EUROPEAN CENTRE FOR
MEDIUM-RANGE WEATHER FORECASTS

THE DESCRIPTION OF THE
ECMWF/WCRP LEVEL III-A GLOBAL ATMOSPHERIC DATA ARCHIVE

Technical Attachment

1994
CONTENTS

This attachment to the description of the ECMWF/WCRP Level III-A Global Atmospheric Data Archive contains essential technical information for the users of the data.

It meets a requirement and need expressed by many of the recipients of data from the archives. The information is presented in six parts.

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This technical attachment will be updated regularly. User comments on the contents are welcome and will be taken into consideration in future editions of this attachment. Please send all comments to

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PART I: ECMWF ANALYSIS AND FORECASTING SYSTEM

The ECMWF data assimilation system in 1987 (Fig. 1) consisted of a multivariate optimal interpolation analysis, a non-linear normal model initialisation and a high resolution spectral model which produced a first-guess forecast for the subsequent analysis. Data were assimilated every 6 hours.

The forecast model in 1987 (Fig. 2) used a spectral formulation in the horizontal, with triangular truncation at total wavenumber 106, a vertical coordinate with 19-level resolution which was terrain-following at low levels. The comprehensive physical parametrisation schemes included shallow and deep (Kuo) convection, a radiation scheme which allowed interaction with model generated clouds and the diurnal radiative cycle.

Note that before 1 May 1985 for the first four months of the TOGA period ECMWF still operated the T63 model with 16 levels in the vertical. The detailed analysis and model changes are given in Part II. The next major change in model resolution was introduced into operations 17 September 1991 with the T213 model on 31 levels. The most recent version of the forecasting system (status June 1992) is described in the panel of Fig. 3.

The operational schedule

ECMWF produces routine global analyses for the four main synoptic hours 00, 06, 12 and 18 UTC and global 10-day forecasts based on 12 UTC data. The operational schedule with the approximate running times of the analysis and forecast suite is shown in Fig. 4. As a forecasting centre with the emphasis on the medium-range, ECMWF operates with long data collection times of between 18 hours for the 18 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.
**ECMWF Analysis System (1987)**

**Vertical Coordinate**
- Table (NL=19)

**Disposition of variables in the vertical domain**
- Global
  - Data assimilation frequency: 6-hr (± 3-hr observation time window)
  - First guess: 6-hr forecast
  - Dependent variables: \( P_s, \phi, u, v, \text{RH} \)
  - Vertical coordinate: Hybrid, \( P_{k+4} = \sum A_{k+4} B_{k+4} P_s \), details as above
  - Horizontal grid: 160 x 320 points on a quasi-regular (1.125°) "Gaussian" grid
  - Analysis method: Mass and wind: 1-dimensional multi-variate statistical interpolation
  - Relative humidity: 1-dimensional uni-variate statistical interpolation up to 250 hPa
  - Surface: Sea surface temperature from NMC analysis
    - Soil water content using rainfall observations, estimated evaporation
    - Snow depth using snow depth and snowfall observations

**Initialization method**
- Non-linear normal mode, 5 vertical modes, non-adiabatic
ECMWF Forecasting System - Forecast Model (1987)

Domain
Initial data time
Dependent variables
Vertical coordinate
Vertical representation
Horizontal representation
Horizontal grid
Time integration
Horizontal diffusion
Orography
Vertical boundary conditions
Physical parameterisation

Global
128
\( \xi, \partial T, q, \ln(P) \)

Hybrid, \( P_{k+1/2} - k+3/2 \), details as above

Finite-difference, energy and angular-momentum conserving

Spectral, with triangular truncation at wavenumber 106

160 x 320 points on a quasi-regular (1.125°) Gaussian grid

Leapfrog, semi-implicit (\( \Delta t = 15 \) min), time filter (\( \epsilon = 0.1 \))

Linear, fourth-order (\( K - 1 \))\( (\partial P/\partial z) \)

Grid-scale average from high resolution data set, enhanced by one standard deviation of sub-grid scale orography, spectrally-fitted

Kinematic

(i) Boundary eddy fluxes dependent on local roughness length and stability (Monin-Obukhov).

(ii) Free-atmosphere turbulent fluxes dependent on mixing length and Richardson number.

(iii) Gravity wave drag scheme. Stresses due to orographically-forced gravity waves.

(iv) Kuo convection scheme. Shallow convection parameterised by an eddy mixing scheme.

(v) Interaction between radiation and model-generated clouds. Albedo dependent on model snow cover.

(vi) Large-scale condensation when grid-square saturated. Evaporation of precipitation.

(vii) Computed land temperature with diurnal cycle (3 layers in soil).

(viii) Computed soil moisture and snow cover.

(ix) Fixed, analysed sea-surface temperature.

None
COMPUTER: CRAY Y-MP16/C90

Computation rate during operational forecast: 3.5 Gflops (2.5 x 10^9 operations/second)

Memory: 128 million words central memory
512 million words Solid-state Storage Device (SSD)

MODEL:

Numerical scheme: T213L31 (triangular truncation, resolving 213 waves around a great circle on the globe; 31 levels between the earth’s surface and 30 km), semi-Lagrangian formulation

Smallest wavelength resolved: 190 km Time-step: 15 minutes
Number of grid points in model: 4,154,868
Number of computations required for each 10-day forecast: 2 x 10^{13}
Variables at each grid point (recalculated at each time-step): Wind, temperature, humidity (also pressure at surface grid-points)

Included in model: orography (terrain height, US Navy data-set, 10 minutes of arc resolution), three surface and sub-surface levels (allowing for vegetation cover, gravitational drainage, capillarity exchange, surface and sub-surface runoff, deep-layer soil temperature and moisture), clouds (high, medium, low, convective), stratiform and convective precipitation, carbon dioxide (345 ppmv fixed), aerosol, ozone, solar angle, diffusion, ground & sea roughness, ground and sea-surface temperature, ground humidity, snowfall, snow-cover & snow melt, radiation (incoming short-wave and out-going long-wave), friction (at surface and in free atmosphere), gravity wave drag, evaporation, sensible & latent heat flux.

DATA ASSIMILATION:

Analysis of: Mass & wind (three-dimensional multi-variate analysis on 31 model levels)
Humidity (three-dimensional on model levels up to 250 hPa)
Surface parameters (sea surface temperature from NMC Washington analysis - update daily), soil water content, snow depth

Initialisation by use of the normal modes of free oscillation of the model atmosphere

Data used: Global satellite data (SATOB, TOVS, SATEM), Global free-data (AIREP, AMDAR, TEMP, PILOT), Oceanic data (SYNOP/SHIP, PILOT/SHIP, TEMP/SHIP, DRIBU), Land data (SYNOP). (40,000 observational data are used in each analysis. Data checking and validation is applied to each parameter used.)

Fig. 3: The Operational Forecasting System in January 1993
Fig. 4: The ECMWF operational schedule in late 1987, all times shown in UTC
PART II: EVOLUTION OF THE ECMWF ANALYSIS AND FORECASTING SYSTEM

This part summarises the modifications of the ECMWF operational data production system from 1 January 1985 (beginning of the TOGA project) to the current date.

Revisions of the model and the data assimilation system are discussed in the highlight of data consistency (for known repercussions) as far as they affect the ECMWF/TOGA Data Sets.

Most of the revision information have been taken from the ECMWF publication series ECMWF FORECAST REPORT, ECMWF NEWSLETTER, the ECMWF Forecast Update Bulletins, and the ECMWF TECHNICAL MEMORANDUM.

2 January 1985  Indian SATOB excluded from analysis if data mislocated.

15 January 1985 Forecast model cycle 20. Surface pressure is computed from analysed field instead of first-guess in post-processing.

19 February 1985 SATOB winds over land between 20°N and 20°S were included in the operational analysis. Previously only SATOB winds over the sea had been used.

26 February 1985 High resolution satellite soundings data (TOVS) were included in the operational analysis. TOVS data are similar to SATEMs but have 250 km horizontal resolution compared to 500 km for SATEMs.

In the analysis the matrix size was increased, the large scale wind correlation was introduced and the height overlap was changed.

7 March 1985 NOAA-9 TOVS and SATEMs are included in analysis.

1 May 1985 Forecast model cycle 22. The T106 model became operational. The spectral representation in the horizontal is truncated at wavenumber 106. The vertical resolution was not changed.
The vertical diffusion scheme was modified which allows larger time-steps to be used (Δt = 900s). A parametrisation scheme of shallow cumulus convection has been introduced.

The Kuo cumulus convection scheme has been replaced by a modified Kuo scheme.

Evaporation of large-scale rain and melting of snow have been reformulated.

A new cloud prediction scheme was formulated to overcome the deficiencies of the previous scheme (too many deep clouds, too little tropical cirrus, too little subtropical cloudiness, poor representation of the diurnal variation in cloudiness).

Sea ice has been re-specified and is now assumed to exist whenever sea temperatures are below -2°C (previously 0°C).

9 May 1985

Satellite thicknesses south of 60°S were excluded from analysis, but was retained in statistics.

21 May 1985

A more stringent first-guess check for high resolution satellite soundings was introduced.

11 June 1985

Include all NOAA-6 data in analysis (still excluded south of 60°S).

18 July 1985

Forecast model cycle 24. The production of rain in convective parametrisation scheme and the evaporation efficiency over land was modified due to the over-forecasting of precipitation (particularly over Europe) and the marked negative bias in the 2m temperature in daytime (in particular when dry, sunny conditions were observed). After the correction was introduced the over-forecasting of precipitation was eliminated and the 2m temperature bias was reduced.
31 July 1985  Surface temperature set to climatology over sea if SST analysis not received or rejected.

1 August 1985  Remove change of 31 July 1985. Surface temperature set to first-guess over sea if sea surface temperature analysis (SST) not received or rejected.

