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FORECASTING SYSTEM FOR

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L. B E N G T S S O N

EUROPEAN CENTRE FOR MEDIUM-RANGE WEATHER FORECASTS

1. Introduction

As laid out in its convention there are 8 different objectives for ECMWF. One of the major objectives will consist of the preparation, on a regular basis, of the data necessary for the preparation of medium-range weather forecasts. The interpretation of this item is that the Centre will make forecasts once a day for a prediction period of up to 10 days. It is also evident that the Centre should not carry out any real weather forecasting but merely disseminate to the member countries the basic forecasting parameters with an appropriate resolution in space and time. It follows from this that the forecasting system at the Centre must from the operational point of view be functionally integrated with the Weather Services of the Member Countries. The operational interface between ECMWF and the Member Countries must be properly specified in order to get a reasonable flexibility for both systems.

The problem of making numerical atmospheric predictions for periods beyond 4 - 5 days, differs substantially from 2 - 3 days forecasting. From the physical point we can define a medium range forecast as a forecast where the initial disturbances have lost their individual structure. However, we are still interested to predict the atmosphere in a similar way as in short range forecasting which means that the model must be able to predict the dissipation and decay of the initial phenomena and the creation of new ones. With this definition medium range forecasting is indeed very difficult and generally regarded as more difficult than extended forecasts, where we usually only predict time and space mean values.

The predictability of atmospheric flow has been extensively studied during the last years in theoretical investigations and by numerical experiments. As has been discussed elsewhere in this publication (see pp.338 and pp. 431) a 10 day forecast is apparently on the fringe of predictability.

However, we must keep in mind that most predictability studies, as well as forecast verification in general, use very simple means as RMS-error and correlation coefficients to evaluate the forecasts. For extended integration these simple measures can be misleading. The variance of atmospheric flow consists of a quasi-stationary part and of a transient part. At middle and high latitudes the transient part dominates and a major part of the energy in the atmosphere can be found in the travelling cyclones. For forecasts longer than 3 - 4 days there is little hope to predict the correct timing of individual cyclones. They will be out of phase and consequently they will contain large RMS-errors when verified against corresponding observations. In fact, a trivial statistical forecast or excessively smoothed forecast will most likely show higher scores. Hopefully there are many important users of weather forecasts who will find the forecasts useful even if individual cyclones are predicted out of phase, and consequently RMS-errors can be almost as high as the total variance. For planning purposes in agriculture and transportation for instance the meteorologists are mainly interested in the quasi-stationary flow (semi-permanent centers of action or "Grosswetterlagen"). They are also interested to know areas of cyclone generation, the cyclone tracks and the connected weather systems and areas where anticyclones are generated and where they decay.

It is therefore necessary to regard a medium range forecast or any extended dynamical forecast as a complete process. To evaluate and verify a snapshot of this process can be misleading.

Either being an optimist or a pessimist, it is far too early to have any well-founded reasons about the useful predictability of the atmosphere. We shall remember that our knowledge about medium range prediction is as unsatisfactory as our knowledge about short range forecasting with numerical models was in the beginning of the 1950's. At the time of writing, no more than 20 medium range forecasts have been performed by dynamical models realistic enough to describe the evolution of second and third generation of disturbances.

We will not in this lecture carry out any complete derivation of a forecasting model, but merely discuss different problems connected with the formulation of a model or a forecasting system for medium range weather forecasting. We will not treat the initial data problem, since that has been discussed at length elsewhere in this publication.

In the first four sections we will treat different numerical aspects on extended integration on the globe. Section 6 takes up the parameterization problem, and section 7 the computational problem. The last section presents how the forecast products will be disseminated.

2. Area of Integration

The area of integration is a function of the area for which we want forecasts as well as the length of the forecasting periods. Comparative integrations between hemispheric and global predictions have been carried out by Baumhefner (1972) and Miyakoda (1973). These experiments indicate that a fixed boundary placed at the equator effects the major parts of the Northern Hemisphere (Fig. 1). If the boundary is placed somewhere in the Southern Hemisphere outside the Tropics, it is quite likely that we could disregard the boundary effect on forecasts for the european area which certainly will be small compared with the errors in the initial stage and errors in the parameterization.
However, there are several needs for forecast products outside the european area and at low latitudes (for ship routing) and thus there is a good reason to let the forecast area cover the whole globe.
Moreover, a forecasting area covering the whole globe removes the problems of having horizontal boundaries and it also makes it possible to have a representation in spectral eigenfunctions.

3. Horizontal and vertical Resolution

Due to the non-linear behaviour of atmospheric motion, atmospheric phenomenon of a given scale will ultimately influence all other scales. That means that if we treat phenomena above a certain scale with deterministic methods the phenomena below the scale limit will after some time influence and successively destroy the information above the scale limit.

