undesired gravity waves will appear.

For forecasts beyond 1-2 days, initialisation is really not necessary, since the model itself would have smoothed out most of the gravity waves during the forecast process. Initialisation is still performed for the requirements of the data assimilation. Unless initialized, spurious waves in the First Guess, especially in the surface pressure, would have lead to the rejection of good observations and acceptance of bad ones, and to a wrong estimation of the necessary increments to be caused by the selected observations.

Variational analysis

The optimum interpolation method was designed and further developed mainly to cater for observations made at the same time and reporting quantities directly related to model variables. But in today’s operational meteorological environment data vary considerably both in type and quality, not to mention that they more often than not are made at asynoptic hours. To some extent it has been possible to extend the OI to take into account this diversity in the data flow, but several other shortcomings in the OI have made a new approach necessary - the variational analysis, in which better use can be made of many new types of measurements, which have a complicated, indirect, relationship with the analyzed quantities e.g. radiance data from satellites.

Depending on the complexity of the approach we distinguish between 1-, 3- and 4-dimensional variational analysis.

1-dimensional variational analysis (1D-Var)

From the orbiting satellites observed radiances from the atmosphere are relayed to stations on the earth, where they are translated into temperatures or geopotential thicknesses. These SATEMs are sent out on the GTS and have been used at ECMWF for the global analysis in the stratosphere and over the oceans, although only over the Southern Hemisphere since Spring 1991.

The computation of SATEMs is not trivial or reliable and a significant part of the errors emanate during this process. A better approach would be to use the radiances directly. The model temperature and humidity are interpolated to the locations of the satellite measurements. The corresponding “first guess” radiances are computed and compared with the measured radiances. If they roughly agree, in principle no major modification is made to the vertical structure of the analysis; if they disagree the 1D-Var makes an adjustments of the vertical “first guess” temperature and humidity profile so as to produce a radiance that fits the observation better.

Three dimensional variational analysis (3D-Var)

In the adjustment of the vertical profile by 1D-Var there is no direct horizontal correlation; each vertical observation point is treated separately. The horizontal coupling comes later during the subsequent optimum interpolation.

In 3D-Var surrounding observation points are simultaneously taken into account; the adjustment along one vertical is not unrelated to adjacent adjustments. For conventional observations 3D-Var operates generally as optimum interpolation, its advantage being

- a more accurate mathematical treatment of the first guess error characteristics,
- better capability to handle observations of quite different types (for example satellite data can be used directly),
- better analysis of planetary waves which will be analysed as a whole and not pieced together from analyses in numerous “boxes”,
- a more general mass-wind balance constraint on analysis increments possible,
- the first guess errors should not be assumed to be barotropic, i.e. the vertical correlation (or influence) of an upper air observation is primarily vertical. Instead it should be able to have sloping influences. This will make it possible to use single level data to correct the position of a slightly wrongly placed front or a trough in a vertically consistent way.

In order to make the first operational implementation a bit simpler, the quality control will be made using the optimal interpolation scheme described earlier. 3D-Var also has the advantage to facilitate the extension into 4D-Var, where time enters as the fourth dimension.

Four dimensional variational analysis (4D-Var)

The 4D-Var technique actually meets some very old demands from forecasters, raised already when the first NWP analysis schemes were introduced in the 50’s:

- the analysis should not only rely on the latest available information, but make use of information also 12- 24 hours back. OI does this implicitly through the first guess, but 4D-Var will make this in an optimal way. This means that it should be possible to reconsider observations that initially were weighted down, but which might appear realistic in light of later data.
- the errors in the first guess should be dependent of the flow pattern. For example, larger observation weights should be applied near a rapidly moving or deepening cyclone where the forecast uncertainty is rather large.

The four dimensional variational analysis is able to cope with these problems since the influence of an observation in space and time is controlled by the model dynamics and is therefore more realistic. The implicit first guess errors are carried by the dynamic flow patterns calculated by the forecast model.

4D-Var is to some extent similar to a forecaster’s analysis of a chart. Working on say 18 UTC, he goes back to the previous 12 UTC and even 06 UTC charts and modifies them in the light of the 18 UTC analysis: he might see that a trough should have been drawn sharper at 12 UTC, a rejected observation at 06 UTC might in hindsight look quite realistic. He modifies the 06 and 12 UTC and these will in turn have feedback on his current analysis for 18 UTC.

3. The products

The operational schedule

ECMWF produces global analyses for the four main synoptic hours 00, 06, 12 and 18 UTC, and global 10-day forecasts based on 12 UTC analysis.

The operational schedule with the approximate running times of the analysis and forecast is shown in figure 6. As a forecasting centre with the emphasis on the medium-range, ECMWF operates with long data collection times, varying between 15 hours for the 00 UTC analysis and 8 hours for the 12 UTC final analysis. This schedule ensures the most comprehensive global data coverage, including the Southern Hemisphere surface data and global satellite sounding data. An additional analysis is run for 00 UTC with a cut-off time of around 3 hours, followed by a global 3-day forecast to provide some Member States with boundary conditions to their limited area models.

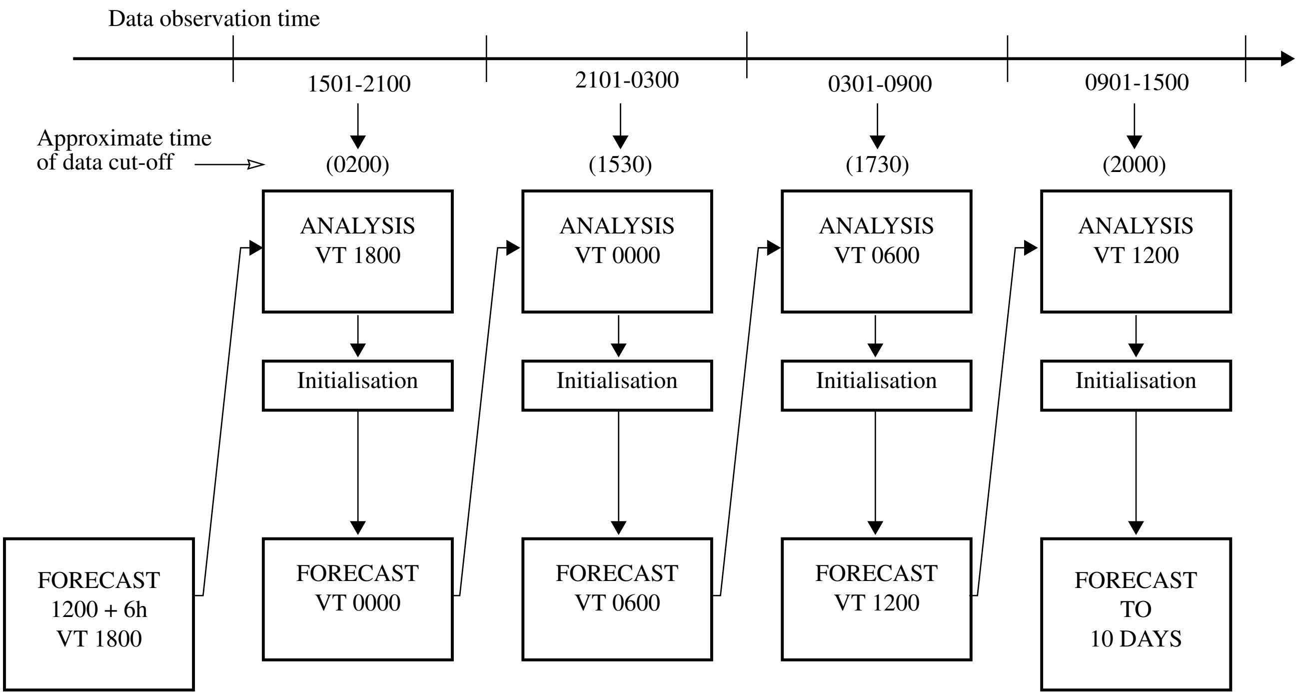


Figure 6 : The ECMWF operational schedule (all times shown in UTC)

Direct model output

The model variables for the computation of the forecasts are temperature, wind and specific humidity. These primary parameters are converted into other atmospheric parameters. Tables 3 and 4 summarize the main output of the forecast model.

Table 3: Upper air parameters

Geopotential height (not on model levels) Temperature Vorticity and Divergence Wind (U and V components) Vertical Velocity Specific Humidity
Upper-air parameters are produced on the original model levels and on standard pressure levels (1000, 925, 850, 700, 500, 400, 300, 250, 200, 150, 100, 70, 50, 30 and 10 hPa).

Table 4: Surface and single level parameters

Mean sea level pressure
10 metre wind 2 metre temperature 2 metre dew point Maximum and minimum 2m temperature since previous post-processing
Large scale and convective precipitation Snowfall
Surface temperature and soil wetness Snowdepth
Total cloud cover Low, medium, high and convective cloud cover
Surface fluxes, surface stress, surface roughness, albedo Solar and thermal radiation

These parameters are computed at 6-hourly intervals from 6 to 120 hours and at 12-hourly intervals from 120 to 240 hours, based on 12 UTC data.

The 2 metre temperature and dew point and the 10 metre wind are computed from the values at the lowest model level (approx. 30 metres above ground) and at the surface, taking into account a prescribed state of the surface (albedo, roughness etc.).

Analysis fields for 00, 06, 12 and 18 UTC including additional fields such as model orography, land sea mask, percentage of vegetation, etc... are also available. However, it should be borne in mind that surface parameters and cloud and radiation parameters *are not analysed* in the present system.

The analysis and forecast output is archived into MARS (the ECMWF archiving system of meteorological data, cf. Meteorological Bulletin M1.9/2).

Dissemination products

A subset of parameters is available to ECMWF Member States through the operational dissemination system (table 5; cf. Meteorological Bulletin M 3.1 (2) for a description of the system). Upper air parameters are available in spectral form or in grid points.

Table 5: ECMWF dissemination products

Operational products	Additional experimental products
Upper air parameters (on pressure levels and model levels) Mean sea level pressure to day 7	Upper air parameters (on pressure levels and model levels) Mean sea level pressure from day 7 1/2 to day 10
2 metre temperature 2 metre dew point 10 metre wind total precipitation total cloud cover to day 7	2 metre temperature 2 metre dew point 10 metre wind total precipitation total cloud cover from day 7 1/2 to day 10 Additional weather parameters: large scale precipitation convective precipitation low cloud cover medium cloud cover high cloud cover snowfall snowdepth throughout the forecast range

Products on the GTS

A limited quantity of ECMWF analysis and forecast products is disseminated via the GTS. The product range is summarized in table 6.

Table 6: ECMWF products on the GTS

Northern and southern hemisphere: MSL pressure 850 hPa temperature 500 hPa geopotential Validity: 12 UTC analysis, 24, 48, 72, 96, 120, 144 hour forecasts
Tropics (30N - 30S): 850 hPa winds 200 hPa winds Validity: 12 UTC analysis, 24, 48, 72 hour forecasts
Code form: FM47-V GRID (5^ox5^o resolution) FM92-Ext. GRIB (2.5^o x 2.5^o resolution)

Data services

ECMWF operates a comprehensive data service from its archives. In particular, it maintains an archive of level III-a atmospheric data in support of projects associated with the WMO World Climate Research Programme.

Verification of the upper-air forecasts

Several types of objective verification scores are computed after every forecast run for a number of areas and parameters, and stored in a historical data base. The most commonly used are the Root Mean Square Error (RMSE) and the Anomaly Correlation Coefficient (ACC).

- RMSE measures the difference between the forecast field and the verifying one. In most cases, the smaller the value the better. However, RMSE will yield lower (apparently better) values for smoothed fields, or for a forecast model with decreasing activity.

- ACC is the correlation between the forecast and analysed anomalies. It mainly measures the skill of the forecast positions and thus implicitly of the phase speed. The magnitude of the ACC depends strongly on the size of the area on which it is computed. For Europe, it has been observed empirically that forecasts with less than about 0.60 correlation have little if any practical skill. ACC has a tendency to score higher in anomalous situations, for example in blocked situations.

Both RMSE and ACC are computed for specific verification times. In the medium-range, this can give a too critical impression when the exact timing is not crucial for the practical usefulness. For example, a deep low forecasted to move rapidly over Europe between 120 and 144 hours may cause poor RMSE and ACC if the timing is wrong by 12 hours.