8 October 1985  11 thickness layers used in analysis for TOVS and SATEMS instead of 14.

15 October 1985  Modification of rejection criteria for NMC SST analysis (not used on lakes or near coast).

17 October 1985  Modification of the stratospheric Hough smoothing functions in analysis, giving a smoother height and wind analysis.

24 October 1985  Removing SATEMS and TOVS north of 70°N in analysis.

3 December 1985  Modification of the horizontal interpolation in sea surface temperature analysis.

9 December 1985  Forecast model cycle 25. The solar heating rates were modified and the subterranean extrapolation was changed. An error in the vertical diffusion was corrected.

2 January 1986  Bad data was used in the analysis from 860101 00Z to 860102 12Z inclusive due to an error in the earth location of the soundings at NOAA/NESDIS, Washington. No satellite soundings were used in the analysis until 4 January 1986, when the problem was resolved.

4 March 1986  A modification was made to the initialisation scheme in order to help preserve the tidal waves in the data assimilation. As a result, better use is made of surface pressure observations, in particular in the Tropics, where the tidal fluctuations contribute to a large extent to the observed diurnal pressure variations.
11 March 1986 The humidity analysis was modified. The precipitable water content is now used in the atmosphere as observed from space and reported in the satellite data. Furthermore, the procedures for using bogus humidity data derived from synoptic surface reports - dew point, cloud amounts - were used in a modified way. The changes had modest but consistent positive impact on the temperature forecast in the free atmosphere and results in a more realistic forecast of the precipitation amount.

13 May 1986 Forecast model cycle 26. The 16-level model was replaced by a 19-level model. The three extra levels were introduced in the stratosphere.

15 July 1986 Forecast model cycle 27. A parametrisation scheme for representing the momentum transports due to subgrid gravity wave drag was incorporated into the operational ECMWF forecast model. It counteracts the zonalisation tendency of the large scale flow and prevents the development of too strong westerlies in winter. Errors in large scale condensation and snow melting were corrected.

19 August 1986 The calculation of low, medium and high cloud amounts were corrected in post-processing.

9 September 1986 A new analysis system was implemented which makes better use of observations; data and differences from the first-guess will be used at reported levels. This will effectively increase the actual vertical resolution of the analysis, in particular in the boundary layer and near the tropopause.

Unnecessary vertical interpolation of analysis increments between model and standard pressure levels are eliminated. Analysis increments on the Gaussian grid of the model were evaluation (1.125° resolution).
The data selection criteria in boxes of flexible size depending on data density and extending over the depth of the troposphere were improved.

A univariate optimum interpolation scheme replaced the correction scheme for the analysis of humidity.

30 September 1986 Modifications to analysis. Indication of inner data in upper analysis slab was corrected. Negative and zero values of q and q, were forced to small positive numbers. The check on the analysis error file date was re-implemented.

7 October 1986 Forecast mode cycle 28. The snow melt logic was corrected. The old scheme caused a drop of the surface temperature when snow has to melt on the ground at the expense of surface energy.

15 October 1986 An error in soil moisture analysis was corrected.

11 November 1986 Analysis modified. The u and v departures are checked together. The persistence error calculation and the indication of inner data in upper slab were corrected. Serious data problems with satellite soundings (SATEMS and TOVS) at the beginning of November. The performance of the ECMWF analysis and forecast especially over the Southern Hemisphere was adversely affected by these data deficiencies.

3 February 1987 The humidity pre-processing was modified.

10 February 1987 SATEM precipitable water content was included to analysis.

7 April 1987 Forecast model cycle 29. The surface and subsurface parametrisation scheme has been revised. Each grid box is now divided into vegetated and bare ground parts which concerns the evaporation over land surfaces. The time evolution of the soil water content takes root uptake, interruption of precipitation and colluvion of dew by a
skin reservoir, surface run off due to sloping terrain and gravitational drainage into account.

The use of specific thermal properties of snow modifies the surface temperature evolution over snow covered ground.

The convective Kuo scheme was modified. The accumulated convective precipitation now includes convective snowfall. Over sea surface convective precipitation is allowed to fall as shown when the sea surface temperature is above 0°C. For both land and sea points the air temperature at the first model level is required to be colder than minus 3°C for snowfall.

The post-processing method to compute the 10m winds, 2m temperature and dew point has been reformulated. The calculations of 10m wind components and the 2m temperature base on realistic profiles of wind speed and temperature gradients within the atmospheric boundary layer which is assumed to be a Constant flux Layer (CFL). The variables (at any height) are obtained by integrating their vertical derivatives.

The 2m dewpoint depression is computed by assuming that the relative humidity is constant in the CFL.

The modifications of the near surface temperature give a more realistic simulation of the diurnal temperature variation under clear sky conditions. The old 2m dew point calculation suffered from a surface layer which was too moist which results in a too narrow dew point spread. The new scheme corrects this deficiency to a large extent.

In stable conditions the new post-processing give lower wind speeds $u$ and $v$ at 10m height. The reduction which is of the order 1 - 3 ms$^{-1}$ is in better agreement with locally observed winds.
Over sea the Charnock constant of 0.032 was replaced by the lower value of 0.018.

Soil moisture analysis is not being done any more. The initial soil temperature and moisture content are taken from the first-guess.

13 April 1987
An error in the computation of 10m wind and 2m T and $T_d$ was fixed. The data of $u_{10}$, $v_{10}$, 2m T and 2m $T_d$ are incorrect within the time period from 7-13 April 1987

16 June 1987
Land wind data in the Tropics were used and the wind direction check was tightened up.

7 July 1987
An error in post-processing of low cloud and total cloud amount was fixed. The total cloud cover is incorrect from 15 July 1986 to 6 July 1987 as a result.

21 July 1987
A number of changes relating mainly to the use of SATEMS was implemented. Now 7 SATEM layers are used in the vertical instead of 11, i.e. 1000/700 hPa, 700/500 hPa, 500/300 hPa, 300/100 hPa, 100/50 hPa, 50/30 hPa, 30/10 hPa.

The modifications allow better use to be made of satellite sounding data in agreement with the vertical resolution given by the satellite instruments.

The satellite observation statistics and quality control were revised.

11 August 1987
A problem with the stratospheric SATEMS during early August caused the analysis to develop an erroneous warm dome in the 50-30 hPa thickness field over the Antarctic which was fixed on 11 August.

27 October 1987
Observations at North Pole were included in data selection. The humidity analysis data selection criteria were made consistent with mass and wind analysis.
8 December 1987  The first-guess rejection limit for winds was tightened and an asymmetric first-guess check on extra-tropical cloud track winds was introduced.

5 January 1988  Forecast model cycle 30. A revised vertical diffusion scheme was implemented. The turbulent diffusion is now limited to below the top of the boundary layer except when static instability is generated. This modification restricts the vertical mixing to the boundary layer. The reduction of dissipation and momentum and heat mixing in the free atmosphere has a positive impact on zonal mean temperatures and reduces the zonal wind errors. The eddy activity becomes stronger.

Modest modifications in the parametrisation of the surface processes were included. The revision of the numerical scheme affects the partitioning of the surface moisture flux in terms of water extraction from the various contributing reservoirs. The interaction between convective precipitation and surface hydrology was revised as well as the interaction between the radiation and both the canopy layer and the snow.

The new surface parameters are only marginal influenced by these changes except in the case when snow is melting. Now the surface temperatures are allowed to be positive even with snow on the ground.

26 January 1988  Divergent structure functions were included in wind correlations of the analysis. The divergent structure functions improve the analysis significantly especially in the Tropics but the improvements were found short-lived during the assimilation cycle.

1 March 1988  The revision of the MARS interpolation software affects especially the surface orographic field of the ECMWF/TOGA Level III Basic Data Set.

12 July 1988  To minimise the impact of bad data in the data assimilation system the quality control algorithm have
been modified which includes a more efficient OI check of SATEMs in areas with sufficient non-SATEM data and a general tightening of first-guess and OI rejection limits.

The structure functions were modified, resulting in an increased effective horizontal and vertical analysis resolution.

22 November 1988

Forecast model cycle 31. A modification of the surface scheme was implemented in order to correct some of the deficiencies of 2m temperature forecast.

1. The root profile was adjusted. The values of the root percentage in each of the 2 soil layers are now 50% (15%) surface layer, 50% (70%) intermediate layer and a 0% (15%) in the climate layer (percentage values within the brackets are valid for the old scheme). In the absence of precipitation no root extraction is allowed from the climate reservoir.

2. The background vegetation cover in dry situations was changed. No plant transpiration is allowed if the soil wetness in the root zone is lower than a threshold value. The background vegetation cover is not decreased linearly to 0 when the root soil wetness decreases to 0.

14 December 1988

A change was made to the analysis, to prevent uncontrolled growth of spurious vortices at the top level of the model.

31 January 1989

A set of changes to the use of satellite data was introduced. They include:

(i) a stability check of the temperature profiles deduced from the TOVS. As large errors in the lowest layer of TOVS data tend to be compensated aloft by errors of opposite sign, incorrect data are spotted by checking the difference in temperature between two layers, namely 1000/700 and
500/300 hPa, against the first-guess. The first-guess check is also tightened for certain layers.

(ii) A revision of the observation error statistics for thicknesses: the horizontal correlation function is flattened and the error variances are distributed more evenly to the different layers.

(iii) A change to the SATOB OI-check: as introduced for SATEM in July 1988, SATOB are now checked without influence from neighbouring data of the same type.

(iv) Modifications to the use of Precipitable Water Content data (PWC) from NOAA-10 and NOAA-11. The PWC are not used over land, nor when no thickness data are available in the same report; their observation error has been increased.