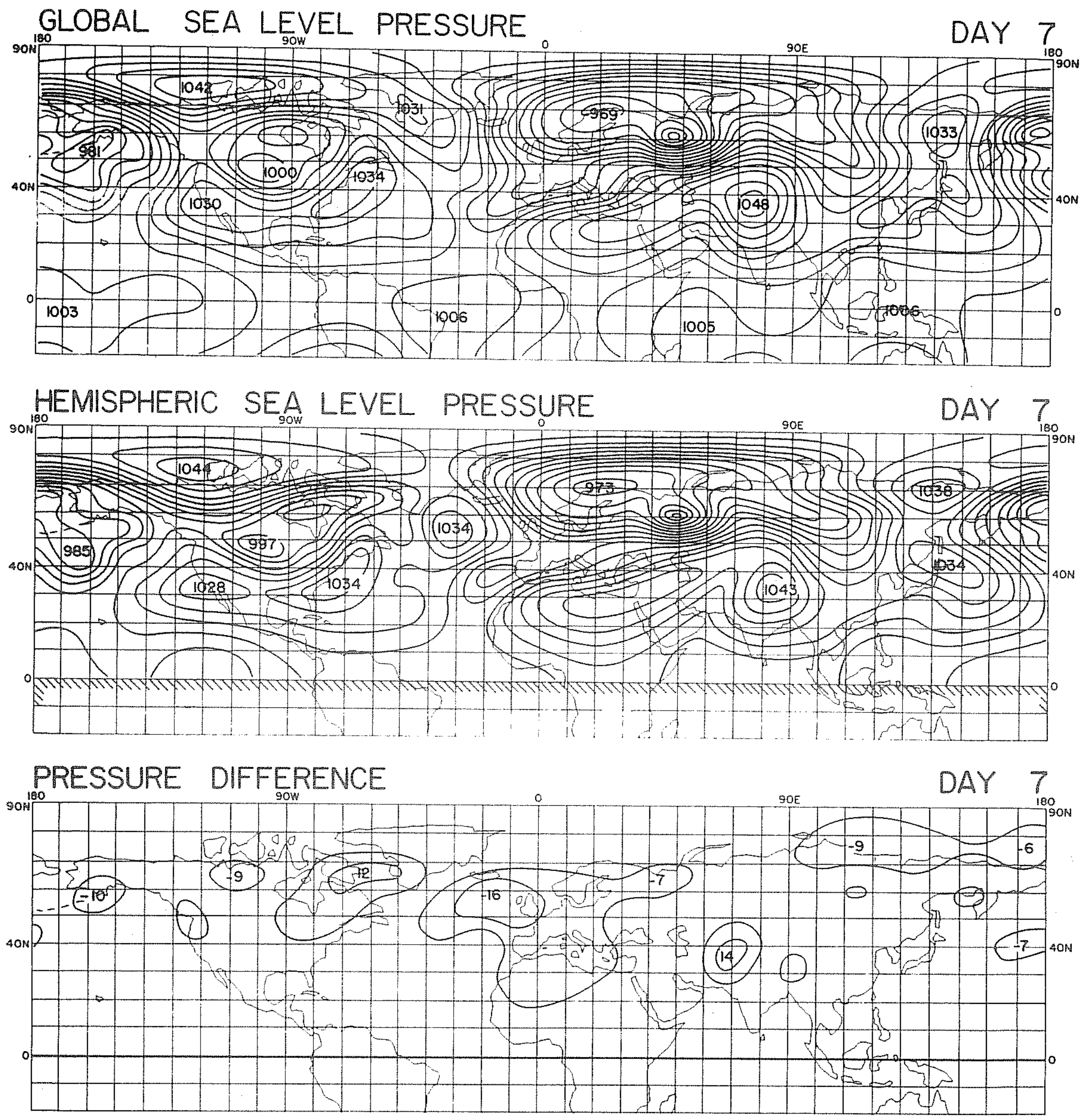

Fig. 1 : Top: global 7-day forecast of sea level pressure. Contour interval is 5 mb, and highs and lows are indicated in whole millibars.

Middle: hemispheric 7-day forecast of sea level pressure for a boundary placed at equator. The contour interval is 5 mb.

Bottom: pressure difference, global minus hemispheric forecasts at 7 days. The contour interval is 5 mb, and maximum errors are in millibars. (After Baumhefner).

The strategy used to handle this problem is to try to describe the processes below the scale limit in terms of scales above the scale limit. This process is called parameterization and we shall treat this subject in 6. The complexity of the parameterization depends on where we put the scale limit, the parameterization procedures generally being more complicated the more energy and the more transient phenomenon there is below the scale limit.

Van der Hoven (1957) and later Vinnichenko (1970) have indicated a spectral gap which mainly covers periods from 5 - 10 hours to 5 - 10 minutes. Assuming a translation speed of the order of 10m sec. this gap corresponds to scales between 360 km and 3 km.
From these considerations it seems natural to specify the horizontal resolution in such a way that we satisfactorily may resolve all scales of motion above the spectral gap. This would obviously simplify the parameterization problem.

Using explicit 2nd order centered scheme this would call for a mesh size of 50 - 100 km.

Barotropic instability is developed in zonal flow when the gradient of the absolute vorticity opposite the flow $\beta - U''(y)$ changes sign. It has been shown by Yanai and Nitta (1968) that a large number of subdivisions, at least 20, are required to describe the velocity profile. If a smaller number of subdivisions is used, the finite difference form will behave in a qualitatively different way than the analytic solution. Assuming a zonal jet with a width of 1000 - 2000 km, which is not uncommon in the atmosphere, this will again call for a mesh size of 50 - 100 km. A complete evaluation of the horizontal resolution must naturally be based on numerical experiments and evaluation against the observed state of the atmosphere. Beland (1973) has carried out numerical experiments to study the RMS differences between five different degrees of resolution, ΔS (mean value pole - equator) = 151,185,222,270 and 322 km. The results of 5 day integrations with a 5-level hemispheric model (primitive equations) are presented in Fig. 2. Miyakoda et al (1971) have carried out two 14 day forecasts using three different horizontal resolutions ΔS (mean value pole - equator) = 500,250 and 125 km. The following general conclusions can be drawn from Miyakoda's computations :

a. With respect to general features as prediction of frontal zones, cyclones and jet streams there is a successive improvement in a qualitative sense as the grid size is reduced.

b. The magnitude of the maximum of eddy kinetic energy improves with resolution as the following figures show

ΔS = 500 km	$8.4 \cdot 10^2$	erg cm^{-3}
250 km	$10.2 \cdot 10^2$	-"-
125 km	$12.9 \cdot 10^2$	-"-
observed	$13.7 \cdot 10^2$	-"-

c. The prediction of the ultralong waves improves in particular for $\Delta S = 125$ km.

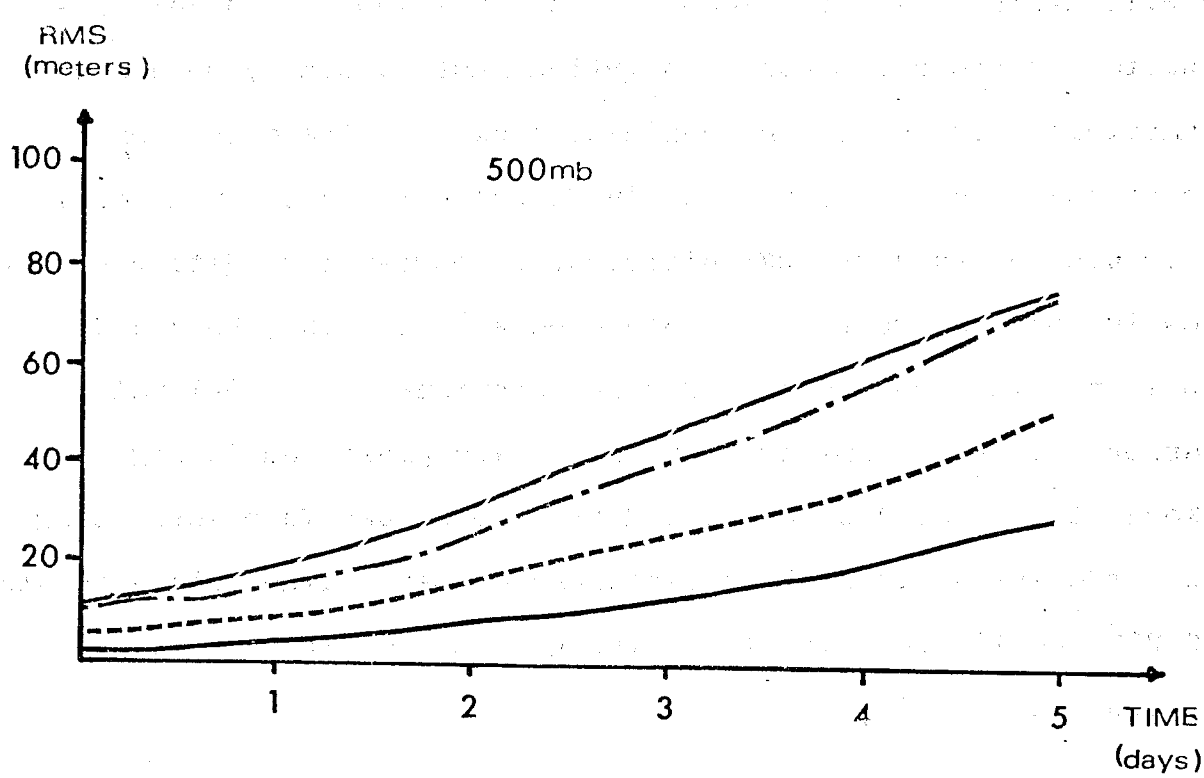

Fig. 2 : RMS differences in meters as a function of time in days for integrations performed with a five-level hemispheric model of the primitive equations. All runs are compared with a basic integration performed with a N66 (ΔS=151 km) resolution. The solid line represents the computation performed with the N54 (ΔS = 185 km) resolution, the short dash line corresponds to N45 (ΔS = 222 km), the dash-dot line to N37 (ΔS = 270 km) and the dashed line to N31 (ΔS = 322 km). The statistics are for the 500 mb geopotential.

