PART II ATTACHMENT I

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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 (cloud 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_20 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.

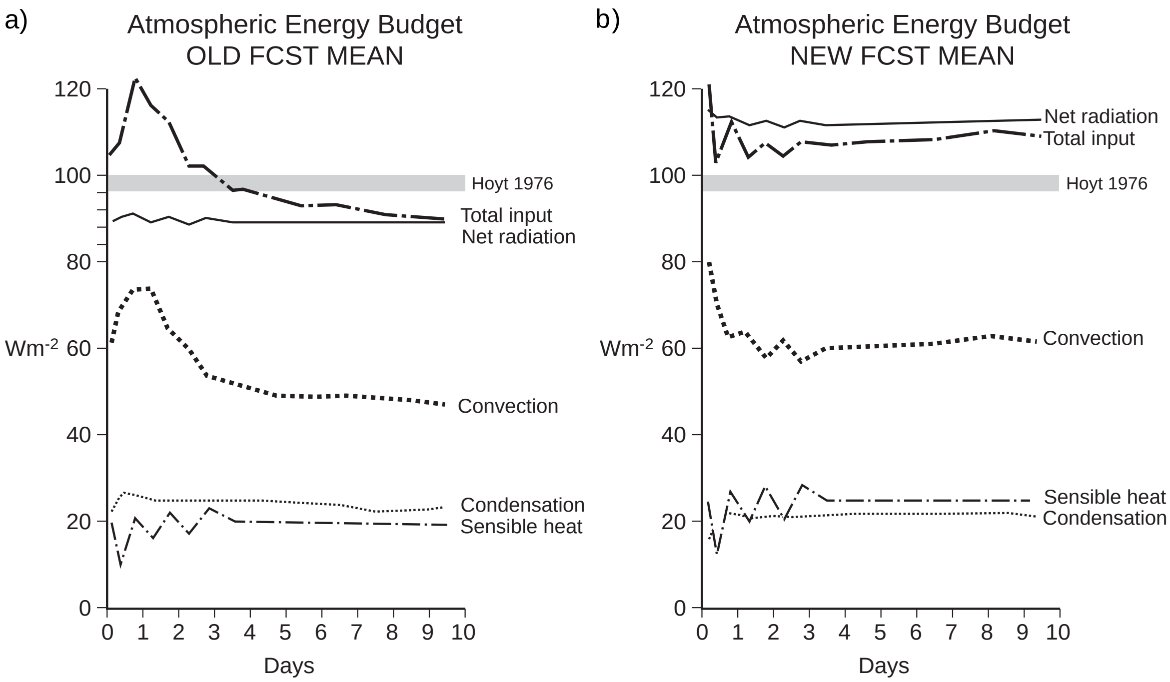

Fig.1 Components of the global atmosphere heat budget averaged for the 13 parallel forecasts a) with previous operational physics b) with new operational physics

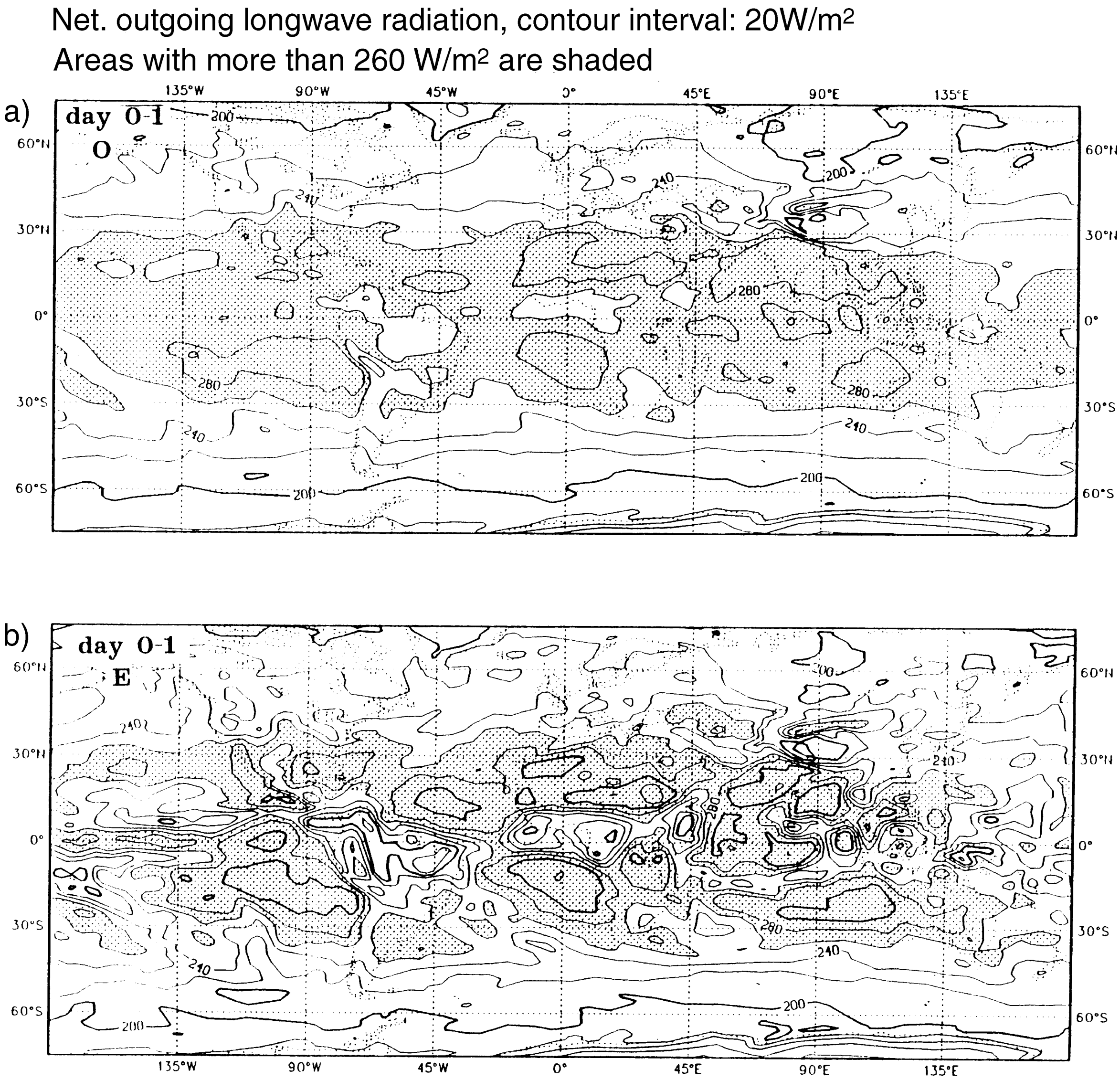

Fig. 2 Top outgoing longwave radiation at day 3 averaged for 13 parallel forecasts a) with previous operational physics b) with new operational physics

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.

(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.