2 May 1989

Forecast model cycle 32. A set of three important modifications to the model’s physics was implemented in the operational forecasting system:

(i) A new parametrisation scheme for radiative fluxes and the representation of cloud optical properties.

(ii) A reformulation of cumulus parametrisation using the mass flux approach.

(iii) A revision of the gravity wave drag formulation.

An article from the ECMWF Newsletter describing the changes is given as Attachment 1.

4 July 1989

Forecast model cycle 33. Modification to the shallow convection scheme.

16 August 1989

Forecast model cycle 34. The surface analysis code was replaced. It was mainly a technical development, the analysis of surface variables now being performed inside the context of the main analysis program rather than in a
separate step. Little meteorological impact should be seen on the sea surface temperature (SST) and snow analysis (the only surface variables currently analysed).

29 August 1989 Various modifications to the analysis were implemented, the most significant of these being

(i) a tighter first-guess check for AIRFs reporting zero wind speed;

(ii) assigning single level pressure (height) observations to the first-guess pressure level instead of the reported pressure - this will remove spurious analysis increments in the temperature of the lowest model level;

(iii) rather than having a uniform global threshold the SATEM stability check will be made dependent on the first-guess error standard deviation.

13 November 1989 Changes to the analysis were implemented:

(i) The SST analysis received from NMC Washington and used in the analysis now has a 2° x 2° resolution instead of 5° x 5°. This gives a more detailed description of the SST, particularly in the vicinity of ice and coastal areas. No significant impact is expected on the forecast.

(ii) The use of SATOB wind data was revised:

(a) the following data are now excluded from the analysis (in addition to the current exclusion of all SATOB over land poleward of 20°):
   - high level GOES winds (P < 500 hPa) north of 20° N,
   - HIMAWARI winds (all levels) poleward of 20°;
(b) the asymmetric first-guess check was tightened.

16 May 1990

The following changes were implemented in the forecast model cycle 35:

(i) A reduction of the run-off of convective rain, increasing the amount of water available to wet the soil. The implied change of energy balance at the surface increases the latent heat flux at the expense of the sensible heat flux, giving a decrease in the surface and near-surface air temperature. This should significantly reduce the warm bias of the 2m temperature over continental areas during the day.

(ii) Modifications to the treatment of snow covered surfaces:

- the thermal budget of the snow is modified to take into account the effect of shade from vegetation;

- the albedo of the snow is no longer only dependent on snow depth; the new formulation also takes into account masking by vegetation, the effects of temperature and the presence of ice dew.

The overall effect is to decrease the albedo of the snow covered areas.

(iii) A modification to the model pressure-gradient calculation and a change in the calculation of pressure level geopotential heights by the model post-processing and in the first-guess for the analysis.

(iv) Modifications to the convection scheme, mainly to the treatment of cloud processes at detrainment
levels for convective clouds, to prevent a spurious moistening at cloud tops which was noticeable over the subtropical oceans in connection with shallow convection.

21 March 1990

An error in the handling of the climate fields of deep-soil temperature and deep-soil wetness was corrected (these fields had been static since August 1989, instead of being updated at the beginning of every month).

5 June 1990

The following changes were implemented in the forecast model cycle 36:

(i) The parametrisation of surface fluxes at low wind speed over sea was modified by replacing the transfer coefficients for heat and moisture in unstable conditions (free convection limit). The change has had a considerable impact on the latent heat flux which, over the Western Pacific (warm pool), can increase by up to 25 W/m². Synoptically it primarily affects the tropical flow which becomes more realistic at lower levels (e.g. improved monsoon flow) as well as at upper levels (reduced zonal mean wind error);

(ii) the formulation for the convective cloud cover was modified to account for non-precipitating shallow cumuli. The effects of this change are an increase of total cloud cover (most noticeable in the trades and over the continents in daytime), a reduction of continental precipitation, and enhancement of evaporation over subtropical oceans (by 5–10 W/m²).

12 February 1991

A change was introduced in the analysis so that the departures of the observations are now calculated against a first-guess valid at the time of the observation, obtained by interpolation from first-guess at 3, 6 or 9 hours range. Therefore, synoptic observations are used more consistently.
9 April 1991

The following modifications were implemented in the forecast model cycle 38:

(i) Modifications to the cloud and radiation subroutines, both to improve the cloud/radiation processes and to facilitate their use with increased vertical resolution. In particular, the overlapping of cloud layers was changed from a random overlap to a maximum overlap assumption.

(ii) A revised scheme for vertical diffusion in the free atmosphere, developed following the switching off of vertical diffusion above the PBL in 1988; the vertical mixing represented by the revised scheme is smaller by an order of magnitude than under the scheme which was operational until 1987.

(iii) Two revisions to the convection scheme, to ensure consistent cloud physics within the cloud model, and to introduce a cloudtop temperature check to improve the onset determination of shower precipitation.

1 May 1991

A new procedure for the quality control of satellite temperature profiles was implemented; a pre-selection of the data to be passed to the analysis is made, using the high resolution cloud-cleared radiances received from NESDIS.

17 September 1991 A high resolution analysis and forecasting system at T213 31 levels was put into operations as cycle 39. In addition to the change of resolution, the new model includes the following aspects:

- the Gaussian grid used for the computation of the physics is now a reduced Gaussian grid, i.e. the number of grid points along a latitude circle decreases towards the poles in order that the spacing of the points be approximately 60 km on the
whole globe. The effective resolution in the free atmosphere is around 100 km at half wavelength;

- several changes are made to the dynamics of the model, including use of a semi-Lagrangian advection scheme and modified horizontal diffusion. A change in the link between the dynamics and the parametrisation of vertical diffusion is expected to reduce the surface wind by about 3% over sea and about 10-15% over land;

- a new version of the cloud scheme, mainly to allow the stratiform clouds to form in any number of layers instead of the three layers in the previous version.

An article from the ECMWF Newsletter describing the changes is given as Attachment 2.

26 November 1991 A technical error in the model library was corrected in cycle 40. It was caused by an insufficiently discriminating table look-up in the long-wave radiation code, which created an erroneous systematic cooling between 150 and 400 hPa and warming above.

10 December 1991 Enhancements to the quality control of AIREP and SATOB data were introduced. In particular, the restrictions to the use of SATOB data over land have been relaxed.

7 January 1992 In model cycle 41 the horizontal diffusion was increased and the time-stepping for cumulus momentum transfer was changed. The diffusion was modified again on 15 January 1992.

20 February 1992 PAOB surface data from the Australian Bureau of Meteorology re-introduced for use in the analysis.

2 June 1992 A change to the determination of sea ice in the SST analysis was introduced, leading to an improved description of the ice edge.
9 June 1992 Two changes were introduced in the analysis:
- humidity data from SYNOP observations were excluded from the analysis, to reduce excessive convective precipitation in short and early medium-range forecasts;
- a redundancy check on aircraft data was introduced so that new high density data (ACARS) can be correctly used in the OI scheme.

23 June 1992 The temperature data from the NOAA satellites used in the analysis of the Northern Hemisphere are now derived from cloud cleared radiance data received from NESDIS, using a 1d-variational inversion technique.

17 August 1992 A change was made to the forecast model (cycle 43), to include:
- introduction of vertically non-interpolating semi-Lagrangian scheme and smaller time filter;
- suppression of inversion clouds at the lowest three model levels rather than just the lowest level;
- introduction of a prognostic equation for sea-ice temperature to replace the use of climatological values;
- other minor parametrization changes.

7 December 1992 A modification to the model post-processing was implemented (model cycle 45) to improve the extrapolation of temperature and MSL pressure under model orography. The resulting extrapolated fields better continue the free atmosphere distribution of fields and show much less dependence on the overlying orography.

1 February 1993 Changes were introduced to the horizontal diffusion and to the cloud-radiation scheme (cycle 46, inclusion of shortwave optical properties for ice and mixed phase clouds, and revision to the clear-sky absorption coefficients.
4 August 1993

Changes were made in the model's physics to improve the representation of surface and planetary boundary layer processes (model cycle 48, cycle 47 was a technical change):

- introduction of entrainment at the top of the planetary boundary layer;
- increased entrainment in shallow clouds;
- modified roughness length and air-sea transfer coefficients;
- enhancements to the parametrisation of the soil processes (four layers with prognostic variables for soil moisture and temperature plus a skin layer temperature).

The meteorological impact of these changes are:

- an overall synoptic improvement of the predicted flow, particularly over Europe in summer;
- a significant reduction of the warm bias in continental boundary layer during daytime in summer;
- a large improvement of the humidity in the boundary layer, with a more realistic diurnal cycle.

The impact on the temperature in the daytime boundary layer is noticeable with a typical reduction in the warm bias at 2 metre of 2-3 degrees. However, an increase in the cold night-time bias has been noticed. Depending on the prevailing cloud cover, the 2 metre night temperatures will, in places, be too low by several degrees.

An article from the ECMWF Newsletter describing the changes is given as Attachment 3.

5 October 1993

A change to the boundary layer parametrisation was introduced, further to the change of 4 August 1993 (cycle 49). The profiles of 2 metre temperature in stable conditions were revised to reduce the coupling between the skin temperature and the temperature of the lowest model levels. The cold bias of the predicted night-time temperature was reduced by this change.
11 November 1993 The pre-processing was modified to correct radiosonde observations for systematic biases prior to their use in the data assimilation. The correction is applied to the radiosonde stations which present a significant bias in geopotential height due to radiative effects on the sonde (long wave cooling and short wave heating, mainly in the stratosphere).
PART II - ATTACHMENT 1

The following text by G. Sommeria, M. Tiedtke, M. Miller, J.-J. Morcrette was published in the ECMWF Newsletter, June 1989.