Results from long term integration as well as for numerical simulation with general circulation models show in particular that the ratio between the zonal and the total eddy kinetic energy is larger than in the atmosphere where it is found to be close to 1 . During the initial phase in computations based on real data the model preserves the ratio. After some time, however, which seems to depend on the horizontal resolution, the ratio increases rather fast and a new higher value is established. This value is then usually preserved during the remaining part of the calculation. Fig. 3 taken from a paper by Somerville et al (1974) illustrates this. It is found that when the smaller horizontal resolution is used this change usually occurs at a later time in the integration. (A.Gilchrist pers.comm.).

The vertical resolution should be consistent with the horizontal resolution. Phenomenon which are possible to resolve in the horizontal plane should therefore also be possible to resolve in the vertical plane. The vertical resolution must thus be sufficient to describe :

a) Baroclinic development and structure of baroclinic waves. Fig. 4 giving the result from a 5000 km wave during idealized conditions indicates that the resolution should be at least 10 levels in the troposphere. It should also be stressed that shorter waves have a more complicated vertical structure and an even higher vertical resolution may be necessary.

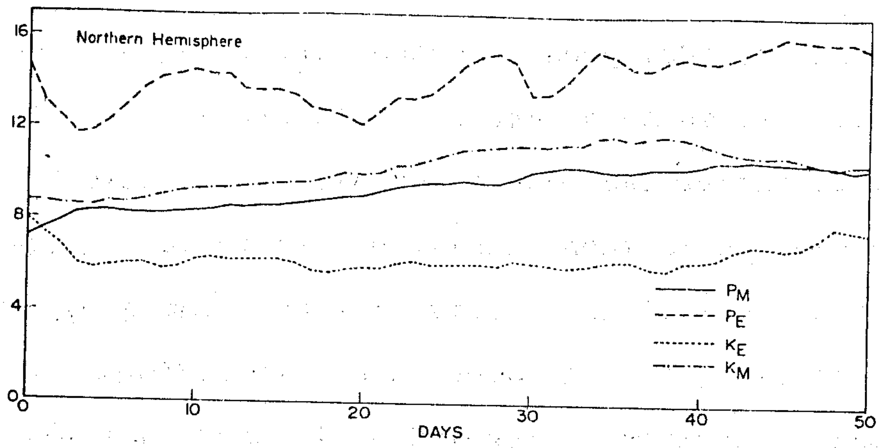

Fig. 3: Time evolution, in the Northern Hemisphere model troposphere (layers 2-9) in the GISS model of the integrated zonal available potential energy (P_M), eddy available potential energy (P_E), eddy kinetic energy (K_E), and zonal kinetic energy (K_M).
Units: P_M, 10^6 J m^{-2} ; P_E, K_E, K_M, 10^5 J m^{-2}.
(After Somerville et al) .

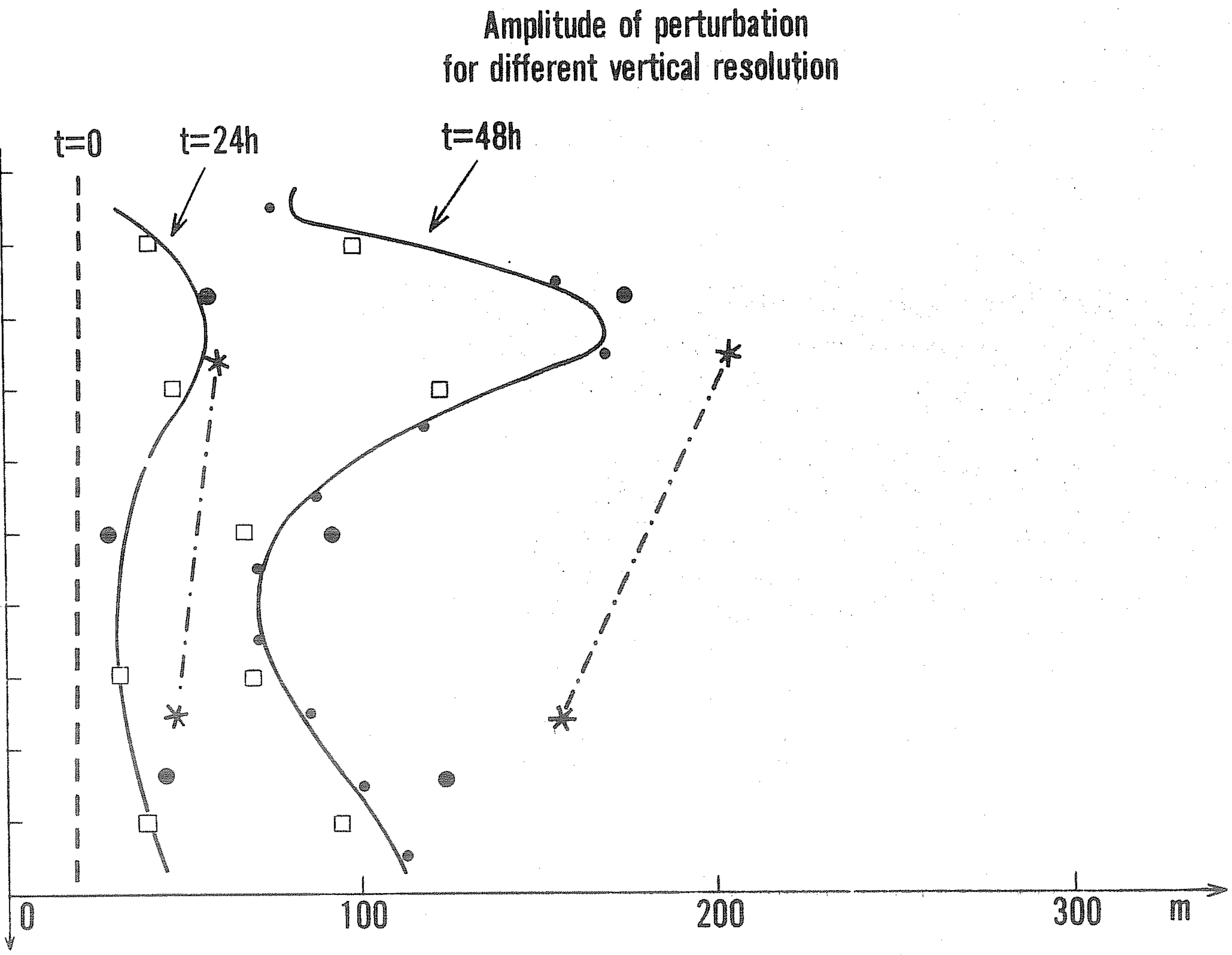

Fig 4: Time change of the amplitude of an unstable baroclinic wave in a β-channel, as computed from the quasi-geostrophic equations. Wavelength along the channel 5000 km and across the channel 15000 km (channel width 7500 km) The zonal wind-profile has a maximum in the middle of the channel and around 250 mb (38m/sec.). The initial amplitude corresponds to 10m through the whole atmosphere.

* indicate results from a 2-parameter model
● " " " " 3- " "
□ " " " " 5- " "
· " " " "10- " "

and the continuous line the result from a 20-layer model.

(After L. Bengtsson)

b) Resolution of frontal surfaces. It seems reasonable that the ratio between the horizontal and vertical scales in the model should be similar to that of a typical frontal slope. With a horizontal resolution of 100 km this implies a vertical resolution of about 75 mb in mid-troposphere.

c) Resolution of jet streams. Using the same kind of arguments as under b) the ratio of the width to the depth of the jet stream implies a resolution of about 35 mb around 200 mb.

d) A satisfactory representation of the boundary layer, in order to obtain temperature and humidity gradients needed for modelling the surface fluxes near the ground.

e) A satisfactory resolution to describe deep cumulus convection.

