A major operational forecast model change

Reprinted from ECMWF Newsletter Number 70

On 4 April 1995, a substantial and wide-ranging set of IFS modifications was introduced operationally (IFS-CY13R4). This set of model changes was the culmination of several years of development and testing of new parametrization schemes and refinements of the semi-Lagrangian model. This article briefly reviews the substance and rationale for these various changes, and summarizes typical impacts on synoptic/weather parameters. For reference the meteorologically relevant model changes are listed at the end.

It is convenient to discuss those changes involving the numerical formulation separately from the physical parametrization ones, even though there are, of course, fundamental interdependencies. The various components were developed and tested separately and then combined and run in parallel mode before implementation. For conciseness, results from this final combined testing will mostly be used as illustrations.

Numerical formulation

a) Problems in the T213 model

In September 1991, ECMWF began the operational use of a high resolution model with a spectral triangular truncation at 213 wavenumbers and 31 levels in the vertical. This model used a semi-Lagrangian treatment of the advection in which a three-dimensional interpolation was needed to the departure point of each semi-Lagrangian trajectory (scheme SLI). However, a significant increase in the RMS error became apparent, and this was related to an excess of the eddy kinetic energy developing during the 10-day forecast. This could also be seen as an increase in the day-to-day forecast inconsistency. After much study, the semi-Lagrangian treatment was changed in August 1992 to a non-interpolating-in-the-vertical (SLNI) version in which part of the vertical advection is treated in an Eulerian rather than semi Lagrangian way. This scheme (together with later radiation changes) significantly improved the energetics and levels of consistency.

Nevertheless, the SNLI scheme was not free from problems, the most obvious one being the occurrence of noisy vertical structures when an Eulerian treatment of advection is applied with irregularly spaced model layers.

One hypothesis to explain the improved eddy energy characteristics in the SLNI version compared to the SLI version was that the vertical structures which appear in the former and not in the latter could make the vertical diffusion work much harder, so producing a decrease of the eddy kinetic energy. However, a series of experiments run without vertical diffusion in the free atmosphere, both with the SLNI and with the SLI schemes, indicated that the effect of the vertical diffusion is not very different for the two semi Lagrangian versions.

Another possibility was that the increase in eddy kinetic energy is produced by over/under-shooting in the dynamical fields either from the spectral truncation of the fields (Gibbs phenomena) or the high order interpolation used in the semi-Lagrangian scheme. The SLNI scheme, which uses only bi-dimensional interpolations, should have less of a problem than the SLI which uses three-dimensional interpolations. Furthermore, the first order only accuracy in space of the Eulerian treatment of the vertical advection in the SLNI scheme could act as a damping mechanism for eddy kinetic energy, therefore compensating somewhat the excess produced by the horizontal interpolations. To test the relevance of the Gibbs phenomena, a series of experiments was run with a Gaussian grid in which the number of degrees of freedom is much closer to the number of degrees of freedom used in spectral space than in the standard Gaussian grid. In the semi-Lagrangian treatment of the advection there is no explicit calculation of quadratic advection terms and the problem of aliassing is not apparent for these terms. Using this ‘linear’ Gaussian grid, the Gibbs phenomena are greatly reduced but the increase in eddy kinetic energy remained.

If the excess eddy energy was produced by the over/under-shooting in the cubic semi-Lagrangian interpolations, then a shape-preserving or other form of monotonic interpolation should cure the problem. The quasi-monotone scheme proposed by Bermejo (1992) (with some improvements) was chosen as it is computationally inexpensive. With this technique, the SLI algorithm produced an evolution of the eddy kinetic energy during the forecast very similar to the one obtained by the SLNI procedure.

Another problem, independent of the advection scheme, was noise in the vertical velocity field at the lowest levels of the model in the vicinity of even quite small orographic features. Present in almost all forecasts, independently of the synoptic situation, it was particularly marked over the sea near Taiwan or in a circular pattern around Hawaii. An attempt was made to reduce this noise by increasing the horizontal diffusion in the model but this actually increased it.

Various tests were carried out which demonstrated that the problem of low-level noise in vertical velocity near orographic features was not due to some form of aliassing.

However, inspection of the spectra of vorticity and divergence at the lowest model level of a T213 forecast after 24 hours of integration shows that the shape of the high wave-number part of both fields is clearly different, Fig 1. The one for divergence is ‘raised’ relative to that of vorticity. ‘Lowering’ the high wavenumber tail of the spectral representation of the orography through the application of a high (8th) order diffusion operator resulted in a close matching of the tails of the spectra of vorticity and divergence. The corresponding low-level vertical velocity fields exhibited none of the noise seen previously. More details of the above experimentation can be found in Hortal (1994).