REVISIONS TO THE MODEL PHYSICS (Implemented on 2 May 1989)

Introduction

A set of three important modifications to the model's physics was implemented in the operational forecasting system on 2 May 1989:

a) A new parametrisation scheme for radiative fluxes and the representation of cloud optical properties.
b) A reformulation of cumulus parametrisation using the mass flux approach.
c) A revision of the gravity wave drag formulation.

These changes were the outcome of an extensive research and experimentation programme followed by a series of 13 parallel assimilations and 10-day forecasts during the period 19 April - 1 May 1989. This article describes the model changes and their main physical impact as deduced from the experimentation programme and confirmed during the parallel runs. A second article covers the effect of those changes on the operational performance of the model.

DESCRIPTION OF THE MODEL CHANGES

Radiation

After a thorough validation of the previous operational scheme and other available schemes against detailed line-by-line, narrow-band models and against satellite data, it was decided to adapt a code developed earlier at the University of Lille to the ECMWF model. The main differences from the old scheme in the new scheme are:

(i) smaller shortwave $H_2O$ absorptivity, which reduces the clear-sky shortwave heating and increases the downward solar radiation at the surface;

(ii) a correct temperature and pressure dependence of the longwave absorption, which increases the longwave cooling in mid-troposphere and the stratosphere;
(iii) the presence of water vapour continuum absorption, which cools the tropical boundary layer;

(iv) cloud optical properties derived from a more realistic model cloud, and a diagnostic formulation of the cloud liquid water content independent of the model's vertical grid. These features both contribute to more radiatively active clouds and thus to the better representation of the radiation fields at the top of the atmosphere.

Convection
The Kuo scheme for cumulus convection which has been used in the ECMWF model up to now is replaced by a "mass flux" scheme. In this approach, subgrid 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 mass flux concept is supported by theoretical as well as observational studies and offers good prospects for further developments. The new scheme is applied to penetrative convection, shallow convection and mid-level convection and considers the effects of cumulus updrafts, saturated downdrafts and cumulus-induced subsidence in the environmental air. It also considers vertical transports of momentum by convective scale circulations. Updrafts and downdrafts are modelled as one-dimensional entraining plumes with simple cloud physics. The scheme is based on a moisture convergence hypothesis and is thus comparable to the previous Kuo scheme; however, it differs by these additional features:

(i) heat and moisture transports by cumulus-scale circulations, including downdrafts: this accounts for most of the differences concerning the vertical profile of heating and the spin-up of the hydrological cycle.

(ii) Momentum transport: this produces down-gradient momentum fluxes in the Tropics and thus acts to decelerate the large-scale zonal flow in the upper troposphere.

(iii) Mid-level convection: this stabilises the air above the boundary layer in the presence of conditional instability and large-scale ascent (extra-tropical fronts).
(iv) Entrainment of environmental air for calculating cloud ascents: this is important for producing realistic cloud profiles, particularly in the case of shallow convection.

Gravity wave drag
The current gravity wave drag (GWD) parametrisation in its first version has been shown to provide excessive upper level drag and does not take into account some boundary layer dissipation processes which occur in nature. A revision to the GWD scheme has therefore been introduced to

(i) increase the surface momentum flux and introduce an additional low-level drag over orographic features, decreasing the low-level wind over mountainous areas;

(ii) modify the vertical distribution of the GWD stress, resulting in a reduction of the upper level drag; this increases the stratospheric flow over and downstream of mountain ranges, and leads to a better forecast of the jet.

Experimentation programme and main effects of the model changes in terms of physical quantities
The development and experimentation programme has been conducted over approximately two years with the above changes being tested individually and in combination, both in forecast and climate mode. The changes significantly affect several key features of the model dynamics and thermodynamics, as summarised below. Whenever possible, the results presented here come from the comparison of the 13 forecasts made during the parallel runs.

a) Energy and hydrological cycle
The new radiation scheme produces more realistic flux divergences, which were previously underestimated. This, in addition to a better formulation of cloud properties, leads to a cooling and thermal destabilisation of the troposphere. In association with a more active convection scheme, the overall effect is an increase in the various terms of the energy and hydrological cycles. They are intensified by 25% and 20% respectively, as is evident from the global mean values of net radiative cooling and net heating by convection, large-scale condensation and surface heat fluxes (Fig. 1) and from the values of precipitation and surface evaporation. In
fact, whereas the energy balance after the spin-up in the previous operational model was maintained at too low values, the new physics now produces too high values as compared to climate estimates, with similar results for the hydrological cycle.

The spin-up of the hydrological cycle in the early stages of the forecasts is generally smaller with the new physics, which seems to indicate that the new convection scheme is more compatible with the assimilated data. However, during the first two days there is still a large imbalance between the moisture supply by surface evaporation and the loss due to precipitation, with the result that the model dries during the forecast, although less so than previously.

The forecast precipitation is now more concentrated along the ITCZ and more intense over the tropical continents.

b) Radiative fluxes and surface temperatures

A direct impact of the revised shortwave $H_2O$ absorptivity and cloud optical properties is to decrease by about 10\% the global shortwave atmospheric heating. Therefore, more solar radiation is available at the surface. This enhancement of the radiative energy at the surface contributes to the enhancement of convection over tropical continents and to warmer surface temperatures at higher altitudes, where the present operational model is often too cold. This temperature difference is somewhat reduced if one compares 2m or 30m (lowest model level) values instead of surface temperatures.

A better temperature and pressure dependence of the longwave absorption corrects the underestimation of the clear-sky longwave fluxes. The modified diagnostic formulation of cloud liquid water content and revised longwave optical properties make the clouds more radiatively active. This leads to increased contrast in radiation fields at the top of the atmosphere, with marked minima over convective areas and maxima over clear-sky or low-cloud areas, in agreement with satellite observations (Fig. 2). This is an important improvement to the previous operational scheme, which failed to reproduce these features.
c) **Tropical analysis and forecast**

The revised physics influences the analysis and forecast of both mass and wind fields. The new scheme produces a warmer tropical lower and mid-troposphere and a colder upper troposphere whereby the temperature bias in short- and medium-range forecasts is greatly reduced (Fig. 3).

The intensification of the diabatic forcing leads to a stronger and more realistic Hadley circulation, which is seen already in the short-range wind forecasts. In the majority of cases, the mean zonal wind error is also reduced in the medium-range. 30-day simulations indicate a slight reduction of the error in winter and a larger one in summer, especially over the western Pacific, Atlantic and South America. This is essentially the result of cumulus momentum transport since the errors are increased to the same level as with the operational scheme, when momentum transport is switched off.

Tropical forecasts typically lose skill after a few days because of errors in the analysis and rapid error growth during the early stages of the forecasts. Since the analysis depends heavily on the parametrisation through the first-guess, verification of short-range forecasts is very difficult and is best done by means of case studies. The study of Hurricane Gilbert (Fig. 4) has shown that the new physics has a marked positive influence on the forecast of the storm track and on the intensity of the vortex, which is considerably stronger than with the operational physics. The vertical structure, for moisture in particular, also appears more realistic with the new physics. An earlier study over tropical Australia (AMEX region) indicated that the new convection scheme intensifies the strength of tropical disturbances and tends to improve their analysis and forecast.

The effect of the stronger convective heating on the large-scale flow is most pronounced in the divergent part. The divergent circulation is intensified compared to the operational physics and maintained at a better level throughout 10-day or 30-day forecasts. In particular, the collapse of the circulation over the Indonesian area and the West Pacific, which was typical of the previous operational model, disappears and there is now a better agreement with the analysed flow.
Fig. 1: Components of the global atmospheric heat budget averaged for the 13 parallel forecasts a) with previous operational physics b) with new operational physics.
Fig. 2: Top outgoing longwave radiation at day 3 averaged for 13 parallel forecasts a) with previous operational physics b) with new operational physics.
d) **Extra-tropical forecasts**

The impact on anomaly correlation scores of the combined new radiation plus mass flux is positive in the average after day 5 for the northern and southern hemispheres, as deduced from 12 cases spread over the year. The corresponding scatter diagrams, however, indicate that this improvement is not systematic. This is probably due to the increase in eddy activity, which tends to spread the forecast skill measured by correlation-based scores. The effect of the GWD modification, tested on 5 Northern Hemisphere winter cases, shows a moderate but systematic improvement in Northern Hemisphere scores, which is additional to the effect of the radiation and convection changes. The effect of the GWD change is smaller in the 10-day range in the Southern Hemisphere.
PART II - ATTACHMENT 2

The following text by A. Simmons was published in the ECMWF Newsletter, December 1991.

DEVELOPMENT OF THE OPERATIONAL 31-LEVEL T213 VERSION OF THE ECMWF FORECAST MODEL

1. Introduction
On 17 September 1991 ECMWF made operational a new high-resolution version of its forecast model. This was the culmination of a five-year programme of research and development following the introduction of a 19-level version of the Centre's T106 spectral model (T106/L19) in May 1986. This programme included not only the design and testing of new numerical techniques and meteorological software, but also a major enhancement of the Centre's computing facilities, with the replacement of the CRAY X-MP/48 by the CRAY Y-MP/864 computer. A target resolution of T213 in the horizontal and 31 levels in the vertical (T213/L31) was set, entailing a doubling of horizontal resolution, and an approximate doubling of vertical resolution between the boundary layer and stratospheric model levels (see Figure 1). Support for this was provided by the encouraging results of experiments at T159/L19, T213/L19 and T63/L31 resolutions, some of which were presented in Newsletter articles in June 1987 and March 1988.