The horizontal as well as the vertical resolution is related to what kind of vertical coordinates one uses. The θ-coordinate system, which can be regarded as a "natural" system for adiabatic flow, is very useful to resolve atmospheric phenomena since most parameters vary less on θ-surfaces than along other coordinate surfaces. In order to resolve fronts we need a higher horizontal resolution on p and σ-surfaces than on θ-surfaces. In particular an extra high resolution is needed for σ-models since the independent parameters $Z, T, \mathbf{V}$, and r (relative humidity) will have a very strong variation in areas with steep slopes of the σ-surfaces (mountain areas).

For further comments on choice of appropriate vertical coordinates, reference is made to Kasahara (1974).

4. Numerical Integration on the Globe

Methods for integrating the basic atmospheric equations are in a stage of rapid development. Spectral models have now started to be used operationally and semi-implicit or splitting integration schemes are becoming more and more common as well for grid point models as for spectral models.

A comprehensive discussion can be found in a recent summary of progress in numerical weather prediction by Haltiner and Williams (1975).

Let us start here to examine one of the problems related to global integration of grid point models.

Only a few attempts have been made to solve the equation using conformable map projections which are commonly used for limited area integrations. Phillips (1957) combined two polar-stereographic projections at middle and high latitudes and a Mercator projection for the Tropics and used this with success for the barotropic model. The research group at the Geophysical Fluid Dynamics Laboratory in Princeton tried to combine 2 polar-stereographic projections as a general frame for a general circulation model. Due to several attempts to circumvent the difficulties in trying to match the two grids the idea was abandoned due to loss of mass at the boundary between the two grids.

Global gridpoint models are, therefore, using spherical coordinates in spite of the seriousness of the convergence of the meridians and the singularity at the poles.
As the distance between the longitudes shrinks toward the poles a shorter time step is needed to avoid computational instability.
As is easily seen, a time step short enough to maintain stability in polar regions is exceedingly wasteful in low latitudes.
Also large variations in resolution at different latitudes and different resolution in different directions is very unsatisfactory.
Various techniques have been used to overcome this difficulty with varying degrees of success.

Different irregular quasi-homogenous grids have been suggested in which the number of grid points on a latitude circle is reduced poleward. Kurihara (1965), Washington and Kasahara (1970) and Corby et al (1972).

However, the properties of these irregular grids are not very well known.

The natural way of studying the properties of different grids is to carry out numerical experiments using if possible known analytic solutions. Tiedtke (1972) has reported a study with the non-divergent barotropic and using a Haurwitz-Neamtan wave as initial condition. Resolution was 2.8125°. A non-divergent Haurwitz wave moves with constant angular velocity and without change of slope.

A Kurihara type of grid* yields instability after some days and was terminated after 12 days due to instability (Fig. 5). The regular grid was stable at least for 20 days (Fig. 6).

In order to be able to use a larger time step in spite of very small grid distance at high latitudes a common approach during the last years has been to filter waves which are not fulfilling the CFL-criteria. Below we will show a procedure applied in the Arakawa-Mintz general circulation model (1974). For the purpose of illustration, we will consider a simple system of equations which governs the one-dimensional barotropic model.

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* 128 grid points per latitude 0 - 60°

64	"	"	60° - 75°
32	"	"	75° - 82°
16	"	"	82° - 86°
8	"	"	86° - 90°

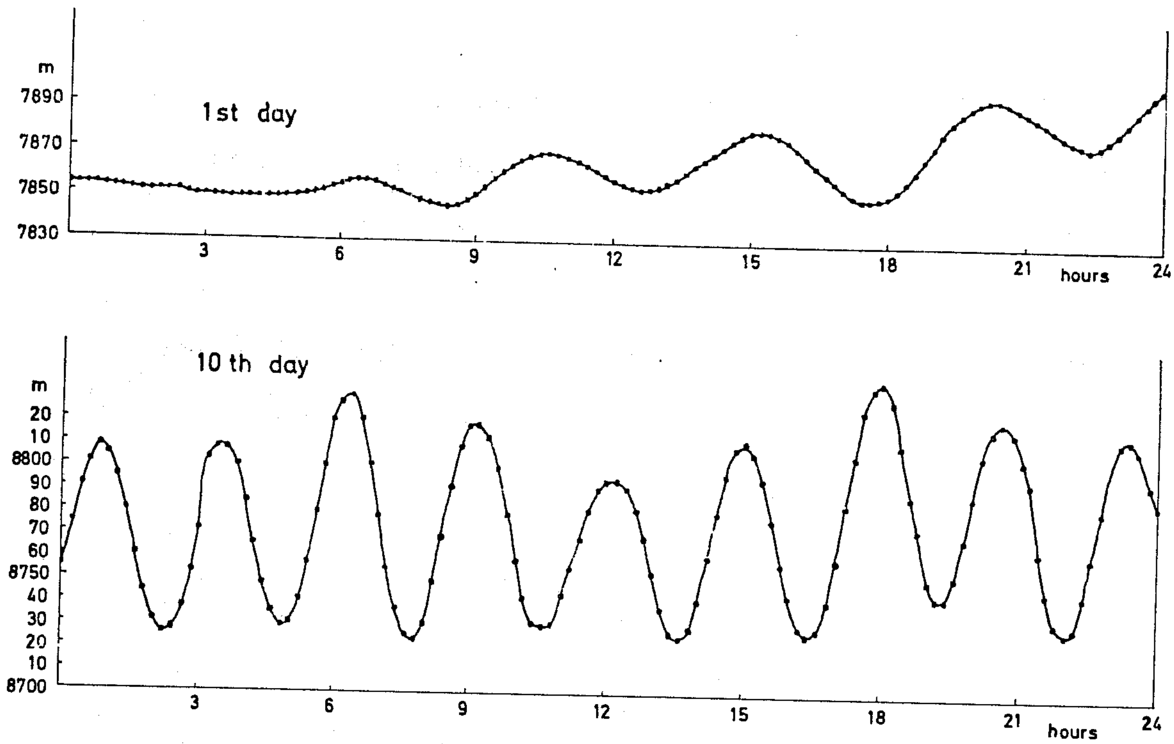


Fig. 5 : Variations of the height H of the free surface at one selected grid point at the latitude circle $\varphi = 85.2^{\circ}$ for the Kurihara type of grid given in the text at the 1st and 10th day. Plot is made for every 12 minutes. (After Tiedke) .