Verification of weather parameters

Verification procedure

The weather parameters precipitation, cloud cover, 2m temperature and humidity, and 10m wind are verified against surface observations on a daily and monthly basis.

The verification performed at ECMWF is based entirely on direct model output values interpolated to the locations of the observation stations. It does not involve any statistical correction method, except for temperature to which a correction based on the standard atmosphere lapse rate is applied to account for the differences between the height of the model orography and the real station height (stations with too large deviation from the model orography are excluded from any statistics of temperature and wind).

Error sources in the verification

Apart from the errors in weather parameters due to inaccuracies in the forecasts of the synoptic flow, the following effects can affect the verification against synoptic observations:

- representativeness: Surface observations include local effects that cannot be represented due to the model resolution and/or inappropriate description of the state of the surface. Since there are often large differences in the structures of the boundary layers over land and adjacent sea points the model land-sea mask information is used. In coastal areas, the values at the nearest land grid point should therefore be used rather than the interpolated value between surrounding land and sea grid points.
- sampling: to avoid unrepresentative biases, care is taken to avoid an unbalanced choice of observation stations. However, this is not always possible, e.g., when averaging precipitation errors over mountainous areas, many relatively dry valley stations are compared to precipitation forecasts over higher model orography.
- observation errors: the only quality control applied to the observations prior to their use in verification is a gross error check.

Nevertheless, the verification of direct model output values against observations gives a good guidance as to the regional and seasonal behaviour of weather parameter errors.

Random errors

These are measured using the standard deviation which is a measure of de-biased, random forecast errors. Typical values over Europe at day 3 (60-72 hour forecasts) are for

- precipitation: 1.5 mm/6h in winter and 3.0 mm/6h in summer,
- total cloud cover: 3-3.5 octas. It is fairly constant throughout the year. Clouds associated with synoptic frontal systems are generally well predicted,
- 2 metre temperature: around 3 degrees. Also fairly constant throughout the year,
- 2 metre humidity: between 1 g/kg in winter and 2 g/kg in summer,
- 10 metre wind: around 3 m/s in force and 40 to 50 degrees in direction.

Biases

- Precipitation: practically no bias during the cold half of the year. In summer, especially over mountainous regions, the model overestimates precipitation during the day and to a lesser extent underestimates during the night.
- Total cloud cover: on average the model has no bias during the night, a negative bias of about 0.5 octa during the day (since the introduction of a new cloud scheme in April 1995; the previous scheme had a tendency to strongly underestimate the cloud cover).
- 2m humidity: after substantial changes to the surface and soil parametrization scheme in August 1993 the model's boundary layer humidity fits observations well, removing a previous tendency to dry out the lowest layers.
- 2m temperature, night time: too low by about 2° on average in all seasons (more in winter than in summer).
- 2m temperature, day time: too low in winter and spring. In summer the forecast has had little bias since the introduction of the cloud scheme in April 1995 (the previous scheme produced a large positive bias over continental areas).
- 10m wind: the wind force is generally underestimated by 1 to 2 m/s during the day. There is almost no bias at night. This is consistent with the fact that small scales in local wind systems cannot be resolved in the model.

Presentation of medium-range forecasts

Charts

Together with the mean sea level surface pressure, the parameters from the free atmosphere have for long been the forecasters' most important tools for synoptic weather forecasting. The 500 hPa geopotential field, the 850 hPa temperatures and the 250 hPa velocity field etc. provide him with data that are essential for the conceptual models of air mass and long waves.

MSL pressure or 1000 hPa charts can favourably be plotted with fields superimposed such as 850 hPa temperature or moist potential temperature as air mass indicators. 10 m wind arrows give extra "force" to the MSL charts, especially if coloured according to the 850 hPa temperature.

- The 850 hPa temperature is the main parameter for tracing air mass and significant fronts. The forecasts of temperature and moisture reflect the atmospheric conditions just above the friction layer. The wind is very close to the pressure gradient wind at the surface.
- The 700 hPa chart is a suitable field to study temperature advection and movements of convective systems. In particular the 700 hPa relative humidity is highly correlated with the synoptic patterns as fronts or cloud systems. It is recommended for use as forecast guidance in preference to the vertical motion, which can be adversely affected by small scale gravity waves.
- The 500 hPa chart derives its usefulness from its long use as a representative picture of the tropospheric average flow. Especially for assessments beyond D+5 the 500 hPa forecast can provide valuable indications of large scale changes. Long experience has been collected in interpreting the typical gradients and configurations. It is often useful to note the positions of troughs and ridges in the contour and temperature/thickness patterns.
- 200, 250 or 300 hPa level charts have their operational importance in the representation of the jet streams, with their strong ageostrophic deviation from the streamline/isohypses. Since the ECMWF model treats the wind and mass fields very realistically, jet winds are predicted with useful synoptic skill up to at least five days. In some cases the forcing from a jet-streak can cause rapid developments. In addition, the subtropical jet, which derives its speed from air transported at high levels from the equatorial latitudes in the Hadley circulation, can hardly be traced from the 500 hPa gradients. It is particularly important for the weather over the Mediterranean, especially when it interacts with a southerly branch of the Polar Front Jet (figure 7).
- Stratospheric charts are plotted more rarely, and then very much as the traditional 500 hPa charts with isohypses, occasionally also isotherms or isotachs. Potential vorticity might be a useful parameter in increasing understanding of the processes involved.

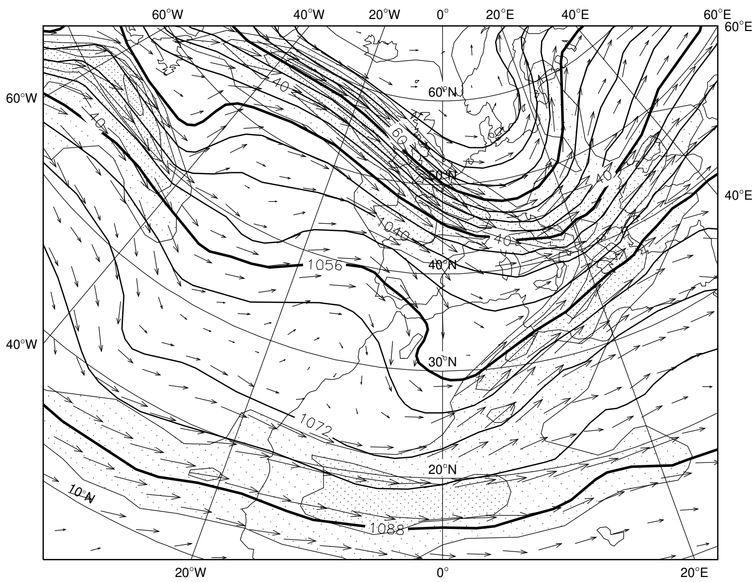


Figure 7 : 250 hPa height and wind, ECMWF analysis, 16 December 1993 12UTC.

Geographical coverage

The charts plotted to be used in medium-range forecasting are often too limited in geographical coverage. A European-Atlantic coverage, preferably also including the easternmost part of North America, is necessary to be able to cope with forecast problems in the short range (up to 3 days). For forecasts up to 5 days the coverage should be extended to the whole of the North American continent and easternmost Pacific. For forecasts beyond 5 days the whole hemisphere should be considered.

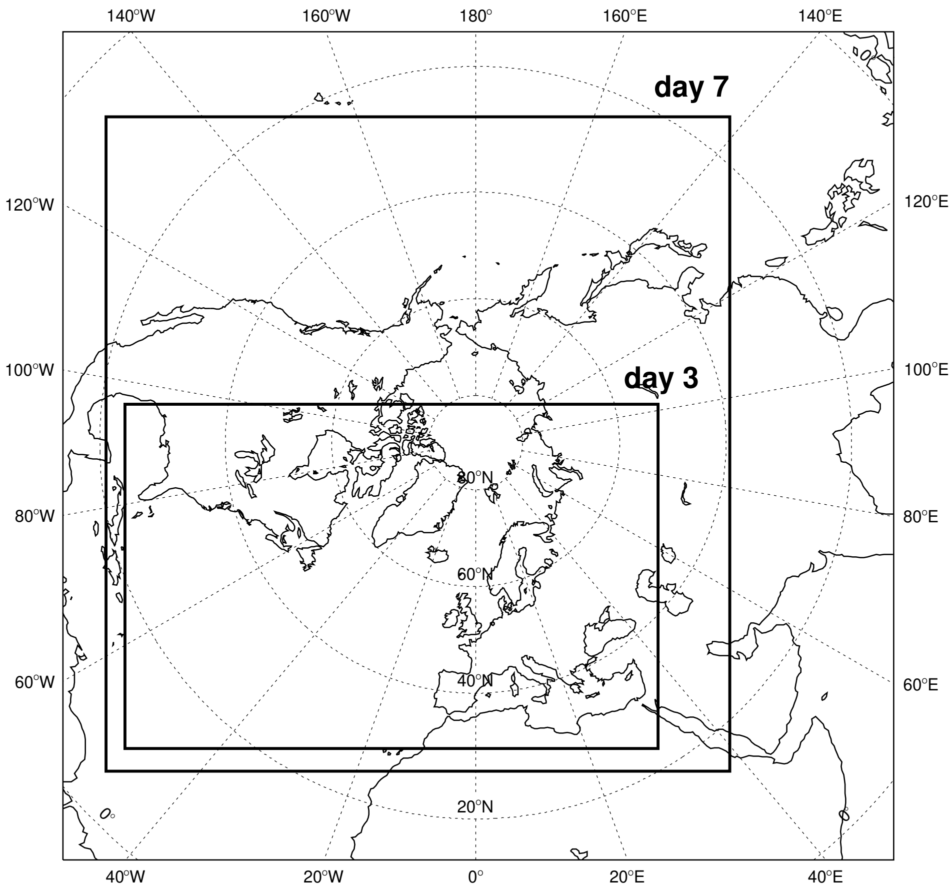


Figure 8 : Suitable areas for different lead times

Meteograms

Plotting the forecast parameters as time series (“meteograms”) is a convenient way to present and familiarize oneself with the weather related forecast output. The quality can be enhanced by applying statistical corrections to the parameters to be plotted. A specific problem with meteograms is that they convey a too confident impression for the non-professional user.

Spatial and temporal resolutions in the retrieval

From the standard parameters in the ECMWF forecast, various derived parameters can be computed ranging, from simply corrected 2 m temperature to complex turbulence parameters. The user should be aware of the spatial and temporal resolutions in the retrieval and of the role of orography.

Horizontal resolution

The ECMWF forecast products can be retrieved at a wide range of resolutions, from a coarse 5˚ x 5˚ to the original reduced Gaussian grid of the model. For near surface parameters the distinction between land and sea points may be crucial, for example for 2 m temperature, precipitation or 10 m wind, and the use of the model's own reduced Gaussian grid is highly recommended.

Vertical resolution

The data can be retrieved both from model and pressure levels.

Orography

When choosing a grid point to represent a station or a certain area, the user should keep in mind that the geographically closest grid-point might not always be the most suitable. Vertically interpolated values can for some parameters distort or smooth vital information.

Due to the difference between model orography and actual orography, at many grid points the direct model output of 2m temperature is representative of an altitude significantly different from the real one. A correction is therefore necessary (simply using the Standard Atmosphere).

Temporal resolution

Forecast fields are produced every 6 hours out to day 5, then every 12 hour out to day 10. Interpolation to 3 hours, to coincide with the synoptic hours, can be performed when required. Care is needed with parameters which display a strong diurnal variation. In such cases, more refined methods than linear interpolation ought to be used.

Precipitation forecasts can present some problem in that they are time integrated values for the last six hours (or the last 12 hours beyond day 5), and do not exactly fit in synoptically with the pressure pattern which refers to the end of the accumulation period. It is of course possible to plot 12 hour accumulated values centred around the forecast time. Beyond day 5, 24 hour accumulated precipitation could be plotted. The same applies to the other parameters which are accumulated between post-processing times, such as evaporation.