In seeking a replacement for the CRAY X-MP it became evident that the computer power required to run a T213/L31 version of the then-operational model code could not be provided on the time scale envisaged. Two significant gains in the computational efficiency of the model have nevertheless enabled the target resolution to be achieved. The first is a reduction in the computational grid of the model, following the work of Machenhauer (1979). This gives a resolution in physical space which is approximately uniform over the globe, and results in an important saving in secondary memory requirements in addition to a saving in computation time. A more major saving in time comes from adopting the semi-Lagrangian method for the treatment of advection pioneered by Robert (1981). Code reorganization necessitated by the latter also enabled a more efficient calculation of Legendre transforms, and a small reduction in the primary memory requirement of the model.
2. The reduced grid

Tests of the use of the reduced Gaussian grid in the conventional Eulerian version of the spectral model were reported in a Newsletter article in December 1990, and have been presented more fully by Hortal and Simmons (1991). A saving in excess of one-third the number of points covering the globe was obtained by increasing grid-lengths in the zonal direction under the conditions that they did not exceed the grid-length at the equator, and that the number of points around each latitude circle enabled use of a fast Fourier transform. Results showed that such a grid could be used for global forecasting (and presumably also for climate studies) with no significant loss of accuracy compared with use of a conventional grid uniform in longitude. Such differences as did occur appeared to be principally due to differences in the model orographies and sub-gridscale orographic variances computed for the new and conventional grids. The saving in computational time was around 22% for T106/L19 resolution, and 27% for T213/L19. The reduced grid for T213 resolution is illustrated over Europe in Figure 2.

Provision for using the reduced grid was then built into the semi-Lagrangian version of the model which was under development at the time. This involved some increase in computation in the interpolation stage of the model, but its cost was more than compensated by the extra savings resulting from the higher proportion of the overall calculation that is carried out in grid-point space for the semi-Lagrangian scheme. Initial testing gave satisfactory results for the most part, but noise was evident in vorticity and surface-pressure fields in polar regions for some flow orientations. This was traced to the representation of the cancellation between pressure-gradient terms near the Greenland and Antarctic plateaux, and necessitated a change to the zonal-wavenumber truncation in Fourier space and in the number of points used in the immediate vicinity of the poles. These changes had little impact on the computational cost of the model, and a quite negligible impact on the quality of the forecasts apart from removal of the noise.

3. The semi-Lagrangian scheme

The semi-Lagrangian scheme that has been adopted is a natural extension of the work of Ritchie (1987, 1988 and 1991) in applying the technique to spectral models. It preserves, however, as much as possible of the vertical discretization of the original Eulerian hybrid-coordinate model, and this discretization is retained in full in the Eulerian "u-v" option
Fig. 1: The 19- and 31-level vertical resolutions
Fig. 2: The reduced grid over Europe for T213 resolution. Heavier dots indicate grid-points treated as land in the model, and lighter dots indicate sea points.
which has been included in the new model code. In developing the semi-Lagrangian approach to the point of operational implementation, attention was devoted to three aspects. These were the basic formulation, the introduction of approximations of acceptable accuracy, and the production of an efficient computer code.

A limited number of tests of the original Eulerian version at T213/L31 resolution showed that a 4-minute timestep could not be used, and that a 3-minute timestep gave stable integrations. The current semi-Lagrangian formulation enables stable integrations with a 20-minute timestep. At T213/L31 resolution the cost of a semi-Lagrangian timestep is less than 20% higher than that of an Eulerian timestep. The elapsed time of a 10-day forecast without post-processing has been reduced from well over 24 hours with the original Eulerian code to under 4 hours by the combined use of the reduced grid and semi-Lagrangian code, helped also by some gains in coding efficiency. The multi-tasking speed-up of the new version using 8 processors is 7.6, which compares well with the figure of 7.3 obtained with the original Eulerian model on the CRAY Y-MP at T213/L19 resolution.

Experimental results providing a completely rigorous comparison between Eulerian and semi-Lagrangian forecasts at T213/L31 resolution are not available. Some parametrization changes were made in the course of development of the semi-Lagrangian version, and it has not been feasible to rerun earlier Eulerian forecasts as their costly execution was possible only because of a low workload on the CRAY Y-MP soon after installation. Nevertheless, the Eulerian and semi-Lagrangian forecasts are sufficiently close that there appears to be no serious disadvantage to use of the semi-Lagrangian method and 20-minute timestep for T213/L31 resolution. A detrimental impact of the larger timestep on boundary-layer winds has been remedied by a model revision which gives a better representation of steady balances between the resolved dynamical tendencies and turbulent diffusion (Janssen et al., 1991).

An example of the similarity between Eulerian and semi-Lagrangian forecasts is presented in Figure 3. This shows 5-day 500 hPa height forecasts and the verifying analysis for a case in which there was a marked difference between T106/L19 and T213/L31 forecasts over Europe. Differences between the Eulerian and semi-Lagrangian forecasts shown for T213/L31 are evidently much smaller than differences between either of these forecasts and the
Fig. 3: The analysed 500 hPa height (upper left, contour interval 60m) for 20 April 1990, and day-
5 forecasts verifying at this time for:

Upper right: T106/L19, Eulerian, $\Delta t = 15$ min.
Lower left: T213/L31, Eulerian, $\Delta t = 3$ min.
Lower right: T213/L31, Semi-Lagrangian, $\Delta t = 20$ min.
T106/L19 forecast. This case also serves as an example of a significant improvement in forecast accuracy due to use of the higher resolution.

4. **The comparison of T213/L31 and T106/L19 forecasts**

Several sets of forecast experiments were carried out prior to the operational change in order to establish the stability and meteorological performance of the semi-Lagrangian model at T213/L31 resolution. For the early experiments the initial datasets were created by interpolating operational T106/L19 analyses, using T213 resolution for the orography and climatological surface fields. Forecasts were run from initial dates spanning all seasons.

The results show a quite general improvement in the early medium range, both in the details of synoptic evolution and in the accuracy of local weather elements, particularly near mountainous regions. Figure 4 shows T106/L19 and T213/L31 forecasts of 10m wind at the 3-day range for a case of marked differences over the western Mediterranean. The shading illustrates the extent to which topographic features can be better resolved at the T213 resolution. The figure illustrates the expected increase in detail in local wind systems in the higher-resolution forecast, for example the sharp orographically-induced gradient in wind speed in the flow north of Majorca. There are also some pronounced differences in flow direction and speed over the seas surrounding Italy. Comparison with observed wind fields, and verification of the associated precipitation patterns, shows the T213/L31 forecast to be the more accurate of the two.

It becomes increasingly difficult to assess performance differences at longer time ranges. There is an increase in the intensity of synoptic-scale systems in the new version of the model which appears to be beneficial to the quality of forecasts in the early part of the ten-day range, but which can bias objective verification scores against the higher resolution once the overall forecast accuracy has deteriorated significantly. Evidence of the more active nature of the new version of the model is seen in significant increases in global-mean precipitation and eddy kinetic energy.

The increases arise both from the changed horizontal and vertical resolution, and from a change in the parametrization of clouds and radiation (Moccrette et al., 1991) that was introduced operationally at the same time as T213/L31 resolution.
Fig. 4: Day-3 forecasts of 10m wind (ms$^{-1}$) from 12 UTC 15 April 1991 for T213/L31 (upper) and T106/L19 (lower). Model orographies are indicated by shading.
Technical development of the new model, and its incorporation in the data assimilation system, had reached the point in June 1991 that a run of the T213/L31 system (with the revised parametrization) could begin in parallel with the operational T106/L19 system. After removal of some residual programming errors, a set of forecasts was carried out for an 18-day period beginning 11 July. The new data assimilation system was run for a further week to provide consistent analyses for verification. Following a break in August, a second parallel run of 13 days duration was carried out in September immediately prior to the operational changeover.

The two periods of parallel runs were characterized by quite different levels of performance from both the operational and the test versions of the model. The forecasts in July were of higher overall quality, and variations in accuracy from case to case were substantially smaller than in September. Subjective synoptic assessment carried out for Europe and the North Atlantic was in favour of the high resolution version for July and neutral for September. Objective verification such as presented in Figure 5 showed a clear superiority for the T213/L31 version over Europe in July, particularly at the surface (and near the tropopause). The converse was the case in September, though the detrimental impact of the new version of the model was not particularly marked over the time range for which these relatively poor forecasts could be regarded as useful.

Examination of weather parameters for the July run showed that T213/L31 gave an improved fit of 2m temperatures to surface observations over Europe as a whole, although there were regions such as the Alps where the higher orography of T213 increased a cold bias. There was somewhat less of an under-prediction of cloud cover with the new version of the model. Patterns of precipitation from T213/L31 appeared often to agree better with observations than those from T106/L19, though an exception occurred early in the forecast range. Here T106/L19 had a tendency to produce too widespread and too intense rainfall, especially over higher ground. This was clearly worse in the new version of the model. Though a subject of concern and further investigation, this problem was likely to have been seen at its worst in the first parallel run. The forecast experiments carried out for other seasons from interpolated T106/L19 analyses, and the results from the second parallel run and operational use of the T213/L31 system generally exhibit much less excess precipitation at short range than found in July.
Fig. 5: Mean anomaly correlations of 1000 hPa for the European region for the new T213/L31 model (solid lines) and for the operational T106/L19 model (dashed lines) based on the parallel runs carried out in July (upper) and September (lower).
It is perhaps not surprising that with a model change of this order improvements have not been seen in all aspects of model behaviour. Apart from the over-prediction of summertime rainfall in the early stages of the model runs, there has been concern that the model's level of eddy activity has increased from values which were too low to values which may now be too high, giving a higher degree of inconsistency from forecast to forecast in the later medium range. Also, systematic temperature errors in the upper troposphere and stratosphere from the new model were notably different in September and October from those found previously. However, it has recently been found that an error was introduced into the long-wave radiation calculation by some "optimization" of the new model version early in September. This was corrected in operations on 26 November. The implications of this error have yet to be fully assessed, but results from the first two months of operational use of T213/L31 must be treated with some caution. Nevertheless, taking into account the earlier experimental results, it can be said that with its generally more realistic eddy energy and capability for a better description of topographic effects and frontal, boundary-layer and tropopause structures, the new model version has the potential for important future contributions to the improvement of the Centre's forecasts.