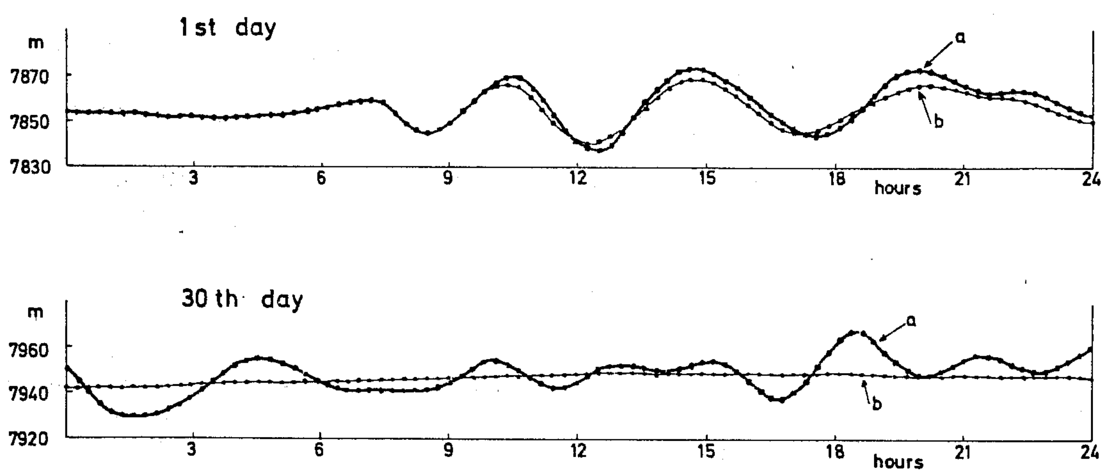


Fig. 6: Variations of the height H of the free surface with time at one selected grid point at the latitude circle $\varphi=85.2^{\circ}$ for the regular grid. (a) indicates integration without diffusion and (b) integration with a time filter ($\varepsilon=0.25$). Result is given at the 1st and 30th day. Plot is made for every 16 minutes. (After Tiedke).

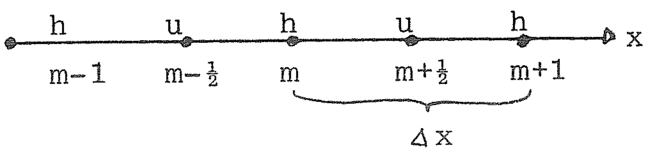
These equations read :

$$\frac{\partial u}{\partial t} + g\,\frac{\partial h}{\partial x} = 0$$

$$\frac{\partial h}{\partial t} + H\,\frac{\partial u}{\partial x} = 0 \qquad (4.1)$$

u is the horizontal wind and

h is the height to the free surface.



$$\frac{\partial}{\partial t}\,(u_{m+\frac{1}{2}}) = \frac{g}{\Delta x}\,(h_{m+1} - h_m)$$

$$\frac{\partial}{\partial t}\,(h_m) = \frac{H}{\Delta x}\,(u_{m+\frac{1}{2}} - u_{m-\frac{1}{2}}) \qquad (4.2)$$

Let us assume solutions of the form :

$$u_{m+\frac{1}{2}} = \hat{u}\, e^{ik\,(m+\frac{1}{2})\,\Delta x}$$

$$h_m = \hat{h}\, e^{ikm\,\Delta x} \qquad (4.3)$$

inserting in (4.2) yields $\frac{k\,\Delta x}{2} = \varkappa$

$$\frac{d\hat{u}}{dt} = -\,ik\,\frac{\sin\varkappa}{\varkappa}\,g\hat{h}$$

$$\frac{d\hat{h}}{dt} = -\,ik\,\frac{\sin\varkappa}{\varkappa}\,H\hat{u} \qquad (4.4)$$

converge if $\frac{|c|\,\Delta t}{\Delta x}\,\sin\varkappa < \frac{1}{2}\varepsilon$

For a centered " leap frog " scheme $\varepsilon = \sin\varkappa$.

Because the meridians converge to the poles the grid size along the latitudes becomes smaller the closer we come to the poles. As a result, an extremely small Δt must be used to assure stability.

An attractive way which conserves the integral constraints of the model and leads to simple algorithms is to introduce a wavelength dependent smoothing operator to modify the amplitude of pressure gradient force and divergence.

Let us denote this smoothing operator by S(k) and insert that in equation (4.4)

$$\frac{d\hat{u}}{dt} = -\, ik \frac{\sin\varkappa}{\varkappa}\, g\, S(k)\, \hat{h}$$

$$\frac{d\hat{u}}{dt} = -\, ik \frac{\sin\varkappa}{\varkappa} H\, S(k)\, \hat{u} \qquad (4.5)$$

Convergence if $\frac{c\,\Delta t}{\Delta x} S(k) \sin\varkappa < \frac{1}{2}\varepsilon$

where $S(k) = \frac{\Delta x}{(\Delta x)^*} \frac{1}{\sin\varkappa}$

$(\Delta x)^*$ = is equal to the constant grid length which is used in the longitudinal direction .

The following example for a $1^{\circ} \times 1^{\circ}$ grid at 89° may illustrate the damping for 2 short waves

Wavelength		Damping
L = 200 km	⟶	S(k) = 0.286
L = 20 km	⟶	S(k) = 0.030

5. General Properties of finite Difference Formation

As the grid size of the model approaches zero, the finite difference solution should converge towards the true solution. The order of accuracy of a convergent scheme determines how rapidly its solution approaches the true solution as the grid size approaches zero. In short-range prediction we are mainly concerned with accuracy in the advection processes and less concerned with the accuracy of the scheme to conserve different integral constraints.

In numerical general circulation simulations, on the other hand, the governing equations are integrated beyond the physical limit of deterministic predictability. Because of the turbulent properties of the atmosphere there is no "true" solution in a deterministic sense in a long-term integration, and long-term integrations (including long-range numerical weather prediction from observed initial states) can therefore only predict the statistical properties of the atmosphere. Consequently finite difference formulation of general circulation models must conserve the essential statistical properties of the atmosphere and the approximative solution should also approach the true solution through a path in a function space where the statistics are analogous to those of the true solution. In medium range forecasting, where we also integrate beyond the life time of most weather systems, the finite differences should conserve with high accuracy the same statistical properties as the general circulation models. These are : the conservation of total mass; the conservation of total kinetic energy during the inertial processes; the conservation of enstrophy (mean square vorticity) during vorticity advection by the non-divergent part of the horizontal wind; the integral constraint on the pressure gradient force; the conservation of total energy during adiabatic and non-dissipative processes and the conservation of total entrophy and total potential enthalpy during adiabatic processes. Finite differences which conserve these constraints have e.g. been used by Mintz-Arakawa (1974).

6. The Parameterization Problem

As was mentioned in section 3 parameterization is defined as the process of describing the statistical effect of the subresolution processes on the macroscale. This means that we must find a way of describing the subresolution processes in terms of the macroscale parameters. The parameterization procedure is highly scale dependent. The larger the spectral gap is and the more random the processes are below the scale limit the easier and more reliable will the parameterization be. An extreme application of "parameterization" is the equation of state. As we know, this relation can be derived from the kinetic theory of gases by assuming the molecules as idealized randomly moving balls. Since the scale gap in this case is enormous, the equation of state is indeed very simple and reliable. Unfortunately the problem we have is very awkward since our microscale is closer and can behave in an organized way.

Let us assume that we satisfactorily can resolve scales which roughly are $\geq 4\Delta S$, where S is the mesh size. Using a grid distance of 100 km this means that we have to parameterize scales $\leq$ 400 km. Most models are using grid sizes of 300 - 400 km which means that we in such cases have to parameterize small scale transient weather systems with life times of 1 - 2 days in terms of the larger scales. Since these waves can create kinetic energy, mainly through latent heat release, they will through non-linear interaction actively affect other waves. Clearly, if we can reduce the scale limit down to 300 - 500 km we will mainly have short-lived weather processes (1 - 3 hr) of a random nature below that scale. Consequently the parameterization will most likely be much simpler and qualitatively different from the larger grid.

As a general guide-line the following steps are necessary for a successful parameterization (GARP report No.8 1972).

1. The process involved must be precisely identified and its role distinguished meaningfully from other processes which may be simultaneously active in the atmosphere.

2. Its importance for the synoptic scale motion must be determined.

3. An intensive study of individual cases must establish the fact that relevant physics and dynamics are adequately understood.