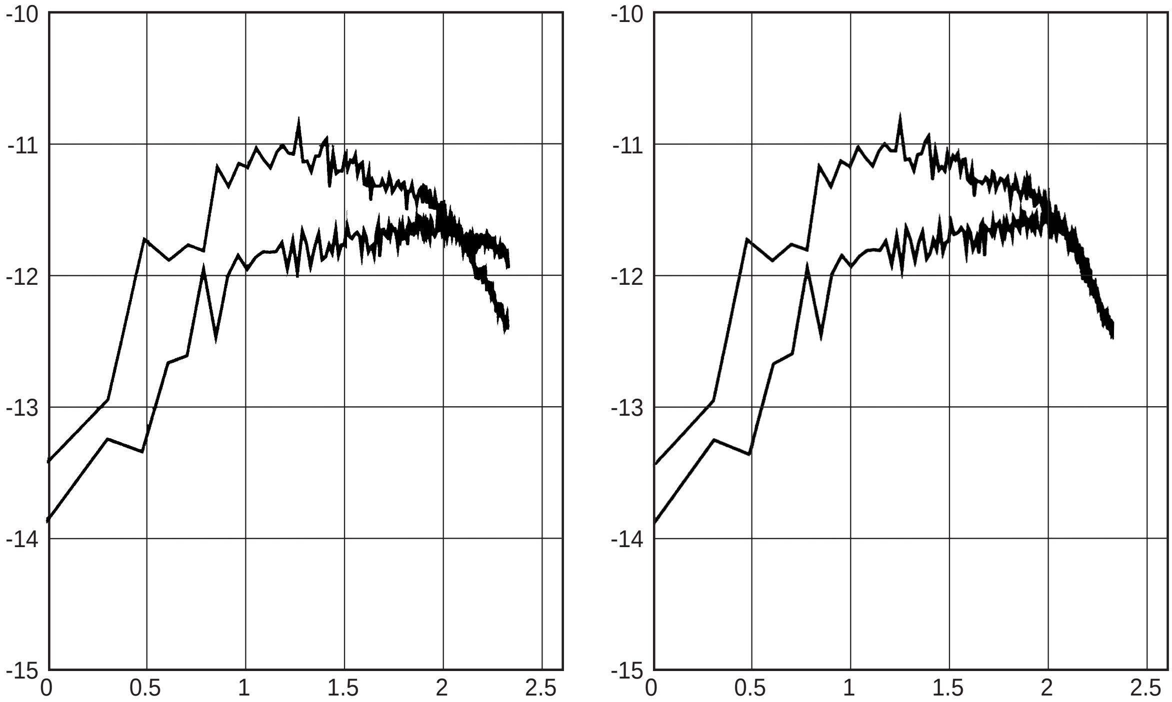

Fig. 1 Spectra of vorticity and divergence at model level 31 of a T213 forecast. Left is unsmoothed and right with smoothed mean orography.

b) Changes

As a result of the above diagnostics, it was proposed switching back to the SLI version of the model in operations but using quasi-monotone interpolations. However, when applied to the vertical interpolation of the temperature field, this produced a ‘smoothing’ of the tropopause leading to a large warm bias. Similarly, the application of the quasi-monotone procedure in the vertical interpolation of the wind fields led to large errors at the position of the stratospheric maximum of the tropical zonal wind (QBO). Since the largest contribution to the improved eddy kinetic energy statistics came from the quasi-monotone procedure in the horizontal, a fully interpolating semi-Lagrangian scheme, using the quasi-monotone procedure in the horizontal part of the interpolations only was chosen.

A further change is that the humidity field is no longer transformed to spectral space, therefore avoiding the introduction of Gibbs phenomena. The advection is handled by the semi-Lagrangian procedure with quasi-monotone cubic interpolation in three dimensions. This ensures that no unphysical negative value of the humidity arises, and the need to correct for negative humidities can only occur from the integration of the moist parametrizations.

Finally, an advective treatment of the Coriolis term in the momentum equation, first proposed by Rochas at Météo-France, has been introduced. In this treatment, the term is $2\vec{\Omega} \wedge \vec{v}_h$ is expressed as $\frac{d}{dt}\ 2\vec{\Omega} \wedge \vec{r}$ and added to the total time derivative of the horizontal wind.