Suggested post-processing

Conservative parameters

To gain an understanding of the thermodynamics of a flow certain thermal and dynamical parameters with conservative properties can be useful. Thermal parameters like potential temperature and wet-bulb potential temperature can be used as air mass tracers, but there are also some interesting conservative dynamical parameters. The simplest is the absolute vorticity (AV), applied at the generally non-divergent conditions at 500 (and 150) hPa:

$$AV = (\zeta + f) = \text{constant}$$

This simple parameter can to a high degree explain the changes of the large scale flow: the deepening of a vortex moving equatorward, the amplification of a high moving poleward.

A further extension is the (barotropic) potential vorticity (PV):

$$PV = (\zeta + f)/D = \text{constant}$$

where D is the height of an air volume. The (baroclinic) potential vorticity where the height is defined as the distance between two isentropes θ and $\theta+\delta\theta$ at pressure p and $p+\delta p$:

$$PV = -(\zeta + f)\,(\delta\theta)/(\delta p) = \text{constant}$$

has during the last years received increased attention as a tool to diagnose dynamical processes in the atmosphere. Dynamical weather disturbances that have sharp gradients, such as jets and fronts, are associated with large anomalies in the potential vorticity.

PV's conservative properties make it useful for identifying and tracing the evolution of meteorological disturbances and air masses. It may also help us to understand dynamical processes, especially in the upper troposphere and lower stratosphere, though exactly how still remains to be explored. A large part of the conservation often seen in PV maps can however also be seen in absolute AV.

Trajectories

Two or three dimensional trajectories can be computed from the ECMWF analyses and forecasts. Trajectories have mostly been used to trace pollution, especially radio-active fall-out, but they can also be an interesting air mass tracer which results can be compared with other thermal and dynamical tracers mentioned above. It will also help the forecaster to grasp the differences between streamlines and trajectories, important for medium range interpretation.

Dynamical-statistical interpretation

The effect of the large scale flow on the local weather can only partly be described by the model because local conditions such as topography and surface characteristics have a major effect on precipitation, cloud, wind and temperature.

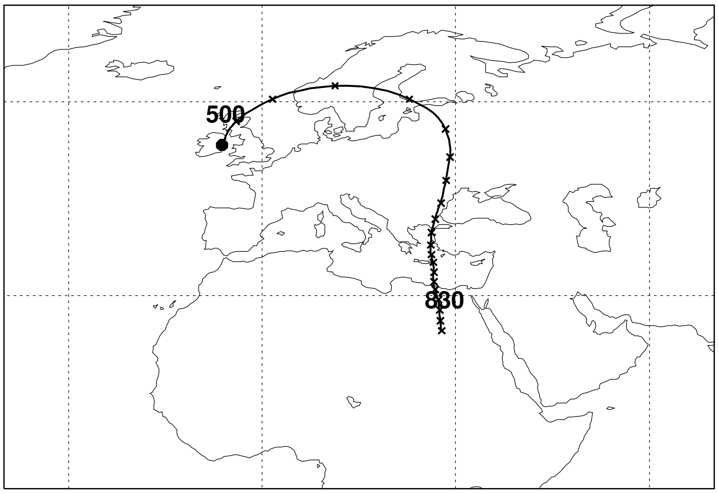


Figure 9 : A 3-dimensional trajectory. Analyses from 12UTC 24 June to 12 UTC 29 June 1994 (cross plotted every 6 hours). Trajectory starting at 500 hPa.

A statistical interpretation, or "dynamic climatology", can be produced for any particular weather parameter (predictand) e.g. precipitation, cloud, visibility, temperature, provided that climatological data for the location exists. Some techniques also partly compensate for the model's systematic errors. There are two traditional statistical techniques: the Perfect Prog Method (PPM) and the Model Output Statistics (MOS) technique.

Perfect Prog Method (PPM)

In the PPM approach, a statistical relationship is established between observed values of the predictand (2m temperature, rainfall etc.) and one or more observed (or analyzed) values of any relevant predictor from the free atmosphere (like 850 hPa temperature, 700 hPa wind, 500 hPa vorticity etc.). Taking then forecast values of these parameters as predictors, the most likely value of the predictand is produced with the underlying assumption that the forecast is correct.

Model Output Statistics (MOS)

Instead of observed (or analyzed) values, MOS relate forecast parameters to the parameters to be predicted. The MOS technique enables the use of Direct Model Output (DMO) values as predictors. If the model has a tendency to under- or over-forecast any predictor, this will be compensated for by the MOS technique.

Advantages and disadvantages of MOS and PPM

While the PPM can be developed using observed data for very long periods and can also be applied to different models, the MOS technique is always related to a specific model and can only use data from periods when there have been no substantial changes in the model. The great advantage with MOS is that it also takes the systematic errors of the NWP model into account. This is especially important to deal with probabilistic interpretations.

Since the PPM statistical relationships are constant through the forecast period, the statistically derived values will have the same variance at D+10 as at D+1, while the MOS equations will tend to damp the variance with lead time. For those end users who are interested in minimizing the forecast error, MOS is to be preferred. Those users who like to get a view of the possible events (e.g. tourist forecast) should prefer PPM because of its greater variability.

Adaptive techniques

Adaptive techniques, in particular the Kalman filter, have gained increased attention over the last years as a way to go round some of the drawbacks of PPM and MOS. Kalman filtering has been extensively used since its invention around 1960. However, applications within statistical interpretation of NWP have appeared only lately.

Adaptive filters share MOS' advantage of being able to compensate for model errors while at the same time being able to continue to work despite changes in the model characteristics. Like MOS, but in contrast to PPM, it can work on forecast near-surface parameters, like 2m temperature. The filter equations can provide interpretation with the same variance throughout the forecast range (like PPM) or with gradually reduced variance (like MOS).

In contrast to MOS and PPM, the adaptive filter applied to statistical adaptation does not need any long historical data base. If the model changes in any significant way, the filter will notice it and gradually adjust the statistical relationship: statistical interpretation for any station can start as early as 2 or 3 weeks after a station has been set up. Figure 10 shows an example case from northern Sweden in November-December 1988.

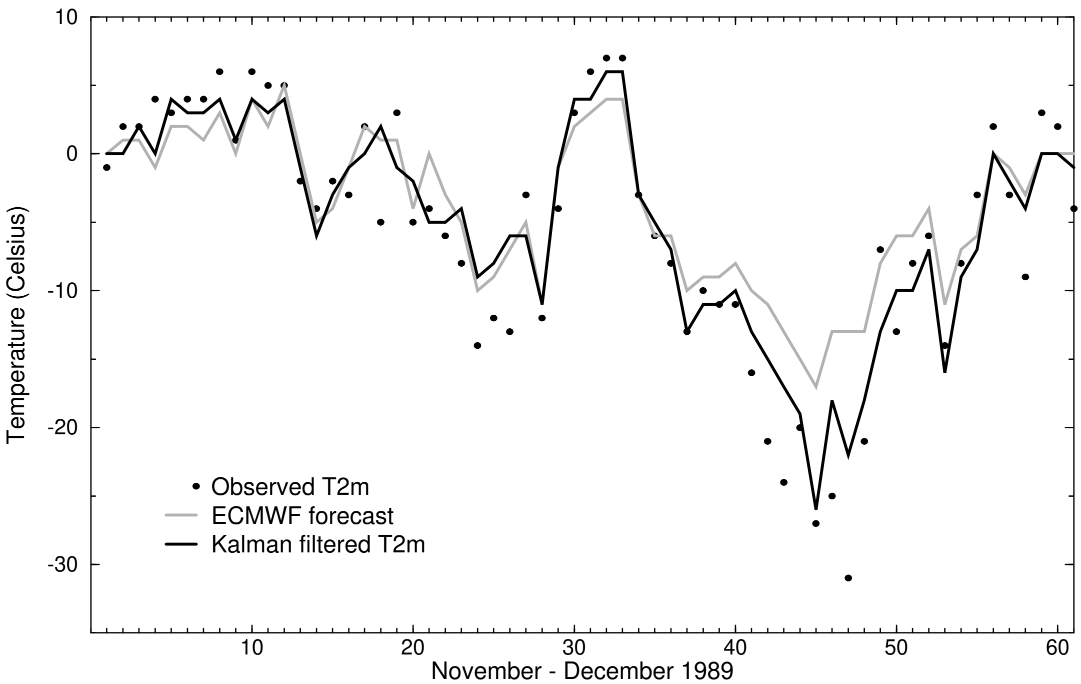


Figure 10 : Direct model output (---) and 2-parameter Kalman filtered 12 UTC t+42h temperature forecast valid at 06 UTC for Lulea, November-December 1988.The 2-dimensional filter actually makes a “cold start” on 1 November and after two weeks manages to identify a relation between forecast bias and forecasted temperature. When a cold spell sets in mid-December the filter manages to make useful corrections, sometimes in the order of 10 degrees.

4. The operational medium range forecast

The forecaster and the medium range

The rôle of the forecaster in the interpretation of the medium range output from Numerical Weather Prediction systems (NWP) is not as well established as in the short range, where a number of traditional and modern techniques are available. The short-range forecaster combines NWP information with later and/or additional observations (automatic stations, radar, satellite images etc.) to make the best possible forecast for every particular need, assuming that new observations will affect the forecast in an almost linear way. This assumption is clearly not valid beyond the first 72 hours of the forecast.

Another difficulty is that, although the medium range NWP output looks realistic even in the smallest scales, the actual skill is concentrated in larger scales which are not immediately apparent on conventional charts. Associated to that is the problem of the numerical forecast changing from one day to the other, with the risk of conveying inconsistent information to the customer.

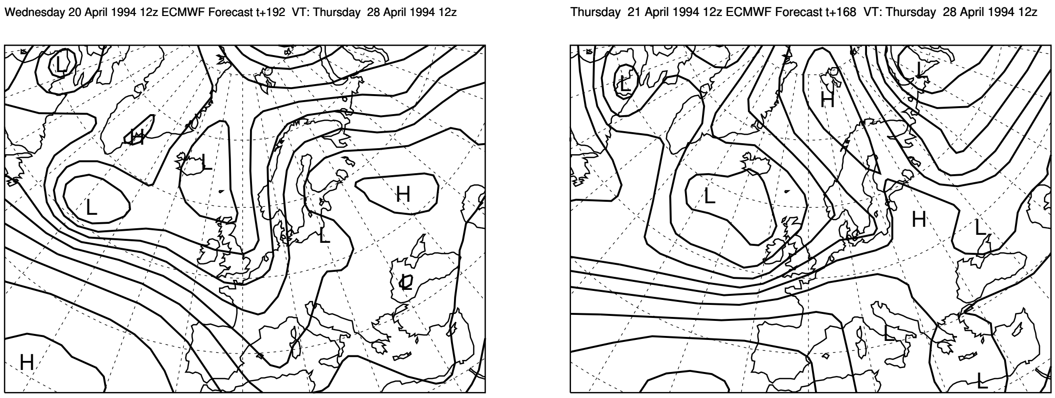


Figure 11 : Two ECMWF forecasts valid at the same time. Both cannot be correct. In the end the last one was right but only caught the broad scale. The realistic looking details did not verify.

Therefore, it is essential for the forecaster in the medium range to focus on the scales which are normally predictable at this time range. The interpretation can be enhanced further by concentrating on the atmospheric developments which are relevant, in particular the behaviour of the planetary waves and the phenomenon of downstream development. Handling of day-to-day forecast differences also benefits from the use of these concepts.

Scale, predictability and forecast range

The larger the atmospheric system, the more predictable it is: a polar front wave is predictable some days in advance, a squall line of thunderstorms only 12-18 hours, a local shower just 30-60 minutes.

Forecasters have always, well before the advent of NWP, been aware of this relation between atmospheric scale and possible extension and detail of the forecast. A general rule in weather forecasting is to associate any forecast event with as large as possible a scale, and disregard scales that are normally not predictable at the forecast range under consideration.

Aviation forecasters, making 2-12 hour cloud, turbulence and visibility forecasts, concentrate on turbulent, radiative and convective processes; short range forecasters, looking 12-36 hours ahead, are more concerned with the position and intensity of fronts, trough lines and baroclinic developments. In the same way medium range forecasters, dealing typically with ranges of three to seven days or even more, concentrate on the movements of the large scale patterns. They should disregard smaller scales, which in the later part of the medium range may for example mean polar front waves or cut-off lows.