4. Quantitative rules must be found for expressing the frequency of occurrence and intensity of the mesoscale process in terms of the synoptic scale variables.

5. Rules for determining the grid scale average of the associated transports of mass, momentum, heat and moisture must be inferred from theory and verified by direct observation.

6. These rules must be translated as accurately as required into practical algorithms for specified numerical models, care being taken to ensure that all important processes are included but that duplication is avoided.

Parameterization is necessary for describing how :

a) energy is generated in the atmosphere
b) energy is transformed between available and kinetic energy
c) energy is destroyed in the atmosphere.

As was pointed out in Dr. Miyakoda's lecture, the atmosphere is a very inefficient engine and only 1 % of the incoming energy is transformed into kinetic energy. It is evident that this conversion is essential for the whole forecasting problem and should be given highest priority.

The energy conversion processes are mainly taking place in three areas and we can possibly identify the following processes :

PHENOMENON	DOMINATING PROCESSES
1. Polar-night jet	. baroclinic instability
2. Rossby waves and polar front waves at middle latitudes	. barotropic and baroclinic instability
	. release of latent heat in synoptic scale systems
	. surface friction incl. mountains
3. Tropical convective systems	. deep cumulus convection

For extended integration generation and dissipation of energy becomes successively more important.

A simplified parameterization of radiation is recommended due to the difficulties to pay attention to clouds which are of primary importance for radiation calculation.

For almost all other processes, generative as well as dissipative, an understanding of the boundary layer is necessary. Even in this case, however, simple descriptions should be looked for. Very little success in forecasting quality has so far been obtained by very complicated descriptions.
What is important is to separate stable boundary layers from neutral or unstable ones. A stable boundary layer is extremely efficient to cut off the surface of the earth from the free atmosphere.

7. The computational Problem

As was discussed in section 3 there are several reasons to use a horizontal grid length of the order of 100 km or less and a vertical resolution of 50 - 100 mb. We have also found in section 6 that such a high resolution most likely will yield a simpler and more accurate parameterization. With a horizontal resolution of 100 km for the whole globe and a vertical resolution implying 15 - 20 vertical levels, we are challenged with an enormous computational problem.

As we will see below the speed of CPU as well as data channel (I / O) capacity and memory size are critical parameters. We will limit the discussion to grid point models and we will also mainly take up a semi-implicit model since an explicit procedure can be regarded as a subclass to the semi-implicit.

In the semi-implicit technique the forcing function, F, is split in 2 parts F_1 and F_2. F_1 are terms associated with gravity waves and F_2 with the slow moving meteorological waves. In semi-implicit schemes F_1 is solved implicitly and F_2 explicitly. In doing so the CFL-condition is the same as for filtered (quasi-geostrophic) models and we can roughly use a time step 3 - 5 times as large as for purely explicit models. Semi-implicit procedures have been used operationally for some years in short range weather forecasting and no apparent drawbacks have been reported.

However, as we will see, the semi-implicit schemes are more complicated from the computational point of view, since they give rise to 3-dimensional elliptic equations and they therefore need more core space.

Formally we will let equation :

$$\frac{\partial \underline{x}}{\partial t} + \underline{F}\,(\underline{x}\,) = 0 \qquad (7.1)$$

represent our set of prediction equations. $\underline{x}$ is here a vector consisting of all the models' dependent variables and $\underline{F}$ represents the forcing functions.

In table 1 we have listed the different variables which are needed for a global model. For a fifteen level model we will need about 90 dependent variables.

Table 1

Parameters in a global model

3-dimensional variables

- θ – potential temperature
- u, v – horizontal wind components
- r – humidity parameter (mixing ratio or relative humidity)
- $\delta\theta$ – heating increment due to radiative effects

2-dimensional variables

- p_s – surface pressure
- T_s – surface temperature
- ϕ – surface geopotential
- Pr, $\frac{\partial Pr}{\partial t}$ – large scale accumulated rain
- Pc, $\frac{\partial Pc}{\partial t}$ – sub-grid scale convective rain
- $\delta\theta_s$ – surface exchange of heat
- δq_s – surface exchange of humidity
- roughness parameters
- climatic type indicators
- surface humidity
- constants for vertical and horizontal diffusion
- cloud cover

A centered semi-implicit form of equation (7.1) reads :

$$\underline{x}^{\tau+1} = \underline{x}^{\tau-1} - 2\,\Delta t\,\underline{F}_1\,(\underline{x}^{\tau}) - \Delta t \left[\underline{F}_2\,(\underline{x}^{\tau-1}) + \underline{F}_2\,(\underline{x}^{\tau+1}) \right] \tag{7.2}$$

$\underline{F}$ has here been split in two parts $\underline{F}_1$ and $\underline{F}_2$. $\underline{F}_2$ represents terms associated with gravity waves. Due to the simple form of these terms (pressure gradients only) $\underline{F}_2\,(\underline{x})$ is a <u>linear</u> vector function of $\underline{x}$. Superscript τ indicates actual time step.

We define

$$\hat{\underline{x}}^{\tau+1} = \underline{x}^{\tau-1} - 2\,\Delta t\,\underline{F}_1\,(\underline{x}^{\tau}) - \Delta t\,\underline{F}_2\,(\underline{x}^{\tau-1}) \tag{7.3}$$

and (7.2) then gets the form

$$\underline{x}^{\tau+1} + \Delta t\underline{F}_2\,(\underline{x}^{\tau+1}) = \hat{\underline{x}}^{\tau+1} \tag{7.4}$$

$\underline{x}^{\tau+1}$ can be solved from (7.4) since $\underline{F}_2\,(\underline{x})$ is a linear function of $\underline{x}$. The inversion of (7.4) leads to the solving of a three dimensional partial differential equation which can be decoupled into a system of NL two dimensional partial differential equations, where NL is the number of horizontal levels.

The central memory requirements depend on how the computations are organized. In table 2 we have listed 2 extremes:

Table 2

Scheme A		Scheme B	
Minimising I/O		Minimising core memory	
CM1	390K words	CM1	195K words
CM2	975K words	CM2	33K words
Total	1365K words	Total	228K words

Memory size for 2 different ways of organizing the computations. All calculations have been made for a $1^o \times 1^o$ regular grid and 15 vertical levels.

CM1 explicit scheme

CM1+CM2 semi-implicit model

Scheme A which minimises I/O demands and results in fairly simple coding and scheme B, which minimises core requirements.

The necessary memory size will be given for 2 areas :

CM1 central memory for solving equation (7.3) explicit part.

CM2 central memory for buffers, necessary for the inversion of equation (7.4)

The necessary memory size for an explicit scheme is equal to CM2.

On a conventional processor with fast I/O devices, it is likely that the two organisations will have similar efficiencies. Cleverly designed I/O routines, using s.c. "cycle-stealing" techniques, can be done almost completely parallel to CPU activities and the total running time is therefore equal to the CPU-time.

On a vector machine, on the other hand, scheme A is likely to be the most efficient, though some organisation between scheme A and scheme B may be just as acceptable.

Referring to table 2 the minimum size of the core memory must therefore approximately be between 250K and 500K words.

An even more critical parameter is the speed of the CPU. Table 3 gives the CPU time for running a 24 hr forecast on the most powerful general purpose (non-vector) computers to-day. We will assign unit speed 1 to these computers. The result is obtained from a complex global model using an explicit integration scheme and values are given for some vertical and horizontal resolutions.