It is a pleasure to acknowledge specifically the work of Hal Ritchie in the design and initial implementation of the semi-Lagrangian scheme, and of Terry Davies, David Dent, Mariano Hortal and Clive Temperton who were the principal contributors to the general development of the numerical formulation of the model and to the testing at high resolution. Thanks are also due to the many other people, from both the Research and Operations Departments, who participated in some way or other in the work summarized here.

References


PART II — ATTACHMENT 3

The following text by Anton Beljaars and Pedro Viterbo was published in the ECMWF Newsletter, September 1993.

A NEW SURFACE/BOUNDARY LAYER FORMULATION AT ECMWF

Introduction

This article describes the model changes introduced operationally on 4 August 1993 and results of forecast and data assimilation experiments with the new model version (Cycle 48). Many of these changes were introduced to cure problems that were identified by comparison with field data (see Betts et al., 1993 and Beljaars and Betts, 1992). The problems of the previous model version (Cycle 47) can be summarized as follows:

- the ground heat flux over land surfaces was too large by a factor of 2 to 3 and had a large phase error in the diurnal cycle;

- the diurnal cycle of the sensible and latent heat flux had a phase error of about 2 hours due to thermal inertia of the 7 cm surface soil layer in the model;

- the boundary layer depth was generally too small, indicating a lack of boundary layer entrainment;

- the boundary layer was too moist, even if the surface fluxes were correct. This was again due to lack of boundary layer entrainment;

- the evaporation from the surface was too large in wet conditions and too small in dry conditions;

- the soil moisture was excessively dominated by the climate layer;

- runoff tended to be a constant fraction of precipitation, resulting in relatively large runoff even when the soil was dry.
These model deficiencies inspired a set of changes in the boundary layer parametrization and in the land surface parametrization.

In addition, the parametrization of air-sea interaction has been modified. The principles of air-sea interaction have already been described by Miller et al. (1992), together with a description of the enhancement of evaporation at low wind speeds that was introduced in Summer 1990, with an empirical formula restricted to low wind speeds. The revised air-sea interaction is now part of the Monin-Obukhov formulation.

**Model changes**

**Boundary layer above the surface layer**

We have to distinguish two different regimes: (i) the stable and (ii) the unstable regime.

**(i) The stable regime**

Two different versions of the vertical diffusion scheme were used for the stable regime in Cycle 47 of the operational model. Below a generous estimate of the boundary layer height, the stability-dependent exchange coefficients were a function of the Richardson number (Louis, 1979, Louis et al., 1982). It was discovered that, when applied to the free atmosphere, the Richardson number formulation results in excessive mixing and is detrimental to the wind jet structures in the vicinity of the tropopause (revised in model version Cycle 29, January 1988). In Cycle 47 a Monin-Obukhov (MO) formulation (Beljaars and Holtslag, 1991) was used above the boundary layer height. An iterative procedure is used to calculate the Obukhov length given the Richardson number. The diffusion coefficients used by the model are much smaller in the free troposphere than below the boundary layer height.

The new model (Cycle 48) follows the same approach; the only difference is that the stability functions of the new MO formulation are slightly modified to get a better Richardson-dependence of the turbulent Prandtl number (ratio of turbulent diffusivities for momentum and heat) in the range of Ri from 0.2 to 1. Originally an attempt was made to use the MO scheme in the boundary layer as well (which makes the estimation of the boundary layer height obsolete), but this was abandoned because of a detrimental impact on the European objective scores from the reduced diffusivities in the stable case.
(ii) The unstable regime

The formulation of vertical diffusion in Cycle 47 (Louis, 1979, Louis et al., 1982) in the unstable regime is similar to the stable regime, with Richardson number dependent stability functions below the boundary layer height. The diffusion coefficients in the unstable regime are large leading to rapid dry adiabatic adjustment. This process is relatively insensitive to the formulation since mixed profiles of dry static energy are always produced, provided that the diffusion coefficients are sufficiently large.

It was shown with help of FIFE data that the lack of entrainment through the stable capping inversion results in mixed layers that are too shallow and too moist. An entrainment parametrization has been introduced in Cycle 48, by specifying the diffusion coefficient in the capping inversion such that the buoyancy flux in the entrainment layer becomes proportional to the surface buoyancy flux. The entrainment constant is 0.2. Since the heat flux becomes negative in the upper part of the mixed layer, the traditional local closure cannot be used any more (since the stable regime of the closure would be selected). A profile of diffusion coefficients is prescribed in the mixed layer as proposed by Troen and Mahrt (1986). Details of how this scheme performs in comparison with FIFE data are given by Beljaars and Betts (1992).

The surface layer

In Cycle 47, the transfer coefficients for heat, momentum and moisture were based on the Richardson number formulation, and a single roughness length was used for all the fluxes (Louis, 1979). Over sea there was a correction to the heat and moisture transfer, enhancing the transfer rates at low wind speeds.

In Cycle 48, the transfer coefficients which are used to parametrize the surface fluxes of momentum, heat and moisture consist of a neutral part determined by the logarithmic profile and separate roughness lengths for momentum and heat (the moisture roughness length is identical to that for heat), plus a stability correction. Over the ocean the roughness length for momentum has been modified at low wind speeds according to smooth surface scaling (see Miller et al. 1992). This concept has been applied for all wind speeds in the roughness lengths of heat and moisture. The high wind part of the heat and moisture transfer coefficients used is virtually independent of wind speed, in accordance with recent reviews of
observational data (see de Cosmo, 1991, for a summary of the HEXOS experiment results).

The roughness lengths over land have been recomputed from vegetation, urbanisation and orographic distributions, where new empirical formulae have been used for the orographic contribution (see Mason, 1992). Where an orographic contribution applies to the roughness length for momentum, the neutral transfer coefficients for heat and moisture are kept constant. This results in orders of magnitude reduction of the roughness lengths for heat and moisture, when compared to the momentum values.

The stability corrections applied to the neutral transfer coefficients are now expressed as a function of the Obukhov length instead of the Richardson number. This allows for a consistent treatment of different roughness lengths for heat and momentum in combination with stability corrections.

**The skin temperature**

In order to have a faster response of the sensible and latent heat fluxes to the radiative forcing and to reduce the heat flux into the ground, the concept of a skin layer has been introduced. The skin layer has no heat capacity and adjusts its temperature instantaneously to the radiative forcing. The heat transfer to the underlying soil is parametrized with the help of an empirical conductivity, the value of which determines the amplitude of the diurnal cycle in the soil heat flux. The skin temperature is calculated implicitly as part of the vertical diffusion scheme in order to reduce time truncation errors. The skin layer together with the reduced roughness length for heat is responsible for a weaker coupling between surface and atmosphere and for a much reduced coupling between surface and soil. The surface temperature is allowed to increase during daytime without increasing the temperature at 2m and without increasing the soil heat flux. Likewise, during nighttime, the skin layer cools radiatively, leading to lower minimum surface temperature. Although this is realistic, two-metre temperatures are currently adversely affected, giving rise to negative biases (see section on parallel run). The problem lies in the post processing of two-metre temperatures and is under investigation.

**Land hydrology**

The Cycle 47 surface scheme was based on the heat and water budget of two active soil layers plus an additional surface layer underneath (Blondin, 1991, Viterbo and Illari, 1993). The fluxes of water and energy between the
layers are based on constant diffusion coefficients. The climate values, kept constant during the forecasts, were used as lower boundary conditions and updated at the beginning of every month. The "Mintz and Serafini" climate (Mintz and Walker, 1993) is used for soil moisture, while for surface temperature the RAND climatology is used (Brankovic and van Maanen, 1985).

From comparisons with FIFE data it was concluded that the land hydrology in Cycle 47 was inaccurate and dominated excessively by the climate fields. This was confirmed by single column simulations where the model's atmospheric forcing is replaced by observational data (see Fig. 1, described below).

The new scheme has 4 prognostic layers, to represent the diurnal to the annual time scales. The diffusivities and conductivities of soil moisture are non-linear functions of the soil moisture. This allows precipitation to penetrate fairly quickly into the soil, and in dry conditions the upward diffusion of water becomes slower. The runoff in the new model is mainly due to gravitational drainage. Boundary conditions at the bottom are zero energy flux and free percolation. The new hydrology scheme has been extensively tested in one column mode with the help of long data sets (see Fig. 1 for FIFE). Results of these comparisons will be published elsewhere. The main conclusion is that the new scheme maintains evaporation in the drying season for a longer time and that it loses less water in runoff when the soil is dry. In general the new scheme tends less to extremes. It produces less evaporation in wet conditions and the soil dries out less quickly.

**Clouds**

The entrainment in shallow cumulus clouds has been increased and the relative humidity criterion for inversion clouds has been modified. The effect of increased entrainment in shallow convection is to have a more rapid mixing of the updrafts with surrounding air, resulting in less deep penetration.

**Long runs**

Two types of long integrations were carried out with the new version of the model at T63 resolution:
- a multi-year run (4.5 years) to examine the long term stability of
  the model;
- 120 day summer and winter runs.

Multi-year integrations (T63L31)
From the multi-year integration, monthly averaged surface fields were
computed (for 12 UTC) and used to make time series for different areas.
Fig. 2 shows the time series for soil wetness averaged over Central Europe
for the control and the NEW model. The first impression is that the NEW
annual cycle is physically more realistic in that we see a decreasing
amplitude of the annual cycle with increasing depth, and that phase
differences occur. The magnitude of soil moisture (in mm of water per 70 mm
of soil) in the two model versions cannot be compared directly because it
has to be interpreted in relation to the settings of field capacity and
wilting point. (At field capacity the evaporation is not limited by soil
moisture availability; at the wilting point, evaporation stops).