The skill of the ECMWF model for various scales can be broadly measured by comparing the energy of the forecast error with the energy of the analysed field in spectral space throughout the forecast range (figure 12). It shows that the forecast of planetary scales is skilful up to and including

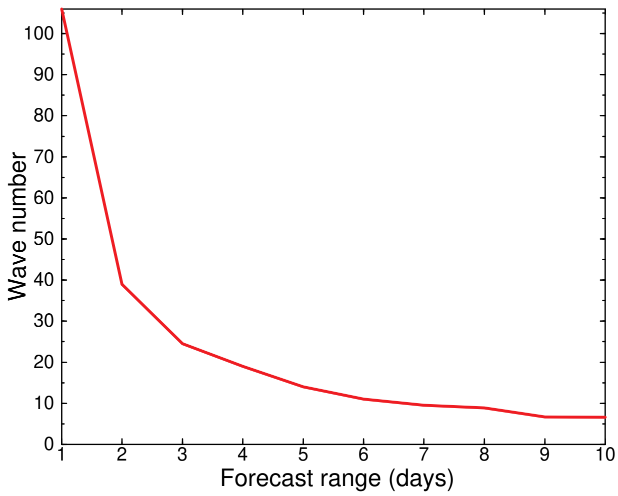


Figure 12 : Wave number for which the energy of the forecast error at a given forecast range exceeds the energy of the initialized analysis, deduced from spectra of global fields of Z500 for December 1993. The forecast for higher wave numbers (smaller scales) has little skill in practice.

day 10, while the day 7 forecast represents properly scales of around T10. Because this large scale is more skilfully forecast than the synoptic scale, it also suffers less from day-to-day inconsistency.

The large scale flow: analysis, inferred weather forecast

The long waves can be identified by smoothing the forecast fields, which can be done both in time and space. Smoothing in time, for example by plotting the mean of D+5, D+6 and D+7, is technically very simple.The mean field can be compared with a mean of the previous day's D+6, D+7 and D+8. Smoothing in space is accomplished e.g. by spectral truncation at T10. It is also very simple and has the advantage of highlighting the model's skill in forecasting the phase speeds of the large scale flow pattern.

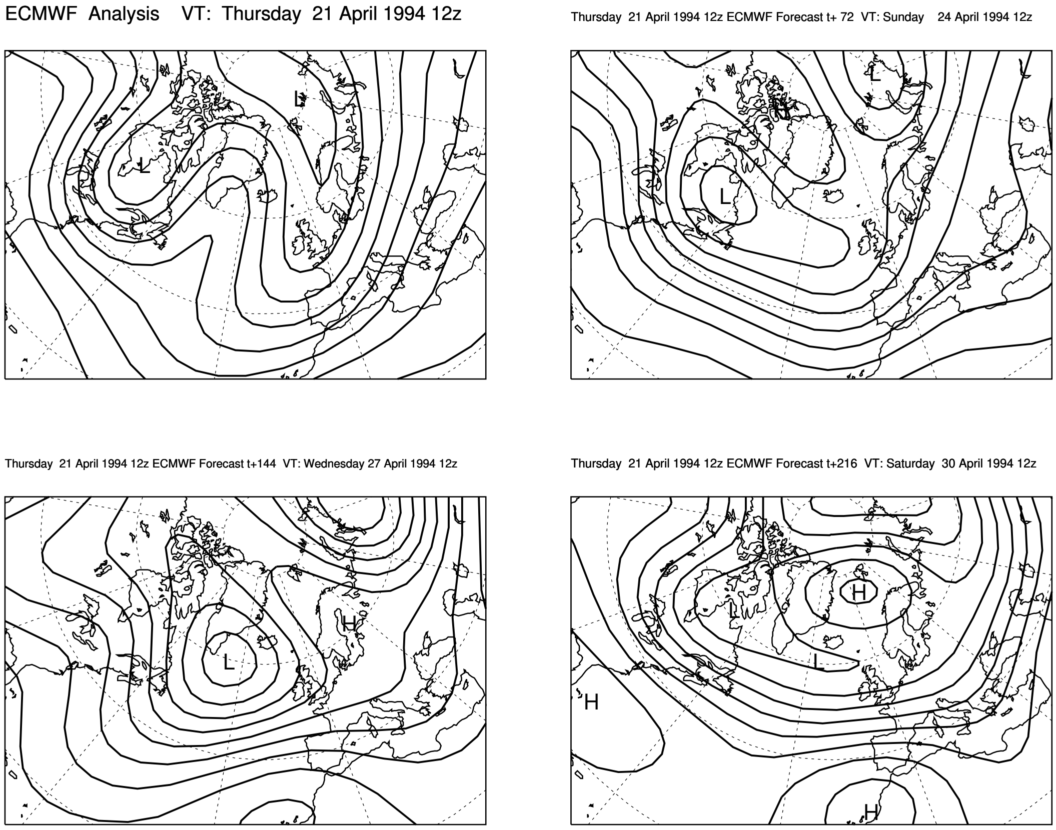


Figure 13 : Example of fields filtered at T10, geopotential at 500 hPa. The forecast evolution becomes clearer with non-predictable systems smoothed out.

Doing this the forecaster will realize that there is more consistency from one day's forecast to the next than meets the eye.

To make best use of the smoothed fields, the forecaster has to use his experience of the relation between large scale flow regimes and surface weather. Large scale pressure systems have a different synoptic behaviour from the conventional frontal disturbances; they can be stationary for long times and even move westward against the prevailing westerly flow (retrogression). A retrogression in the large scale will have significant consequences for the weather type. Since it occurs at low speed it may be disguised by smaller scale systems moving eastward. It will appear much more clearly on a sequence of smoothed forecast plots.

The hemispheric flow pattern: analysis, inferred weather forecast

Retrogressive or progressive movements of the planetary waves often coincide over large sections of the hemisphere. A change from stationary to non-stationary conditions often starts with one long wave, but within a couple of days has spread over a large section of the hemisphere. It is not uncommon to see adjacent Rossby waves moving in the same direction westward or eastward. Verifications show that the ECMWF model with some skill and consistency forecast periods of retro-

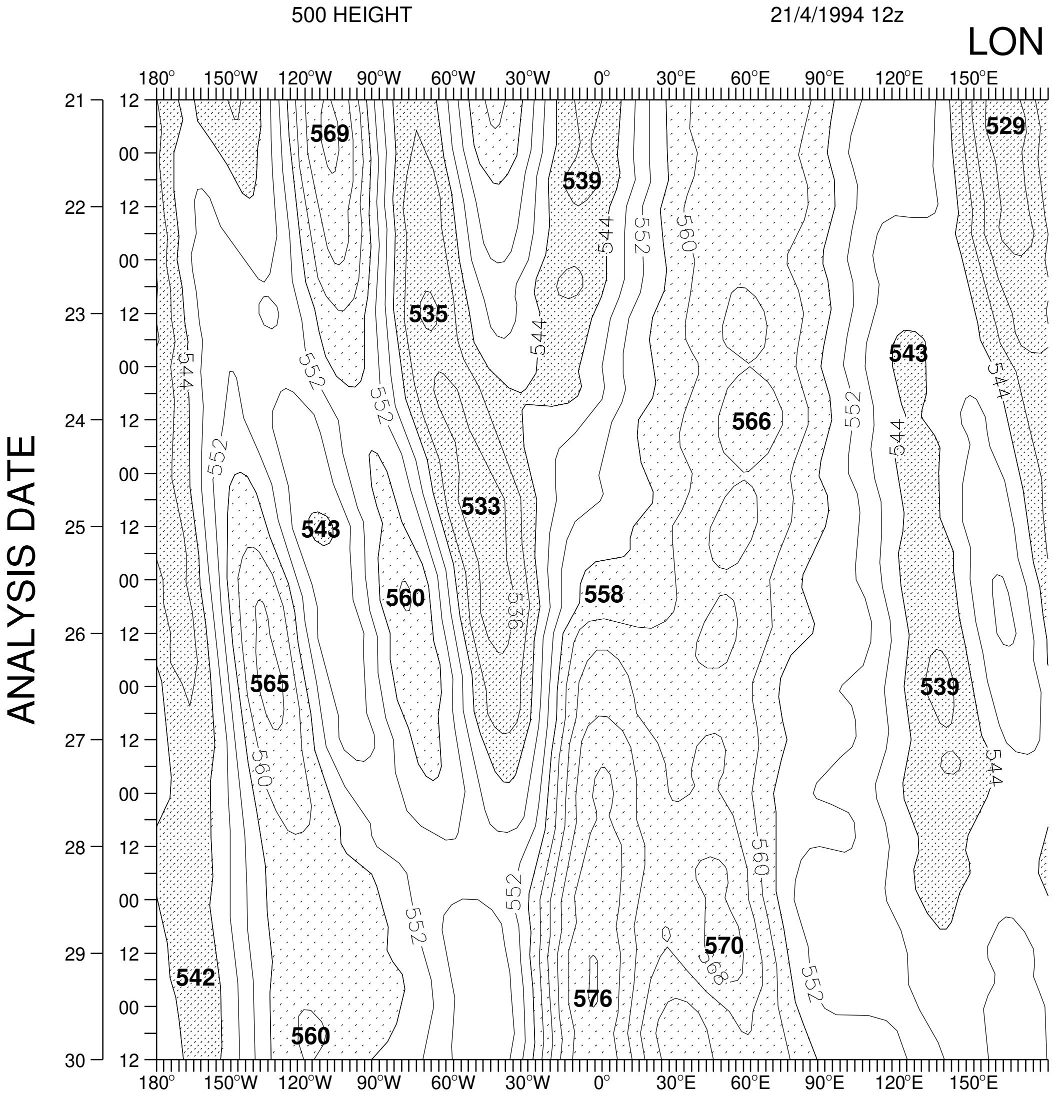


Figure 14 : Retrogression of the large scale flow as seen from trough-ridge diagran (average between 35N and 60N)

gression or progression of the flow pattern over a part of the hemisphere, even beyond day 6, though the positions of individual waves often are in error. For Europe a general progressive movement of the largest scale indicates increasing maritime influence, whereas retrogressive movement indicates increasing continental influence.

Day-to-day forecast differences

Consistency as an indication of skill

During the 1980's many medium-range forecasters began to use the day-to-day agreement (consistency) between successive forecasts to give an indication of forecast quality. Several objective and subjective investigations have, however, failed to confirm any useful relation between day-to-day consistency and skill. The typical correlation in the medium range is disturbingly low, only 0.1- 0.3, mainly because successive bad forecasts quite often are also consistent.

Consistency correlates highly (0.7-0.8) with the skill of yesterday's forecast. This can, unfortunately, not be of much use, since it only means that day-to-day agreement mostly occurs when the one day old forecast is better than normal. But a good D+6 is generally of the same quality as a typical D+5 (anomaly correlation of around 75% at 500 hPa over Europe) so there is actually nothing for the forecaster to gain.

So using day-to-day consistency as a measure of skill actually means making the confidence dependent on a one day old forecast. Experience has shown that in cases of inconsistency the forecaster may be reluctant to issue forecasts beyond D+4. Still, verifications show that 75-80% of all D+5 and D+6 are better than the D+6 and D+7 from the day before. On the other extreme, in cases of consistency, the forecaster may be over-confident and tempted to over-interpret the forecast synoptic details.

Day-to-day differences serve, however, a useful purpose by indicating possible alternative solutions, “Poor Man's ensemble forecast”. The figures quoted above also mean that 20-25% of yesterday's D+6 and D+7 forecasts are better than the current D+5 and D+6 and thus may contain useful information about possible alternative.

Why does inconsistency occur?

Day-to-day changes in the NWP forecast (inconsistency) is an unavoidable consequence of a non-perfect forecast system: bad observations, imperfect analysis system and model deficiencies. The factors which cause bad forecasts also cause inconsistencies. An erroneous observation which has been accepted by the system may introduce an analysis error and cause a forecast failure. But the same is true for factors which cause good forecasts. A good observation may improve the analysis and subsequently the forecast. However, in both cases the forecast will be “inconsistent”: in one case to the worse, in the other to the better.

The work at ECMWF aims at reducing both the “bad” and the “good” inconsistency by improving the model and the data assimilation system. An improved model will not only provide better forecasts, it will also support the data assimilation by providing a better first-guess field and thus more efficiently be able to identify bad observations.