The new prognostic cloud scheme

An important change in cycle 13R4 is the introduction of the new prognostic cloud scheme. The scheme was developed by Tiedtke (1993) and is based on two prognostic equations for cloud liquid water/ice and cloud fraction, respectively. Subsequent modifications and testing are summarised in Jakob (1994). The scheme is process-oriented, i.e. source and sink terms are linked to processes known to produce or dissipate clouds. The comprehensive nature of these component processes is summarised in Fig. 2 and discussed in the following paragraphs.

The generation processes include condensation due to large-scale ascent, cumulus convection, boundary layer turbulence and radiative cooling. Cloud dissipation is accounted for through evaporation due to large scale descent, cumulus-induced subsidence, radiative heating and turbulence at both cloud tops and sides, as well as through precipitation processes. The schemes thus give strong linkages between the physical and dynamical processes in the model.

The link to cumulus convection is achieved by considering convective clouds as being produced by the detrainment of updraught condensates into the environmental air. This description of convective clouds is an important part of the cloud scheme, and, by representing stratiform clouds produced by convection, forms a substantial extension of the cumulus convection parametrization as well. It leads to a much more realistic description of the different types of convective clouds such as precipitating and non-precipitating cumuli, cumulonimbus clouds, anvils and cirrus debris from convective processes.

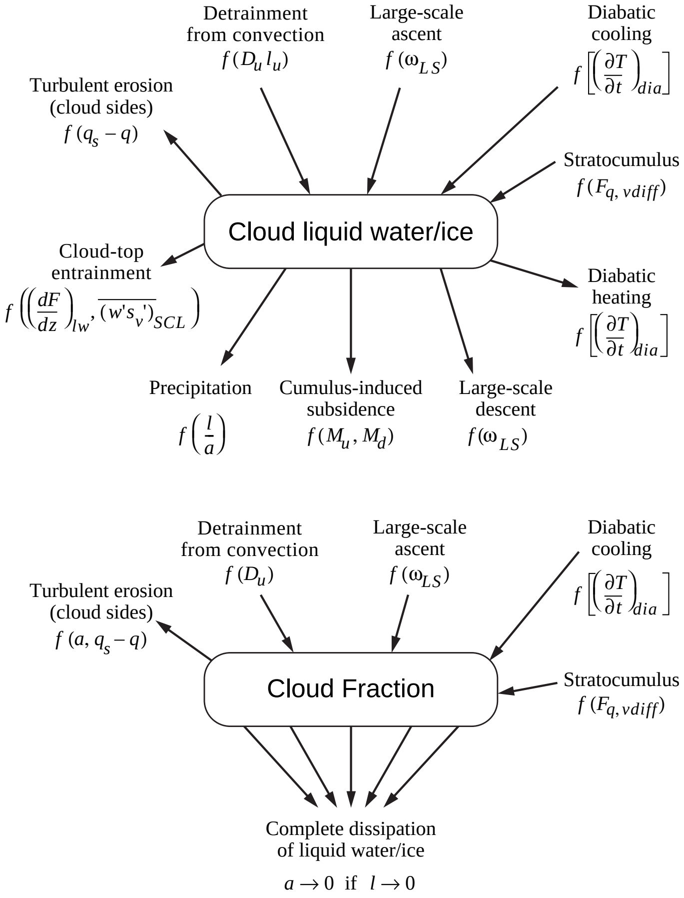

Fig. 2 A summary of the processes incorporated in the prognostic cloud scheme.

Stratocumulus clouds are also specifically included in the scheme. They are represented through the linkage of the scheme to the boundary layer moisture flux produced by the vertical diffusion scheme. Cloud top entrainment processes are taken into account as a function of buoyancy in the mixed layer.

The formation of stratiform clouds is determined by the rate at which the saturation specific humidity decreases due to upward vertical motion and radiative cooling.

Evaporation processes are accounted for in several ways. A main contribution to evaporation is determined by the rate of increase of saturation specific humidity caused by large-scale and cumulus induced subsidence and radiative heating. Turbulent processes lead to evaporation at the cloud sides proportional to the saturation deficit in the grid-box. Turbulent evaporation at cloud tops (entrainment) is represented through a dependency on the radiative cooling rate.

Precipitation processes use simplified microphysical formulations; these relate the generation of precipitation to the local cloud water/ice content and also take into account the main precipitation enhancement processes such as the Bergeron-Findeisen mechanism, collision and coalescence.