To understand the difference between control and NEW it should be realized
that the soil moisture processes are quite different. In the control
model, the top layer and the deep layer have roots (7+42 cm of soil); in
NEW, layer 1, 2 and 3 have roots (7+21+72 cm of soil). The supply of water
from the climate layer in the control run is therefore through diffusion
when the difference in soil moisture between the climate layer and the deep
layer is large. In NEW, the roots have direct access to water from a 1m
deep soil layer; the supply from layer 4 is through diffusion, but this is
relatively slow.

120 day runs (T63L19)
Summer and winter 120 day integrations were done to study the model
climate. Soil moisture and soil temperature were initialized with monthly
averages from the multi-year runs. The zonal mean wind and moisture errors
for the NH-winter run are shown in Fig. 3. The errors are generally reduced
in the tropics: the NEW model reduces the easterly errors, the Hadley
circulation is enhanced (reduced V and W errors, not shown) and the cold
bias is reduced (not shown). Also the moisture bias is reduced considerably
in the tropics. With respect to this it is interesting to note that the
negative bias at 850 hPa as well as the positive near-surface bias between
20 and 50 degrees north are reduced. This can mainly be attributed to
changes in shallow convection and to the boundary layer entrainment. The
shallow convection change makes the convection less deep but enhances the
mixing across the inversion and therefore moistens the levels around 850 hPa (Fig. 4a). Over land, the entrainment dries the boundary layer from above, but it competes with more moistening at the surface due to the new surface hydrology. The net effect is to reduce the moistening by vertical diffusion over land (Fig. 4b).

The effects on the tropical circulation are very similar in the NH summer integration. It is worth noting that about half of the impact (enhanced Hadley circulation, reduced easterly errors and increased tropospheric temperatures) is due to the boundary layer and air-sea interaction changes; the other half comes from the shallow convection change.

**Forecast and assimilation experiments**

A standard ensemble of 12 forecasts was run for the 15th of each month; later the ensemble was extended to 15 with 3 winter cases. Soil moisture and soil temperature were initialized from the monthly climate of the multi-year T63 runs. The mean impact on the scores is fairly small. Furthermore, the T213 tests confirm the earlier findings from the 120-day T63 runs: the Hadley circulation is enhanced and the systematic errors in boundary layer moisture content are reduced.

Ten days of data assimilation (with 10-day forecasts run from the last 5 days) were run for May 1993 with the NEW model. The fit to the data in this experiment is very similar to the operational suite, except for the relative humidity. The relative humidity in the NEW model boundary layer is much closer to the data. This is due to a better control of evaporation from the surface and to the introduction of boundary layer entrainment which tends to dry the boundary layer. The 500 and 1000 hPa European and Northern Hemispheric scores show a clear advantage of the NEW model over the Control run (not shown).

17 days of data assimilation and the corresponding forecasts covering the period of November 1992 were run at T106 with the NEW and Control model. The main signal is again from the boundary layer humidity. The impact of the changes on the mean scores is very small for this data assimilation experiment, although considerable day to day variability was found.
Parallel run

The NEW model was run in parallel (data assimilation and forecast) from 2 July 1993 until it entered into operation (4 August 1993). In this section we compare the Control and the NEW run.

The analysis fit to the data is very similar, except for the humidity, as before. The fit of boundary layer humidity to radiosonde data (not shown) is better over the Northern Hemisphere and worse over the Southern Hemisphere.

Comparison of near surface parameters with SYNOP data also shows an improved moisture structure in the boundary layer. The specific humidity is always closer to the data in the NEW model and the amplitude of the diurnal cycle is reduced (see Fig. 5 for Europe). In the NEW model the moistening from the surface is partially compensated by drying from the boundary layer top. Also the reduced coupling between the atmosphere and surface makes the specific humidity drop less with the reduction in surface temperature during the night. The beneficial effect of Cycle 48 on near surface specific humidity is most pronounced over Southern Europe (not shown).

The daytime two-metre temperature errors over Europe are reduced and they compare better with the SYNOP observations (Fig. 5). The night-time temperatures are also lower and in fact become too low. It should be realized, however, that the daytime near-surface temperatures are coupled to a deep atmospheric layer and that the night-time cooling is restricted to a very shallow boundary layer. The improved temperature structure of the atmosphere over continental areas is probably best illustrated by the 850 hPa temperature error map of the day 5 forecast with the control run and the NEW model, averaged over the entire parallel run, for a total of 31 forecasts (see Fig. 6; night-time plot is not shown, but very similar). That these temperature errors exist over deep layers becomes clear from the cross section along the latitude band 40°-50°N (Fig. 7).

Averages of the scores for Europe and Northern Hemisphere are shown in Fig. 8. Both regions show an improvement in the day 3 to day 4 range which is considered to be quite robust (the scatter from individual forecasts is very small). It is believed to be related to the reduction of the continental temperature bias.
REFERENCES


Blondin, 1991: Parametrization of land-surface processes in numerical weather prediction.

Land surface evaporation: measurement and parametrization, T.J. Schmugge and J.-C. André, Eds., Springer-Verlag, 31-54.


Fig. 1: Latent heat fluxes for FIFE; time in Julian days, from the end of May to mid-October.
Solid line: Observations
Dotted line: One-column simulation using the old operational scheme
Dashed line: One column simulation with the new scheme
Fig. 2: Time series of monthly averages of soil wetness for Central Europe from multi-year runs with T63L31. The upper panel shows results for the NEW model, the lower panel for the control. The labels 1 to 4 in the upper panel correspond to increasingly deeper soil layers.
Zonal mean errors averaged from day 31 to day 119 for the NH winter integrations (from 1-11-91) with NEW model (upper panels) and control (lower panels): a) zonal wind and b) specific humidity.

Fig. 3.
Fig. 4:
a) Moisture tendency from shallow convection averaged for all sea points.
b) Vertical diffusion tendency averaged for all land points.
Mean results from a T63L19 NH summer from day 30 to day 119. Upper panels show results for the NEW model, lower panels for the control run. Units g/kg/day.
Fig. 5: Time series of temperature and specific humidity over Europe (54 to 72 hour forecasts, dashed lines) in comparison with SYNOP data (solid line):

a) Two-metre temperature, NEW model;
b) Two-metre specific humidity, NEW model;
c) Same as in a), for Control;
d) Same as in b) for Control.
Fig. 6: Temperature error of day 5 forecasts averaged from 4 July to 3 August 1993:
Top panel: New model, parallel run
Bottom panel: Operations
Fig. 7: Cross section of temperature error at latitude band from 40° to 50° North for NEW (top panel) and Control (bottom panel).
Fig. 8: Scores averaged over 31 forecasts from the parallel run with the NEW model in comparison with Control.
PART III: SUMMARY OF DATA DEFICIENCIES IN THE ARCHIVES

This section summarizes all known data deficiencies (suspect or missing data) of the ECMWF/TOGA Level III Data Sets from 1 January 1985 to the current date.

Table 1: Summary of miscellaneous data deficiencies in the archives

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<th>LEVEL</th>
<th>NOTES</th>
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<td>surface</td>
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Total cloud cover

All total cloud cover fields archived as analysis data are incorrect.

Cloud cover at ECMWF is deduced during the post-processing of various direct model output fields. Due to some of these fields not having been initialised with respect to analysis data, values archived with the analysis archive are of no practical use.

Precipitation

All precipitation fields archived as analysis data are incorrect.

Research works at ECMWF are developing schemes to use reported precipitation data from observations. To assist this process, precipitation data are contained within the analysis archive; these data are for internal ECMWF use only and are of no practical use to external users.

Forecast precipitation fields before 1991 are of doubtful quality because of limitations in the model physics resulting in "spin-up" problems during the early stages of the forecast.

U- and V-Wind Components at the Poles

In 1991 it was discovered that, on a regular latitude/longitude grid, the ECMWF u- and v- components of wind were incorrect at the poles. The problem was that the horizontal components of wind gave inconsistent polar values of wind magnitude and direction. Changes have been made to the interpolation routines used to create the ECMWF/TOGA Basic Data Sets and to extract data from the ECMWF/TOGA Advanced Data Sets and the Supplementary Fields Data Set. These changes have had the following effects on u- and v-wind fields at the poles:

(a) **Surface data.** The grid points at each of the poles will contain horizontal wind components from the nearest neighbouring Gaussian latitude circle interpolated to the required resolution. For the T213 model the nearest latitude circle is ± 89.578132.
(b) **Upper air data.** The grid points at each of the poles contain the correct horizontal wind components derived from the spherical harmonics coefficients, i.e. the values of the wind magnitude derived from the horizontal wind components will be constant, while the $u$- and $v$- components oscillate with a wave number 1 pattern around the poles.

From 1 January 1992, all $u$- and $v$-wind components at the poles supplied from the ECMWF/TOGA Advanced Data Sets will be in the format described in (a) and (b) above.

From 1 January 1992, $u$- and $v$-wind components at the poles supplied from the ECMWF/TOGA Basic Data Sets for periods from 1 July 1991 onwards will be in the format described in (a) and (b) above. Data for periods before this date will contain incorrect values at the poles.