The model climate and its relation to inconsistency

Paradoxically, a certain degree of day-to-day inconsistency is unavoidable with a realistic NWP model: at every stage in the forecast period synoptic features at all resolved scales should develop with the same frequency, even though many will not verify. Drifts in the model climate indicate undesirable deficiencies in the simulation of the atmospheric processes.

A reduction of the day-to-day inconsistency is therefore not an indication per se that the model has improved; such a reduction can be achieved by changes in the model which make it less realistic, e.g. developing fewer and fewer cyclones or blockings in the later stages of the forecast period. At present the ECMWF model has a practically stable model climate over the Northern Hemisphere, whereas in the Southern Hemisphere a minor but significant increase in eddy kinetic energy takes place (figure 15).

The model's ability to create features of all scales throughout the simulation will unavoidably complicate the interpretation of the forecasts. However, the task of removing unpredictable synoptic features cannot be accomplished during the forecast computation; it must be left to the post-processing, preferably through a mixture of automatic means and of subjective interpretation by forecasters.

Day-to-day inconsistency is not only a problem for the operational forecaster in his relation with the NWP output, it is also important with respect to his customers. End users are very sensitive to inconsistent forecasts and the forecaster may risk losing his customer's confidence if he too often changes his forecast drastically from one day to the next. But just because the NWP model has to obey a stable climate with frequent changes in the forecasts, there is no reason why the forecaster should do the same. He does not have to phrase his medium-range forecast with the same degree of detail and confidence as his short range forecast. He must introduce a “climatological drift” by considering only those scales that are normally predictable at a certain time range.

Investigating day-to-day differences

Instead of regarding day-to-day forecast differences as a nuisance, the forecaster can actively make use of them. It is often useful to compute the difference between today's and yesterday's ECMWF forecasts and trace the differences back to their sources. This can be done for any level in the troposphere, 1000, 500 and 300-200 hPa levels yielding the most significant information.

Up to D+3 the forecast differences evolve linearly and might already have generated the first “generation” of downstream differences (with an opposite sign to the initial difference). This difference will in turn create a new one downstream and by D+5 a chain (or train) of positive and negative differences will have formed over an area covering almost half the hemisphere (figure 16).

Inconsistencies in the forecasts of a synoptic feature is not necessarily due to analysis problems of that particular system. It is quite often linked with inconsistent treatment of a synoptic feature further upstream. If this upstream system appears to be correctly analyzed and forecast, increase confidence can be attributed to the development downstream.

The synoptic phenomenon of downstream development is familiar to forecasters (figure 17): a strong cyclogenesis over the western Atlantic is often followed one or two days later by an amplified ridge over Iceland and one or two days later by a low deepening over the North Sea. This chain of events is often part of a fundamental dynamic process, energy dispersion, whereby weather systems interact over long distances. Usually energy does not propagate with the same speed as the weather system, but faster, at the group velocity. A typical atmospheric group velocity is 25-30

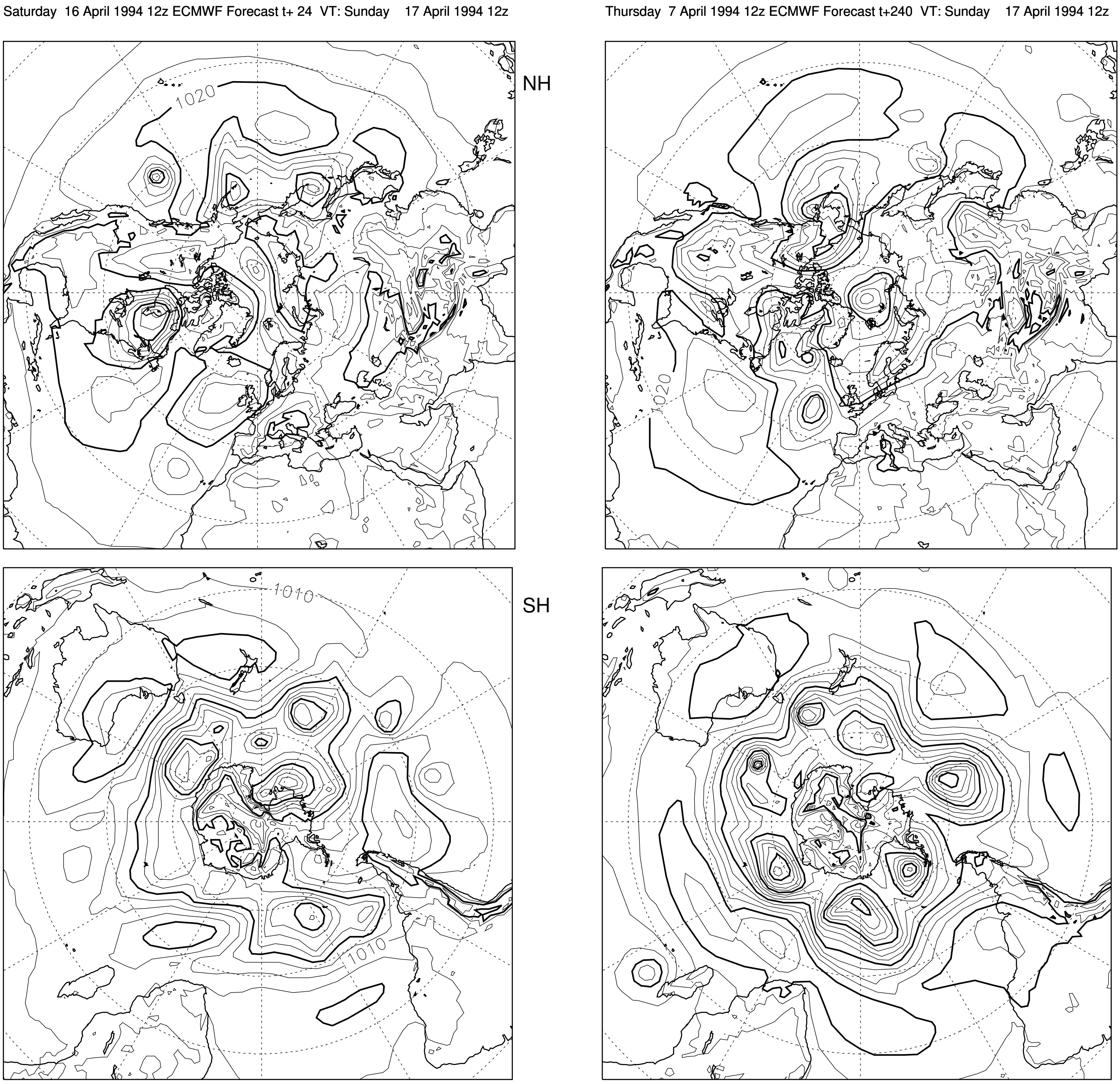
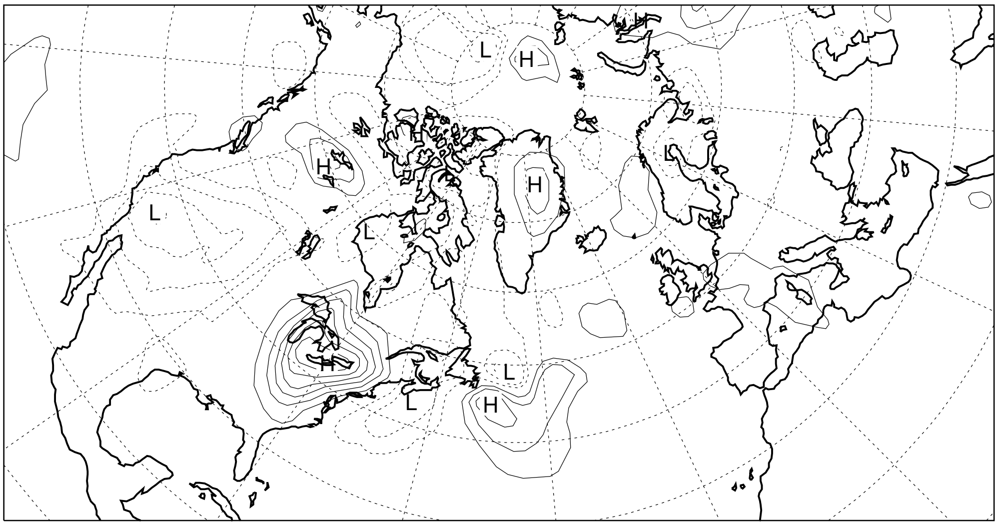


Figure 15 : Examples of MSL forecasts at day 1 and day 10 valid on the same day, Northern and Southern Hemisphere

degrees of longitude per day, which means that influences from the Newfoundland area will reach Europe within three days.

Sunday 15 May 1994 12z ECMWF Forecast t+ 48 VT: Tuesday 17 May 1994 12z



Sunday 15 May 1994 12z ECMWF Forecast t+120 VT: Friday 20 May 1994 12z

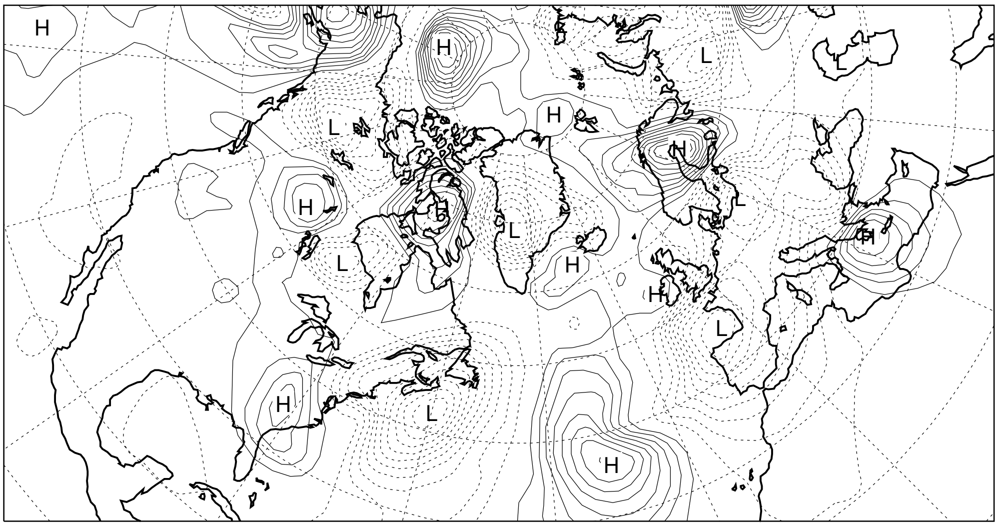


Figure 16 : Propagation of differences over a large part of the northern Hemisphere. 500 hPa geopotential difference between consecutive forecasts (contour every 2 dam, dotted lines: negative).

If a back-tracking of differences points to a source region over an area with a dense network of reliable sounding stations and good density of aircraft reports, the new forecast may be regarded as an improvement compared to the previous one. If the source region is in areas with few or less reliable data, the forecast should be regarded with some doubt and yesterday's forecast might provide a better solution.