Even if a semi-implicit scheme can yield a factor of 3 - 4 a computer with a unit speed of at least 3 is necessary in order to run a high resolution model ($1^{o} \times 1^{o}$ and 15 vertical levels) under operationally satisfactory conditions (a 24 hr forecast in 60 minutes). Recent computer developments make this a very realistic alternative at the time ECMWF will be operational.

8. Dissemination of Forecast Products

As was mentioned in the introduction ECMWF intend to produce a medium range forecast once a day. It is also very clear that the Centre should not make any real weather forecasting but merely disseminate to the member countries necessary forecasting parameters. The coordination between the Centre and the Member Countries is indicated in Fig. 7.

In the process of production of numerical forecasts at ECMWF, a specific internal representation in space will be used. This representation will most probably use normalized pressure (σ) as the vertical coordinate. According to discussions in section 3 the σ-levels will be chosen in such a way that a high resolution will be obtained in the planetary boundary layer and around the tropopause.

Table 3

Estimated CPU time for a regular lat/long system on a computer with unit speed 1 and using an explicit scheme

10 vertical levels

Mesh size	2^o	1.5^o	1^o
CPU time/24 hr	50 min.	170 min.	400 min.

15 vertical levels

Mesh size	2^o	1.5^o	1^o
CPU time/24 hr	75 min.	255 min.	600 min.

RELATION BETWEEN ECMWF AND THE NATIONAL WEATHER SERVICES IN PRODUCING WEATHER PRODUCTS

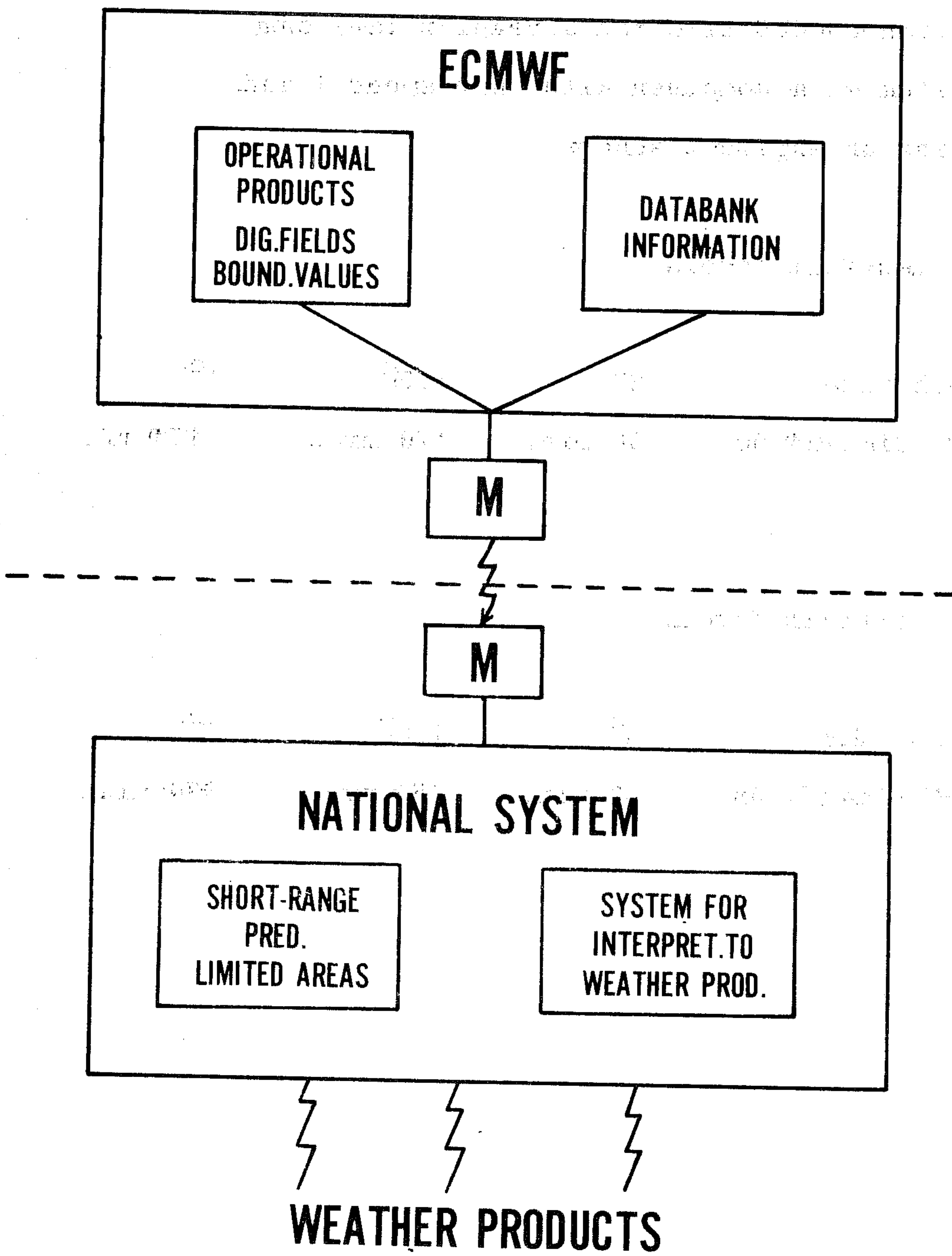


Fig. 7: Integration of the operational functions between ECMWF and the National Weather Services. M indicates modem and forked arrow telecommunication connections. For further information see text.

The horizontal representation will be a regular spherical grid.

The historical variables of the model are supposed to be:

p_s	surface pressure
θ	potential temperature
v	horizontal wind
r	relative humidity.

Additionally, there will be a number of computed quantities as, e.g., vertical wind speed, precipitable water, etc.
However, it should be kept in mind that the internal parameters (historical variables as well as the horizontal and the vertical representations) can be modified rather frequently. We shall therefore assume, as the first principle, that the form of dissemianted products should be independent of the internally used parameters (see Fig. 8).
This implies that interpolation procedures must be applied, which can create small scale errors. However, since the model of ECMWF will have a high resolution, these errors will have a very small amplitude compared to other errors.

The general system will be designed in such a way that the dissemination format can easily be changed. Below is indicated a basic format which is sufficient to meet the data needs as preliminarily indicated by the member countries.