The following paragraph contains a method for calculating wind components at the poles using the values at a neighbouring latitude circle. This is only one method that can be used. The user may wish to use another method for calculating polar winds, for example by using a polar stereographic projection.
Calculation of wind at the pole from values at a neighbouring latitude circle

Given winds \( U_i, V_i \) \( i = 1, 2, 3, \ldots, NLON \) along a latitude circle close to the pole, compute

\[
U^{(1)} = \frac{1}{NLON} \sum_{i=1}^{NLON} (U_i \cos \lambda_i - V_i \sin \lambda_i)
\]

\[
V^{(1)} = \frac{1}{NLON} \sum_{i=1}^{NLON} (V_i \cos \lambda_i + U_i \sin \lambda_i)
\]

where

\[
\lambda_i = 2\pi (i-1)/NLON
\]

\( U^{(1)}, V^{(1)} \) approximate wind at the pole for longitude \( i=1 \) based on the wave number 1 components of \( U \) and \( V \) along the latitude.

Winds at other longitudes are given by

\[
U^{\text{pole}} = U^{(1)} \cos \lambda_i + V^{(1)} \sin \lambda_i
\]

\[
V^{\text{pole}} = V^{(1)} \cos \lambda_i - U^{(1)} \sin \lambda_i
\]

Example

Using T213 wind data at 500 hPa (from September 1991):

Distance of latitude circle from pole

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<tr>
<th></th>
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<th>1.5°</th>
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Relative error in wind strength

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<tr>
<th></th>
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Absolute error in wind direction

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<th>0.7°</th>
</tr>
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</table>

+ Gaussian latitude nearest to pole
PART IV: DISCRETISATION OF SOIL LAYERS

SOIL DEPTHS
The soil is discretized in 3 layers before August 1993 (Cycle 47) and 4 layers afterwards (Cycle 48). In Cycle 47, the values of temperature and water in the two top layers evolve during the forecast, while the values for the lowest layers are kept constant. In Cycle 48 the values in all 4 soil layers change during the forecast. The table below summarises the soil layers distribution and, for each layer, the depths of its top and bottom.

<table>
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<tr>
<th>MARS name</th>
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<th>Bottom (m)</th>
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<th>Bottom (m)</th>
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<td>STL1/SWL1</td>
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SOIL WATER UNITS
Soil water is stored in MARS with the units of metres of water scaled to the depth of the top soil layer (m of water/0.07). The following describes the operations necessary to convert MARS soil water at layer $i$, $\theta^i_{w}$ into other units.

MARS soil water content ($\theta^i_{w}$)

\[ [\theta^w] = \frac{m \text{ of water}}{0.07} \]

Volumetric water content ($\theta^i_{v}$)

\[ \theta^i_{v} = \frac{\theta^i_{w}}{\phi_i} \]

Water content ($\theta_i$)

\[ \theta_i = \frac{\theta^i_{w}}{\phi_i} \cdot d_i \]

SOME CHARACTERISTIC VALUES (IN CYCLE 48)
The maximum value of water in any layer corresponds to saturation (0.47 m$^3$/m$^3$). However, saturation can only occur during very short periods, because the model will lose water due to bottom drainage. Field capacity corresponds to the maximum value that the model can sustain for more than a few hours, in the absence of precipitation. The vegetated fraction of the soil evaporates at the potential rate for soil wetness larger than field capacity (0.32 m$^3$/m$^3$) and stops evaporating below the permanent melting point (0.17 m$^3$/m$^3$), varying linearly between the two extremes.
PART V: DESCRIPTION OF GAUSSIAN GRIDS

N48 Gaussian Grid

The N48 Gaussian grid, introduced with the operational spectral model on 21 April 1983, has a regular interval along a line of latitude of 1.875 degrees, but an irregular interval between latitude lines as listed below. The grid is symmetric about the Equator.

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N80 Gaussian Grid

The N80 Gaussian grid, introduced with the operational spectral model on 1 May 1985, has a regular interval along a line of latitude of 1.125 degrees, but an irregular interval between latitude lines as listed below. The grid is symmetric about the Equator.

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N160 Quasi-regular Gaussian Grid

The N160 Gaussian grid, introduced with the operational spectral model on 17 September 1991, has an irregular number of points along a line of latitude as well as an irregular interval between latitudes. The number of points along each line of latitude are listed below. The grid is symmetric about the Equator.

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</table>

N.B. On a regular N160 Gaussian grid the interval along a latitude is .5625 degrees
PART VI: **TABLE OF DATA VOLUMES PER YEAR**

The following table gives approximate volumes of data which can be obtained from the ECMWF/TOGA data sets, in terms of the units of data, for each complete data set for 1 year in different representations and with different resolutions:

<table>
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<th>Lat/Long Grid</th>
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<th>Spherical Harmonics</th>
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<td>Basic Upper Air Data Set</td>
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<td>Basic Consolidated Data Set</td>
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<td>Supplementary Fields Data Set</td>
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### PART VII: SUMMARY OF ECMWF VERSION OF TABLE 2 FOR WMO FM 92-IX EXT. GRIFF

(This Table is used instead of Table 2 of FM 92-IX Ext. GRIB)

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</tr>
<tr>
<td>130</td>
<td>Temperature</td>
<td>K</td>
</tr>
<tr>
<td>131</td>
<td>U-velocity</td>
<td>m s$^{-1}$</td>
</tr>
<tr>
<td>132</td>
<td>V-velocity</td>
<td>m s$^{-1}$</td>
</tr>
<tr>
<td>134</td>
<td>Surface pressure</td>
<td>Pa</td>
</tr>
<tr>
<td>135</td>
<td>Vertical velocity</td>
<td>Pa s$^{-1}$</td>
</tr>
<tr>
<td>139</td>
<td>Surface temperature</td>
<td>K</td>
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<tr>
<td>140</td>
<td>Surface soil wetness</td>
<td>m (of water)</td>
</tr>
<tr>
<td>141</td>
<td>Snow depth</td>
<td>m</td>
</tr>
<tr>
<td>142</td>
<td>Large scale precipitation*</td>
<td>*m</td>
</tr>
<tr>
<td>143</td>
<td>Convective precipitation*</td>
<td>*m</td>
</tr>
<tr>
<td>144</td>
<td>Snow fall*</td>
<td>*m</td>
</tr>
<tr>
<td>146</td>
<td>Surface sensible heat flux*</td>
<td>* Wm$^{-2}$</td>
</tr>
<tr>
<td>147</td>
<td>Surface latent heat flux*</td>
<td>* Wm$^{-2}$</td>
</tr>
<tr>
<td>151</td>
<td>Mean sea level pressure</td>
<td>Pa</td>
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<tr>
<td>157</td>
<td>Relative humidity</td>
<td>%</td>
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<tr>
<td>164</td>
<td>Total cloud cover</td>
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<tr>
<td>165</td>
<td>10 metre u</td>
<td>m s$^{-1}$</td>
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<tr>
<td>166</td>
<td>10 metre v</td>
<td>m s$^{-1}$</td>
</tr>
<tr>
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<td>2 metre temperature</td>
<td>K</td>
</tr>
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<td>2 metre dewpoint temperature</td>
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</tr>
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<td>170</td>
<td>Deep soil temperature</td>
<td>K</td>
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<tr>
<td>171</td>
<td>Deep soil wetness</td>
<td>m (of water)</td>
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<td>Land/sea mask</td>
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<tr>
<td>173</td>
<td>Surface roughness</td>
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<td>174</td>
<td>Albedo</td>
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<td>176</td>
<td>Surface solar radiation*</td>
<td>* Wm$^{-2}$</td>
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<tr>
<td>177</td>
<td>Surface thermal radiation*</td>
<td>* Wm$^{-2}$</td>
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<tr>
<td>178</td>
<td>Top solar radiation*</td>
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<td>Top thermal radiation*</td>
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<td>U-stress*</td>
<td>* Nm$^{-2}$</td>
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<tr>
<td>181</td>
<td>V-stress*</td>
<td>* Nm$^{-2}$</td>
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<td>183</td>
<td>Climatological deep soil temperature</td>
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<tr>
<td>184</td>
<td>Climatological deep soil wetness</td>
<td>m (of water)</td>
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<tr>
<td>228</td>
<td>Total precipitation*</td>
<td>*m</td>
</tr>
</tbody>
</table>

* denotes field accumulated over 6 hours since start of forecast.
PART VIII: REFERENCES

**Analysis system**


**Initialization system**


Prediction model

Geleyn J.F., Hollingsworth A., 1979: An economical analytical method for
the computation of the interaction between scattering and line absorption

albedo values for operational use at ECMWF. Arch. Meteor. Geophys.

Geleyn J.F., 1988: Interpolation of wind temperature and humidity values
from model levels to the height of measurements. Tellus, 40A, 347-351.

Hortal M., Simmons A., 1991: Use of reduced Gaussian grids in spectral


weather forecasts to the use of an envelope orography. Quart. J. Roy.

Louis J.-F., 1979: A parametric model of vertical eddy fluxes in the

Miller M., Beljaars A., Palmer T., 1992: The sensitivity of the ECMWF model
to the parametrization of evaporation from the tropical oceans. J. of
Climate, 5, 418-434.

Miller M., Palmer T., Swinbank R., 1989: Orographic gravity - wave drag:
its parametrization and influence in general circulation and numerical

Morcrette J.-J., 1991: Radiation and cloud radiative properties in the
European Centre For Medium-Range Weather Forecasts forecasting system.

Morcrette J.-J., 1990: Impact of changes to the radiative transfer
parametrisation plus cloud optical properties in the ECMWF model.

ECMWF medium-range prediction models. Development of the numerical
formulations and the impact of increased resolution. Meteor Atmos.Phys.,
40, 28-60.

Simmons A., Dent D., 1989: The ECMWF multi-tasking weather prediction

Slingo J.J., 1987: The development and verification of a cloud prediction

Tiedtke M., 1984: The effect of penetrative cumulus convection on the large
scale flow in the general circulation model. Beitr. Phys. Atmos., 57, 216-
239.

Tiedtke M., 1989: A comprehensive massflux scheme for cumulus