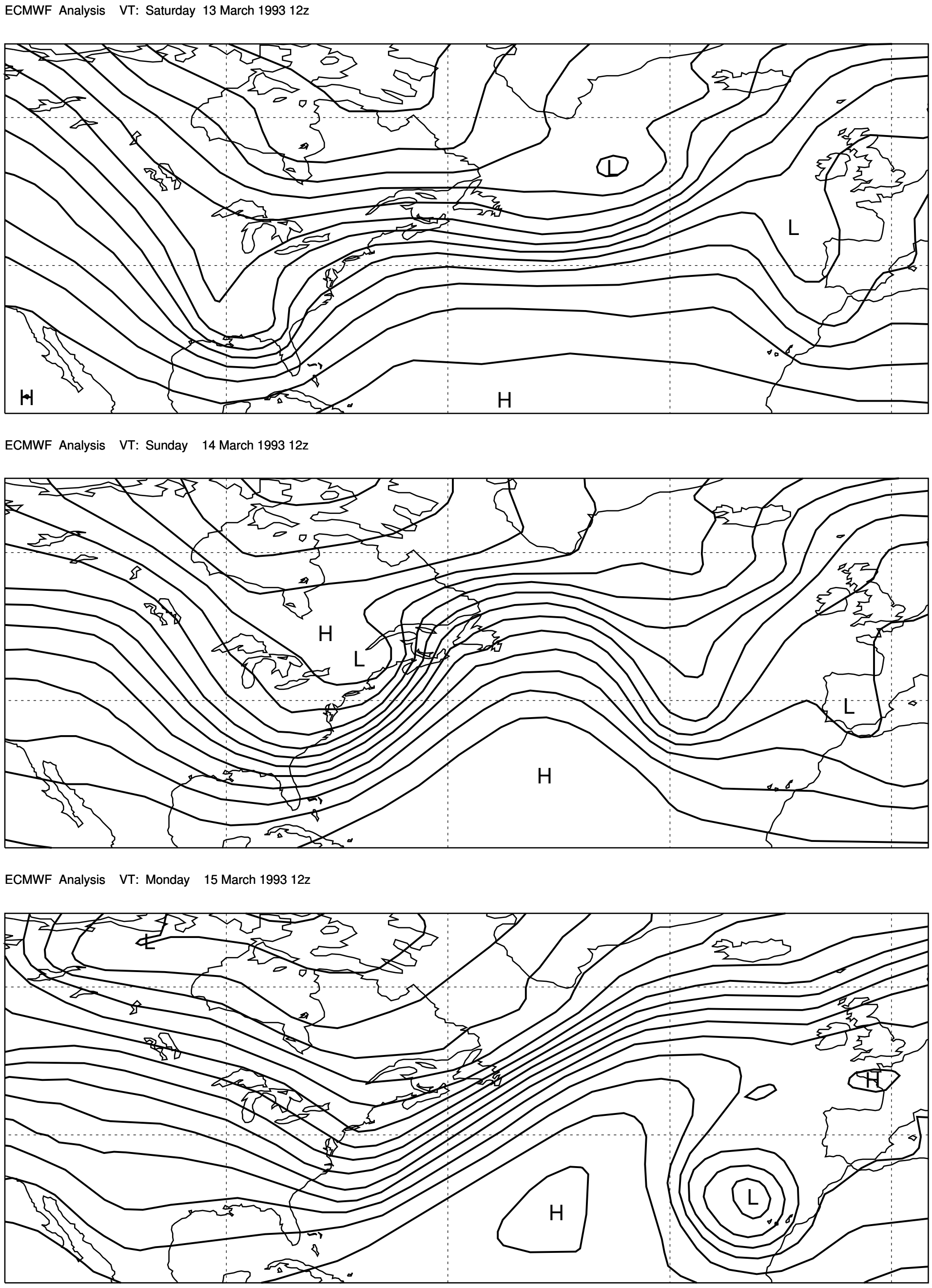


Figure 17 : Example of downstream development

Summary: how to approach the different parts of the medium range

The following is intended as a guide to what the forecaster at present can rely on in the forecast from ECMWF beyond day 3, and how the different forecast ranges can be approached.

- Early medium range (72 to 120 hours):

  Long wave patterns are fairly well predicted, but cyclones or frontal systems cannot always be followed up from the initial analysis, and their predicted positions and intensities might be wrong. Weather parameters have skill as daily means and as means over the period (after removal of possible systematic errors by statistical or other means).

  The general approach is to trace the source of significant day-to-day forecast differences to establish if the main weather systems originate in areas where analysis uncertainties are large (lack of reliable observations) or might have a large impact on the flow evolution. The upstream flow should be examined to see if any new development is forecasted which might affect the downstream evolution.

- Middle medium range (120 to 168 hours):

  Forecast of the long wave pattern is fairly reliable, though the creation of blocks can be underestimated. The predicted positions and intensities of cyclones or frontal systems are doubtful and spurious features may appear. Weather parameters have skill as means over the whole period.

  The general approach is to identify the long waves and changes in the intensity and movements, especially possible retrogressions. Tracking of forecast differences is still possible, but only in rare cases is it possible to trace the source region. The use of the forecasts from the last days (as a “Poor Man's ensemble forecast”) might indicate possible alternative, unless any of the previous forecasts is suspect.

- Late medium range (168 to 240 hours):

  There is some skill in the forecast of the hemispheric flow pattern, but little in the long waves, even blocking anticyclones. The model seems to be able to identify changes in the atmospheric activity, but not their geographical location. Synoptic scale is almost totally unreliable. No skill in weather parameters.

  The general approach is to identify movements and changes in the whole or part of the hemispheric flow pattern.

5. The Ensemble Prediction System

The limits of predictability and the concept of ensemble prediction

Due to improvements in numerics, in the realism of the model and in the definition of the initial state, the skill of numerical models should continue to improve during the coming years. But, because of unavoidable model approximations and limitations in the observational coverage, and, perhaps more fundamental, because of the turbulent nature of the atmosphere, there will always be a limit to how long ahead and how detailed a deterministic/categorical forecast can be produced with some skill. It will probably never be possible to forecast thunderstorm cells 24 hours in advance, individual cyclones more than a week in advance and large scale flow patterns more than a couple of weeks in advance.

The Ensemble Prediction System (EPS) is intended to extend the range of usefulness of the numerical products by exploring the concept of probabilistic forecast. The main idea behind the EPS is to take into consideration the uncertainties in the description of the initial state, exploring what rôle they may play in the development of the forecast. To simulate the effects of possible analysis errors, the basic analysis is slightly modified, perturbed, in sensitive areas identified by the system depending on the current flow pattern. Perturbations are computed for these areas, and those which would amplify most during the first 48 hours are selected. In the current configuration of the system, the perturbations are then combined to form 16 different perturbation patterns. By just reversing the signs another 16 mirrored patterns are created, ending up with 32 slightly different initial analyses. No perturbations are chosen from the Southern Hemisphere.

If the 32 different forecasts for a certain location are quite similar up to a certain range, the forecast is likely to be very accurate for that location within that range. Divergent forecast solutions beyond that range will provide information on possible alternative developments.

In the present system, only the effects of the uncertainties in the initial state are explored. Experiments have shown that analysis uncertainties are a major factor behind poor forecasts up to around D+6. Model errors reflected in the analysis through the first-guess are also covered by the initial perturbations.

The usefulness of the EPS

The EPS can be used on three different levels which complement each other:

- as a measure of predictability in the atmosphere

  Depending on the level of general accuracy required by the end user, a categorical forecast can be issued as long as the internal spread of the ensemble has not exceeded a certain threshold. The spread considered should preferably be the spread of forecasted weather parameters, measured at the place of interest. The general synoptic spread will also serve as a suitable guidance.

  It is not un-natural if the spread of an ensemble forecast does not monotonously increase with lead time. If the spread of a given EPS run is larger at D+5 than at D+7, it means that the forecast five days ahead is more uncertain than later on. Even if the general synoptic flow is predicted with high confidence and the spread of the overall EPS is small, there may be large local uncertainties, e.g. if a small developing low passes north or south of a certain location in the different forecasts.

- as indicator of possible alternative developments

  When a categorical forecast is not possible the EPS can provide possible alternatives. If 70% of the ensemble members forecast a blocking (giving dry weather and weak winds) and 30% a zonal flow (leading to some rain, windy and mild conditions) this information will be useful for many customers. Other customers will benefit from being told also what will not happen, in the same example that gusty northerly winds with frequent showers are most unlikely.

- to produce local probabilistic forecasts of weather parameters

  Like the ECMWF operational deterministic model, each of the individual EPS members produces forecast values of near surface parameters such as wind, temperature, cloud and precipitation for every location. The statistical distribution of these parameters can be used to produce local probabilistic weather forecast (as with the high resolution model, the users are advised to apply a post-processing correction scheme to account for systematic biases).

In the deterministic model, occasional day-to-day forecast inconsistencies act to complicate the interpretation of the latest forecast. This problem should be significantly reduced with the EPS. In such periods with large inconsistencies in the deterministic model, the EPS should consistently display the different solutions among its members. They might change in number and thus in likelihood from one forecast to the next one, but the transitions should be smooth. A general thumb rule would be that 2/3 to 3/4 of the forecast alternatives should persist from one EPS run to the other. The probabilities of a certain cluster solution should at most change by 15-20%, i.e. around five ensemble members.

Limitations of the current EPS

Although the present system already provides useful guidance in all the respects mentioned above, it has limitations caused by current scientific and operational problems. The scientific problems are associated with the computation of the perturbations and the use of a non-perfect model. The operational problems are related to the clustering technique and to the coarse Gaussian grid in the T63 model

- Limitations related to the model

  The resolution of the model used to compute the ensemble is currently T63 L19. The T63 ability to maintain the mean level of eddy kinetic energy is deficient. This implies that the EPS cannot create realistic small scale cyclones and, partly as consequence of this, a reluctance beyond D+5 to create blockings and strong cut-off lows. This will affect the forecasted flow pattern probabilities, making their interpretation more difficult. For example, since blockings are generally underestimated beyond D+5, those occasions when a minority of the members still forecast a block become highly significant.

  The T63 resolution should also be taken into account when working with EPS weather parameters. The coarse grid smooths out many orographic features and give biased values of rain and temperature in particular in mountainous and coastal regions.

- Limitations related to the perturbations

The initial perturbations are currently computed at T42 resolution, which is adequate to catch most of the uncertainties in the initial state. It has been shown, however, that crucial analysis errors can have quite small dimensions, and these relatively coarse perturbations may have difficulties to describe them.

In addition, since only those perturbations which are likely to amplify most within 48 hours are used, cases when an initial error start to amplify after 48 hours are not taken into account. On other occasions, an initially rapidly growing error may weaken after 48 hours and have little impact on the medium range, but still be included among the perturbations.

- Limitations related to the size of the ensembles

  The current ensembles comprise 32 members. The ideal size of an ensemble is difficult to assess, as it depends on factors which are not yet well understood, such as the representativeness of the ensemble members and of the unperturbed forecast. It also depends on the users' expectations concerning the reliability of the probabilistic estimates. However, indications are that much larger ensembles are required in order to sample properly the range of possible solutions.

Clustering

When the ensemble forecast has been computed similar ensemble members are grouped together into clusters. The mean and standard deviation of each of these clusters are computed (as well as the mean and standard deviation of the overall ensemble). Instead of having to inspect 32 or even more different individual forecasts, the forecaster can just look at a limited number (at most six in the current setting) to see the main forecast alternatives identified by the EPS and the clustering algorithm. The clustering technique thus provides a convenient way to assess the EPS output from a synoptic point of view.

However, the advantage of having a reduced number of charts to inspect is balanced by some loss of information. All the members which are used to create a cluster are similar but not identical, and differ in certain aspects, which are smoothed out in the clustering process. The problem is that what is considered to be important varies with weather situation, location and forecast practices.

Five sets of clusters are computed, one for the entire European area, and four for the smaller areas indicated in figure 18. The European clustering naturally emphasizes the most dominant synoptic features: blockings, cut-off lows and zonal flow regimes, covering the whole or a major part of the area.

The clusters over smaller geographical areas should generally be more detailed. On the other hand, with smaller areas there is an increased risk of grouping together forecasts which happen to look similar in a limited region but are quite different on a larger scale.

The present clustering is performed simultaneously on the D+5, D+6 and D+7 forecasts. This means a cluster will contain not only forecasts that are similar at a specific forecast range, but also have followed similar synoptic evolution in the range from day five to day 7. A cluster will therefore represent a logical and consistent development. It also has the advantage of yielding the same number of clusters at every forecast range.