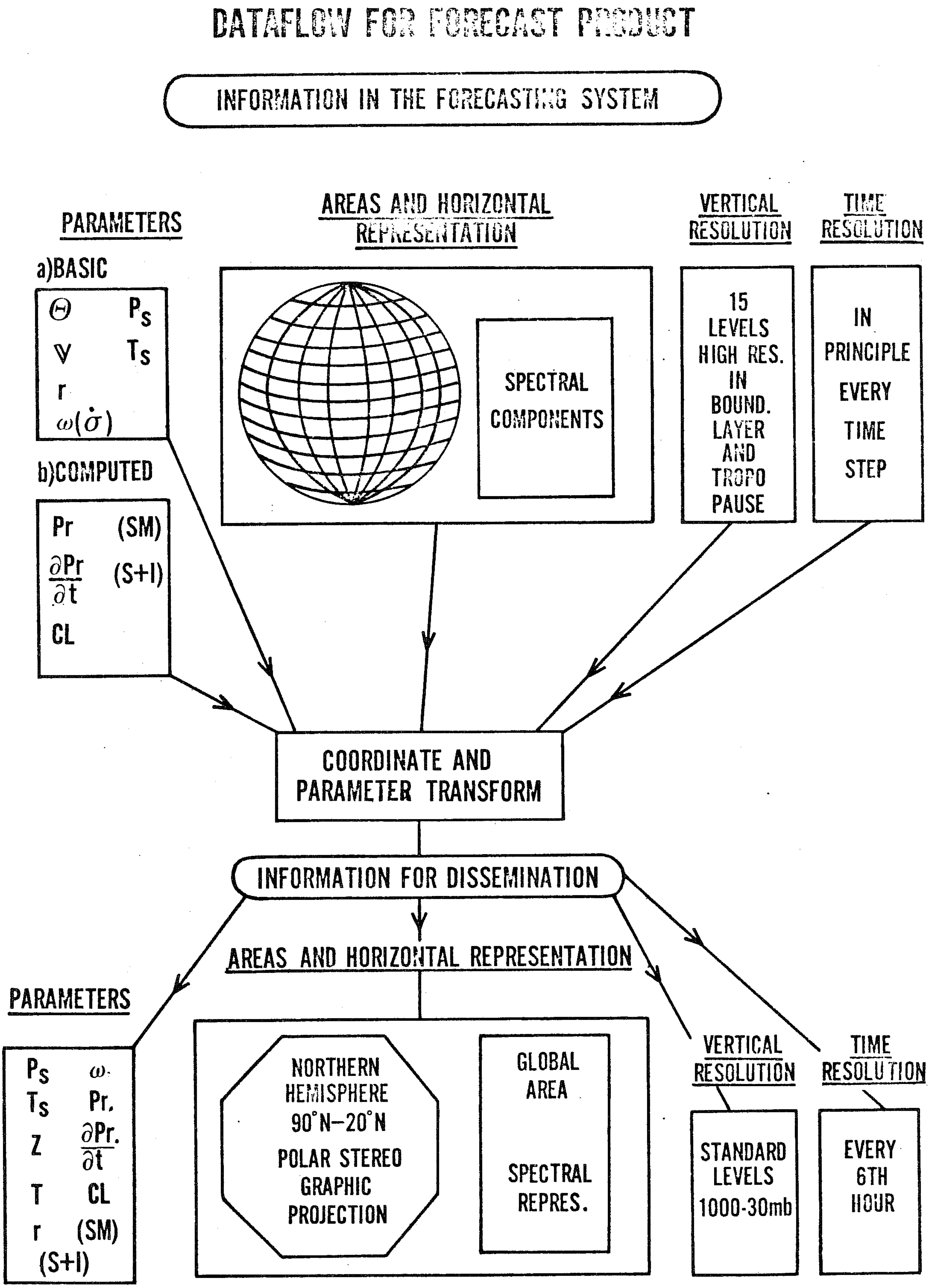


Fig.8: Data flow for forecast products. For detailed information see text.

The following parameters will be available in the system* :

p_s	surface pressure
T_s	surface temperature
Z	geopotential
T	temperature
$_s$	surface wind
	wind
r	relative humidity
w	vertical motion
P	accumulated precipitation (6,12 or 24 hours interval)
P_t	precipitated intensity (mean value for 1 hour)
(CL)	cloud levels (about 3 levels)
(S+I)	snow and ice distribution

A. Global data set.

- parameters : p_s, V_s, T_s, Z(500 mb)
- representation and resolution:

  vertical - pressure surfaces

  horizontal - spectral (consistent with the internal resolution);

- time availability :

  every 6 hours
  0-10 days (inc. analysis).

B. Polar stereographic data set.

- parameters: p_s, V_s, T_s, Z, T, r, w, P, P_t, (CL), (S+I);
- representation and resolution:

  vertical - pressure surfaces (standard levels)

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* Parameters indicated by ( ) will be decided later.

horizontal - grid points (150 km mesh size)

- time availability:

  every 6 hours
  0-10 days (inc. analysis)

In order to maintain a simple interface between the Centre and the individual weather services we will assume as a second principle that the dissemination should be confined to the basic quantities.

This will mean:

the user should compute in his own system:

- derivatives as e.g. vorticity and divergence;
- other quantities as e.g. thickness, dewpoint depression, potential temperatures and so on;
- mean values as e.g. the integrated vertical motion and extreme values as maximum wind.

Exception from this principle will be made if the user prefers receiving the basic quantities with a coarser resolution that can make it impossible to compute mean and extreme values accurately. It will of course be possible for the user to receive aerial subsets and also information which will have a coarser resolution than the original data set.

Due to the loss of details in the forecasts as time goes on it is proposed :

- the number of parameters to be reduced towards the end of the forecast validity period, (e.g.wind and vertical motion is left out out after 4 - 5 days);
- horizontal resolution to be decreased towards the end of the period;
- vertical resolution to be decreased towards the end of the period.

Following the discussion in the introduction, we may also have to look for alternative ways of presenting the results from a medium range weather forecast. A composite map showing areas of generation and decay of cyclones and anti-cyclones as well as cyclone paths can be more useful for the user and also more consistent with our capability in making forecasts for such long periods.

REFERENCES

Arakawa, A. and Mintz, Y., 1974: The UCLA Atmospheric General Circulation Model Department of Meteorology, University of California, Los Angeles California.

Beland, M., 1973: Evolution of Horizontal Truncation Errors in a Primitive Equation Model. M.Sc.Thesis. Department of Meteorology, McGill University, 66 pp.

Corby, G. A., Gilchrist A. and Newson, R.L., 1972: A general circulation model of the atmosphere suitable for long period integrations. Quart.J.R. Met.Soc. 98 pp 809-832.

GARP Publication Series No. 8, 1972: Parameterization of sub-grid scale processes. Global Atmospheric Research Programme.

Haltiner, G.J. and Williams R.T., 1975: Some recent advances in Numerical Weather Prediction. Monthly Weather Review Vol. 103, No. 7, pp 571-590.

Kasahara, A., 1974: Various Vertical Coordinate Systems used for Numerical Weather Prediction. Monthly Weather Review Vol. 102 No. 7,pp 509-522.

Kurihara, Y. 1965: Numerical Integration of the Primitive Equations on a Spherical Grid . Monthly Weather Review, Vol. 93, pp 33-46 .

Miyakoda, K., Strickler, R.F., Nappo, C.J., Baker, P.L. and Hembree, G.D., 1971: The effect of horizontal grid resolution in an atmospheric circulation model. J. Atmos.Sci., 28, pp 481-499.

Miyakoda, K. and Umscheid L., 1973: Effects of an Equatorial "Wall" on an Atmospheric Model.
Monthly Weather Review, Vol. 101, No. 8, pp 603-616 .

Phillips, N., 1959: Numerical Integration of the primitive equation on the hemisphere.
Monthly Weather Review, Vol. 87, No. 8, pp 333-345.

Somerville, R.C. et al, 1974: The GISS Model of the GLOBAL Atmosphere.
J. Atmos. Sci., 31, pp 84-117.

Tiedtke, M., 1972: Numerische Integration der primitiven Gleichungen auf der Kugel.
Beiträge zur Physik der Atmosphäre, 45. Band, 1972, S. 43-57

Van der Hoven, J., 1957: Power spectrum of horizontal wind speed in the frequency range from 0.0007 to 900 cycles per hour.
J. Meteor. 14, 2, pp 160-164.

Vinnichenko, N.K., 1970: The kinetic energy spectrum in the free atmosphere - 1 second to 5 years.
Tellus XXII, 2, pp 158 - 166.

Washington, W.M. and Kasahara, A., 1970: A January simulation experiment with the two-layer version of the NCAR global circulation model.
Monthly Weather Review, 98 (8), pp 559-580.

Yanai, M. and Nitta, T., 1968: Finite Difference Approximations for the Barotropic Instability Problem.
J. of Met. Soc. of Japan, pp 389-403.