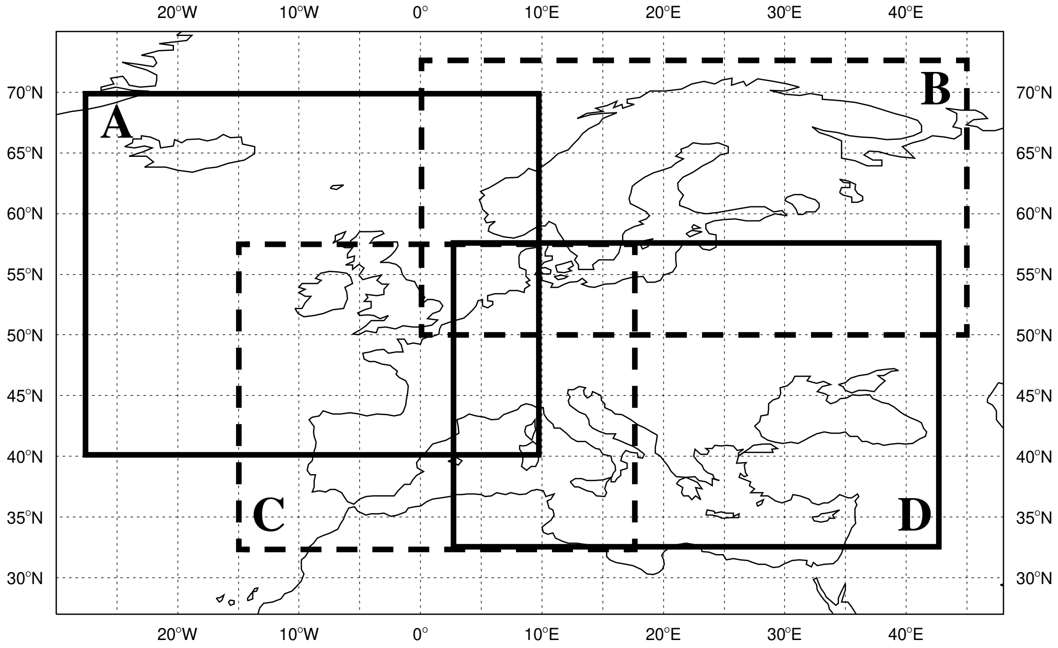


Figure 18 : Clustering areas

The clustering is currently based on the RMS differences between the 500 hPa geopotential fields of the various ensemble members. This favours the geopotential height and puts less emphasis on the shape of the flow. The clustering may therefore occasionally produce two or more clusters which look very similar. The differences may then lay with the general level of geopotential heights, indicating colder or warmer air masses, or with the strength of gradients indicating differences in the phase speed of cyclones and fronts steered by the main flow.

The choice of 500 hPa has the advantage of highlighting the broad scale features which are the most easily predicted beyond D+5. Other parameters like the MSL pressure or 850 hPa temperature could also be used for the clustering. Tests have shown that they yield generally similar results, but from time to time important differences may appear, for example when a uniform zonal flow predicted by most of the members may contain small lows and frontal systems with different intensities and phase speeds.

Other approaches to clustering are possible and have been tried. An approach based on an objective flow pattern analysis has given promising results. However, it is clear that no general solution can be found to accommodate the different requirements of all various users. The trend should be that more and more Member States access the individual ensemble members and produce a clustering as suited to their needs as possible. ECMWF will continue to provide some compromise solution.

The product range

Products from the Ensemble Prediction System include direct output and derived products. The standard dissemination system is used for most products, a limited set of graphical products is sent to Member States by telefax to assist with the initial implementation of the system. No products from the EPS are available on the GTS.

The EPS output is archived into MARS. The control forecast is available in the same way as the T213 forecast, but at T63 (model and pressure levels) and N48 Gaussian Grid (surface parameters). A wide selection of parameters from the ensemble members and derived fields is available (cf. Meteorological Bulletin M1.9/2).

Direct output

The list of fields available from the control forecast and the individual ensemble members is given in table 7 (upper-air fields)

Table 7: Fields from individual ensemble members

Geopotential height Temperature Vorticity and Divergence Wind (U and V components) Vertical Velocity Specific and Relative Humidity
Available on pressure levels 1000, 850, 700, 500 and 200 hPa Forecast ranges from T+12 to T+240 every 12 hours

Derived products

Products derived from the individual ensemble members include fields from the clusters (table 8) and probabilities of occurrence of selected weather events (table 9). The probabilities are estimated

Table 8: Products from clusters

Geopotential height at 1000 and 500 hPa Temperature at 850 and 500 hPa
Forecast ranges T+72 to T+168 every 12 hours The fields provided are the mean and standard deviation of the relevant parameters across the ensemble members belonging to the cluster Available for five clustering areas (Europe and four areas as shown fig. 18)

Table 9: Probabilities of occurrence of weather events

Temperature at 850 hPa	
warm anomaly of at least 4K	
warm anomaly of at least 8K	
cold anomaly of at least 4K	
cold anomaly of at least 8K	
Precipitation	
at least 1 mm in 24 hours	
at least 5mm in 24 hours	
at least 10 mm in 24 hours	
at least 20 mm in 24 hours	
Wind Speed at 10 metres	
at least 10 m/s	
at least 15 m/s	
Forecast ranges T+24 to T+240 every 24 hours	
Average Temperature at 850 hPa	
warm anomaly of at least 2K	
cold anomaly of at least 2K	
Mean Precipitation Rate	
at least 3 mm/day	
at least 5 mm/day	
at most 1 mm/day	
No rain (defined as less than 0.1 mm over the period)	
Forecast ranges	five-day period from day six to day ten
	two-day period from day six to day seven
	three-day period from day eight to day ten

from the ratio between the number of elements from the ensemble indicating the event occurrence and the total number of elements (33, including the unperturbed control forecast)

A last category of derived products is available, namely, the fields from the ensemble mean and ensemble standard deviation.

Deterministic use of EPS

The following guidelines are geared towards the combined use of the EPS and T213 model between D+4 and D+7, depending on the spread of the ensemble and on the agreement with the T213 forecast. The aim is to

decide on a most probable deterministic forecast,
define a level of confidence in this forecast.

If the most probable forecast still has a low probability (less than 50%), it may be possible to decide upon one or sometimes two likely alternatives.

- LARGE ENSEMBLE SPREAD,

  i.e., the ensemble members forecast different meteorological patterns (70 to 85% of cases, depending on the season).

  If the most supported ensemble pattern is in agreement with the T213 forecast (about 50% of cases):

  - the optimal deterministic forecast is based on the T213 model,
  - the confidence in that deterministic forecast is about average; details in the T213 forecast should not be over-interpreted,
  - one or several alternative, less likely, forecasts can be based on the other meteorological patterns indicated by the ensemble.

  If the most supported ensemble pattern is not in agreement with the T213 forecast, two cases may occur:

  the main ensemble pattern is only supported by a minority of members (<50%):

  this case occurs in about 10% of situations. The spread is particularly large and there are several different patterns equally supported within the ensemble.

  - the optimal deterministic forecast is still based on the T213 model,
  - the confidence in that forecast is lower than average, only the very large scale influences are predictable,
  - one or several alternative, less likely, forecasts can be based on the other ensemble patterns.

  the main ensemble pattern is supported by a majority of members (>50%):

  this is a difficult case, occurring in about 20% of situations. The general rule is to consider both forecasts (main EPS and T213) as equally likely alternatives. However, the emphasis can be put on the EPS or the T213, according to the following broad guidelines (considering that the current EPS is run at T63 resolution):

  - on the EPS when it has consistently updated its solutions over the last days, or the most supported pattern forecasts blocking,

  - on T213 in other cases.

- SMALL ENSEMBLE SPREAD,

  i.e., all ensemble members forecast similar meteorological patterns (15 to 30% of cases, depending on the season).

  The single EPS pattern is generally in good agreement with the T213 forecast. Then:

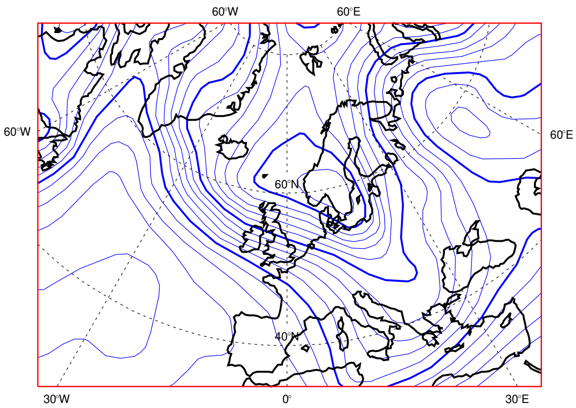
  - the optimal deterministic forecast is based on the T213 model,
  - the confidence in that forecast is higher than average,
  - there are no alternative forecasts.

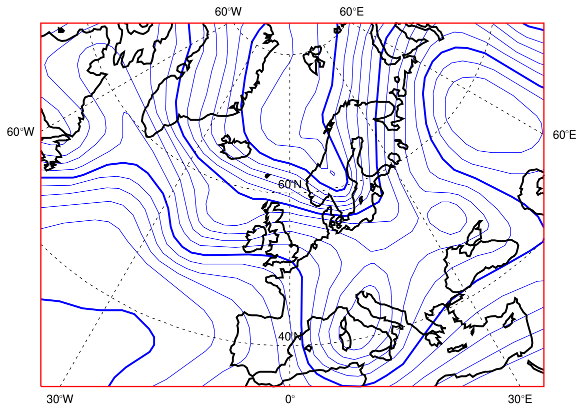
  When the single EPS pattern is not in agreement with the T213 model:

- a very difficult situation which seldom occurs (1 or 2% of cases); the emphasis can be on the EPS or on the T213, according to the previous remarks for the cases with large spread,
- the confidence should be lower than average.

Use of ensemble mean

A better way of using the EPS than just assessing the expected skill, is to consider the mean of the whole ensemble (figure 19). A high degree of synoptic details can remain even at D+7, especially





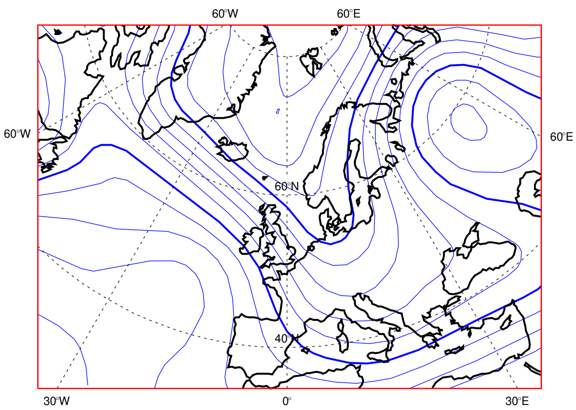


Figure 19 : Analysis for 17 April 1995 (top left), and day 6 forecasts for the same day: T213 (above) and ensemble mean (left)

when the spread is small. However, the resulting fields can be very smooth, and sometimes meaningless when very different forecast patterns are averaged together.

Probabilistic use of EPS

The optimal way of using the products from the EPS is, however, to consider possible alternatives, as shown by the clusters or the forecasted frequencies. Weather forecasting has in reality always been probabilistic: the forecaster has in his wording indicated uncertainties and even suggested alternative developments. Tests have shown that forecasters, even without EPS, do formulate realistic and useful probabilities in quantified terms, both for short and medium range.

Many end users have also found that they can draw larger benefits from forecasts expressed in probabilistic terms, either in numbers or in words. Though the general public is said to favour forecasts expressed in categorical terms, experience has shown that information provided in probabilistic terms is also quickly understood.

The basic principle which makes forecasts expressed in probabilistic terms superior to categorical, relates to the fact that a decision maker who runs the risk of losing L due to bad weather is concerned only when the forecasted risk exceeds c/L if the cost of protecting against bad weather is c.

Verification of the EPS

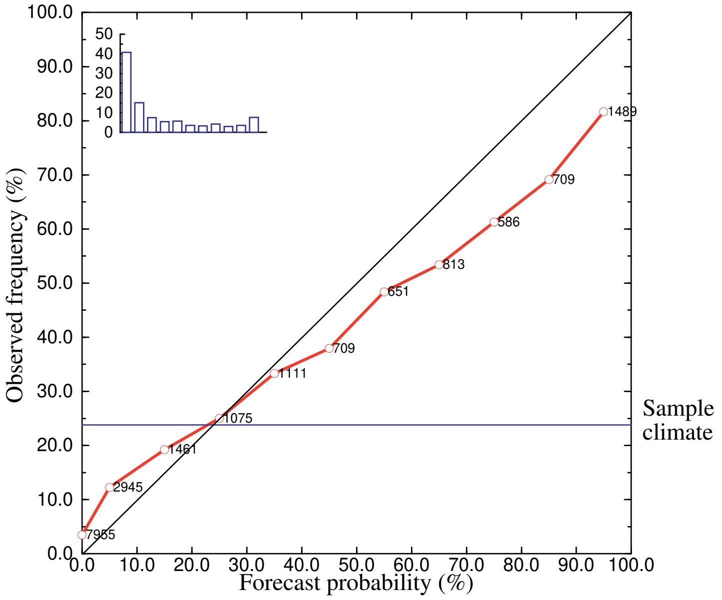
The verification of the Ensemble Prediction System is different in nature from the verification of a categorical forecast. The ensemble system is designed to provide a statistical estimation of the error of the unperturbed control forecast. If the estimation is reliable, the differences between the perturbed forecasts and the control should be representative of the control forecast error.

Results with the current system indicate that the spread of the ensemble is on average too small, i.e., the deviation of the perturbed forecasts away from the control tends to be too small compared with the control error. This can be seen from the number of cases when the verifying analysis is outside the ensemble: around 25% in the early medium range over Europe, down to 15% at day 10, against about 6% as expected in principle with a 32 member ensemble.

The verification of the ensemble forecast is also done on a case by case basis from the synoptic point of view. This is usually based on the cluster fields. The results confirm the tendency of the ensemble to be relatively too close to the control, however, the spread usually gives a consistent indication of the uncertainty of the forecast. This can be particularly useful in changing synoptic situations, as illustrated by the example above.

The ensemble mean is verified as a categorical forecast, with RMS and ACC objective scores. However, it must remembered that its actual spectral resolution is lower than T63 due to the averaging process, and therefore the straight comparison of these scores with scores from higher resolution fields (e.g. from the T63 or T213 models) is misleading. From the synoptic point of view, initial monitoring shows that the ensemble mean is quite skilful in predicting the large scale atmospheric pattern.

The last component of the EPS validation is the verification of the derived probability products. An example of reliability diagram is shown in figure 20 for cold temperature anomalies. Results for temperature generally exhibit a high degree of reliability, even in the later part of the forecast range. Results for precipitation and for surface wind speed show that the system is generally over confident in predicting the event occurrence, which is consistent with lack of spread. This should be accounted for when using the products.



19504 cases, 4639 occurrences, Brier score 0.123, Skill score based on sample climate 0.32

Figure 20 : Reliability diagram for the forecast probability of cold temperature anomaly events (temperature anomaly at 850 hPa less than -4K) over Europe, March-May 1995, forecast range 144 hours

The histogram in the top left corner shows the distribution in percent of the predicted probabilities of occurrences (also indicated by the numbers next to the reliability curve)

Future developments

The Ensemble Prediction System is already contributing usefully to medium range forecasting. In particular, its skill in differentiating between predictable and less predictable situations prevents over-interpretations of realistic looking forecast fields from the T213 model.

During the coming years the EPS will be further refined. Initial perturbations will be computed to better cover possible analysis errors, both in space and amplitude. The T63 model will be replaced with a higher resolution T106 and thus enhance the ability to forecast realistic synoptic features. The size of the ensemble will be increased. All this should improve the value of the EPS in the medium range for the prediction of uncertainties and alternative scenarios in the synoptic flow, and lead to reliable probability forecasts.

6. The ocean wave forecast

Background

Interest in ocean wave forecasting started during the second world war when it was realised that information on the sea state could be of vital importance. The first operational predictions were based on the use of empirical wind sea and swell laws. An important advance was the introduction of the concept of a wave spectrum in the mid 1950's, followed by a dynamical equation describing the evolution of the wave spectrum. This equation has become known as the energy balance equation. It describes the rate of change of the wave spectrum due to advection, wind input, dissipation due to white capping and non linear wave-wave interactions. The wave spectrum gives the distribution of wave energy over frequency and direction and gives a complete specification of the sea state.

The wave model that is used for ocean wave forecasting at ECMWF is the WAM model, developed during the 1980's. The WAM model is the first model that solves the complete energy balance equation, including the computationally expensive non linear interactions. A global version of the model became operational at ECMWF in 1992, followed after a few months by a Mediterranean implementation.

A big stimulus for developing the WAM model was provided by the advent of remote sensing techniques for measurements of the ocean surface by means of microwave instruments (altimeter, scatterometer and synthetic aperture radar (SAR)). Satellite observations may be used to validate and initialise wave models. Assimilation of altimeter data was introduced in the global version of the wave model in August 1993. Buoy data are not assimilated, instead, they serve as an independent check of the quality of modelled wave height.

The products

Two versions of the WAM model are running at ECMWF:

- the global model has a regular latitude longitude grid with a resolution of 1.5 degrees. The advection time step is 30 minutes while the source term integration time step is 15 minutes. The wave spectrum has 25 frequency bins and 12 directions;
- the Baltic and Mediterranean model has a resolution of 0.25 degrees, shallow water effects are included and the advection and source time step is 10 minutes. The wave spectrum has 25 frequency bins and 24 directions.

The 2D-spectra are the so-called wave variance spectra (which follow from the energy spectrum by division by a factor ρ_{water} x g). All integral parameters can be obtained from the 2D-spectrum. The current product range is indicated in table 10, and an example of forecast is shown in figure 21.

Analysed wave spectra and analysed and forecasted integral parameters are archived.

Figure 21 shows wave forecast verification over the northern Hemisphere for the period October-November 1995.

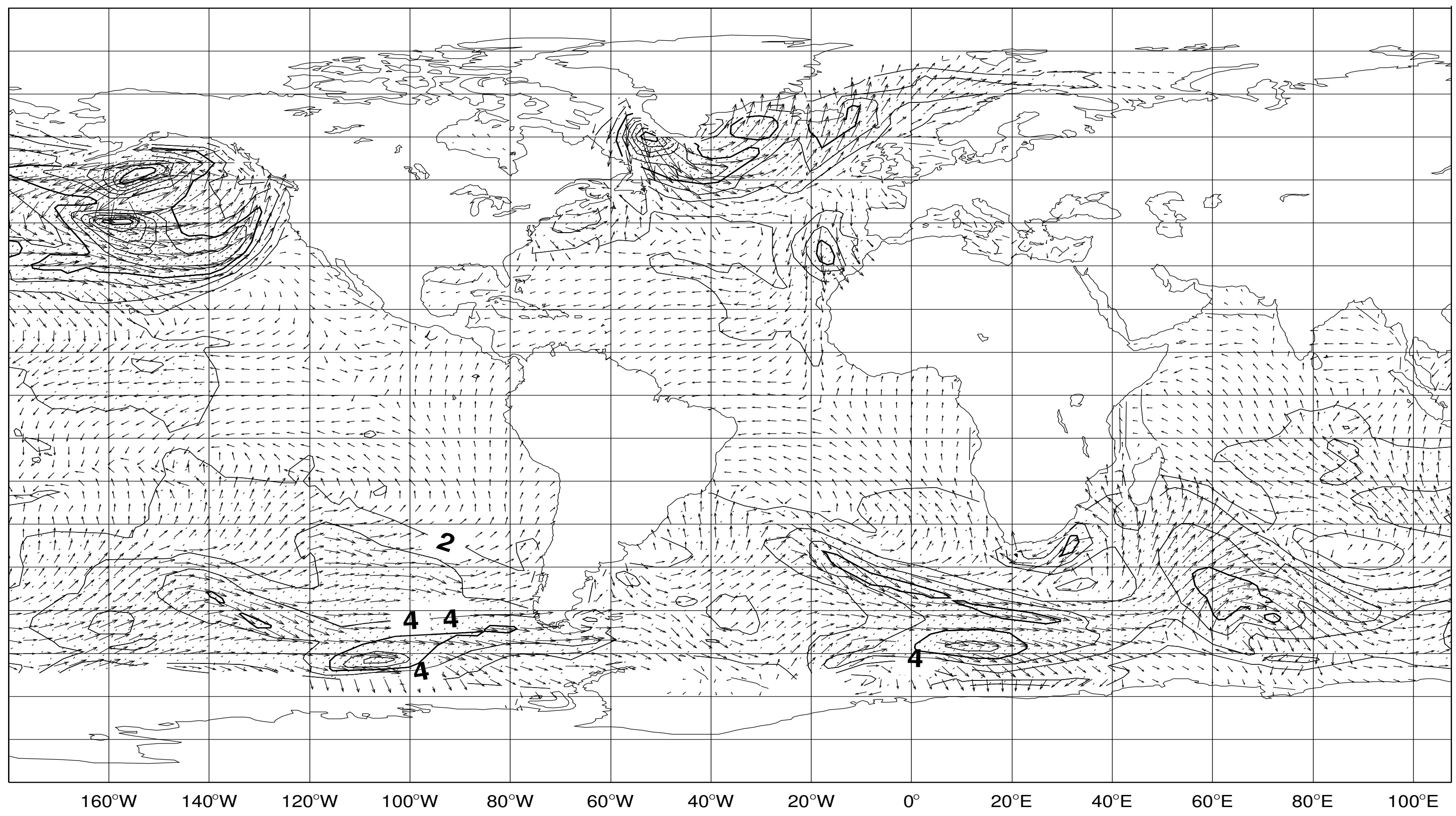


Figure 21 : Forecast of mean wave height and direction
(day 5 forecast based on 5 December 1995)

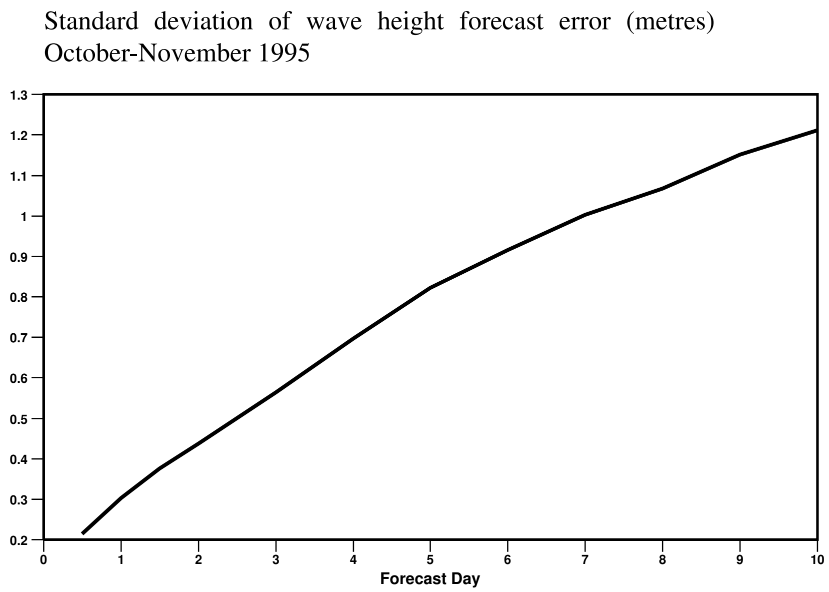


Figure 21 : Wave forecast verification against analysis, northern Hemisphere. The corresponding value for a persistence forecast is about 1.2 m from day 3 onwards.

Table 10: Wave forecast products

2D-spectra Significant wave height Mean wave direction Peak period of 1D-spectra mean wave period
Global model: 1.5° x 1.5° latitude/longitude T+0 to T+120 every 6 hours, T+132 to T+240 every 12 hours Baltic and Mediterranean model: 0.25° x 0.25° latitude/longitude T+0 to T+120 every 6 hours
Code form: FM92-Ext. GRIB (with local extension)

References and further literature

ECMWF documentation and publications

A quarterly ECMWF Newsletter is distributed to national weather services in the Member States and users of the GTS products worldwide. It deals with topics in meteorology and the operational activities at the Centre and provides short descriptions of operational changes to the analysis and forecasting system. The newsletter also deals with computing topics.

Comprehensive documentation of the analysis and forecasting system, the archiving and dissemination is given in the Meteorological Bulletins. The Computer Bulletins provide the guidance to the Centre's computing facilities. Scientific and technical aspects of the Centre's work are discussed in informal ECMWF Technical Memoranda. A limited distribution within the ECMWF Member States applies to these three types of documentation. Individual copies are available from the Centre's library on request.

Proceedings from the Centre's annual seminar and workshops are distributed widely to the national weather services and scientific institutions of the meteorological community.

ECMWF publishes reviewed papers of results in its own series of Technical Reports, available in the libraries of most national weather services and scientific institutions.

A documentation of the analysis and forecast model can be found in the ECMWF Research Manuals:

Data assimilation - scientific documentation (Meteorological Bulletin 1.5/1)
Forecast model - adiabatic part (Meteorological Bulletin 1.6/3)
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