The scheme described above is unique in treating the main cloud-related processes in a consistent way by forecasting both cloud fraction and cloud water/ice content with prognostic equations. The strong coupling of the cloud to the other parametrized processes provides a potentially powerful diagnostic capability for further refinement of the overall model physics.

The representation of orographic effects

The ECMWF model has used an ‘envelope’ orography since 1983 whereby the grid square mean height is enhanced by an amount proportional to the standard deviation of the sub-grid scale heights. This has provided positive impact on the forecast dynamics at the expense of significant loss of low-level data availability due to the mismatch between model and actual station altitudes. Additional problems associated with the use of an envelope orography have been identified; these include a contribution to warm continental biases in forecast temperatures, overprediction of convective precipitation and the spurious broadening and intensification of heavy rain events associated with orographic forcing. Consequently these problems have been met by reverting to a smoothed mean orography (see earlier) together with a new sub-grid scale orography parametrization scheme to combine, and improve on, the benefits of both orographies.

a) Sub-grid scale orography scheme

The new scheme is designed to represent nonlinear low-level mountain drag together with the already familiar ‘gravity wave drag’ due to the propagation and dissipation of orographically-excited waves. An important and novel part of the scheme is that it explicitly represents the blocking of low-level flow and the associated form drag due to flow separation caused by sub-grid scale orography that is assumed to intersect the model levels. The depth over which this drag is parametrized is determined by the height of the sub-grid orography and an inverse Froude number characterising the flow at any given location and time. Flow above this ‘blocked’ layer goes over the orography and can generate gravity waves. Extensive use of PYREX data has been made to examine these ideas, to adjust the parameters of the scheme and to verify T106 and T213 forecasts of drag and momentum profiles above the Pyrenees.

Orography data is provided in the form of four grid-point fields describing the height, orientation, anisotropy and slope of the sub-grid scale orography together with the grid scale mean heights. The combination of *mean* orography and this new scheme has been shown to be equal or superior to that of envelope orography plus the old gravity wave drag scheme while no longer suffering any disadvantages of envelope orography.

Since the new scheme influences the flow well above the mean orographic height, it is possible to derive an ‘effective’ orography increment generated by the scheme which can be interpreted as additional to the mean resolved orography. An example, computed as a ten-day forecast mean, is shown in Fig. 3 together with the basic mean orography. Complete details of the scheme, its development and testing can be found in *Lott and Miller* (1995) and *Baines and Palmer* (1990).

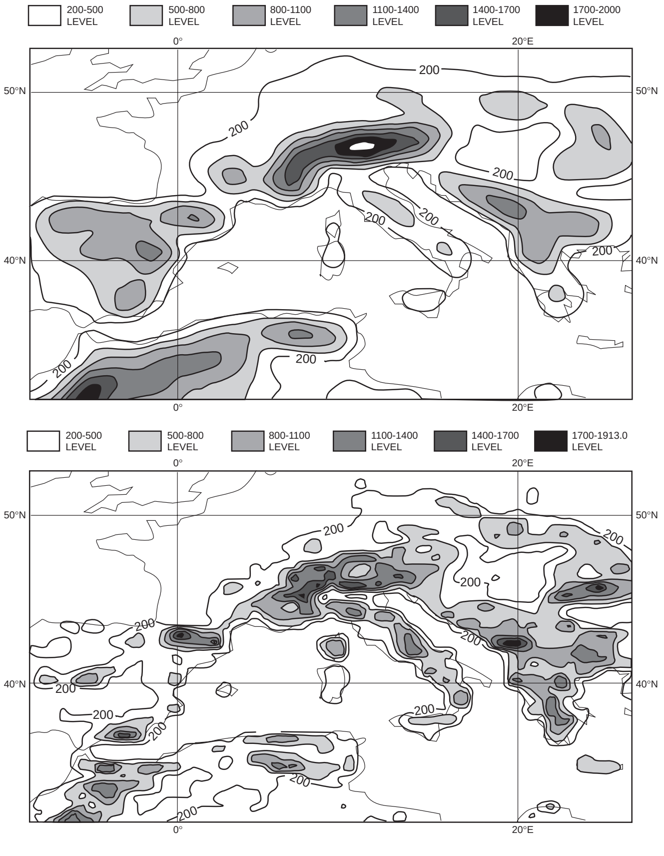

Fig. 3 The smoothed mean orography for the T213 model (top), and (bottom) the ‘effective’ T213 orography increment implied by the new subgridscale orography scheme. (Computed as a ten-day forecast mean, initial date 15/1/95.)

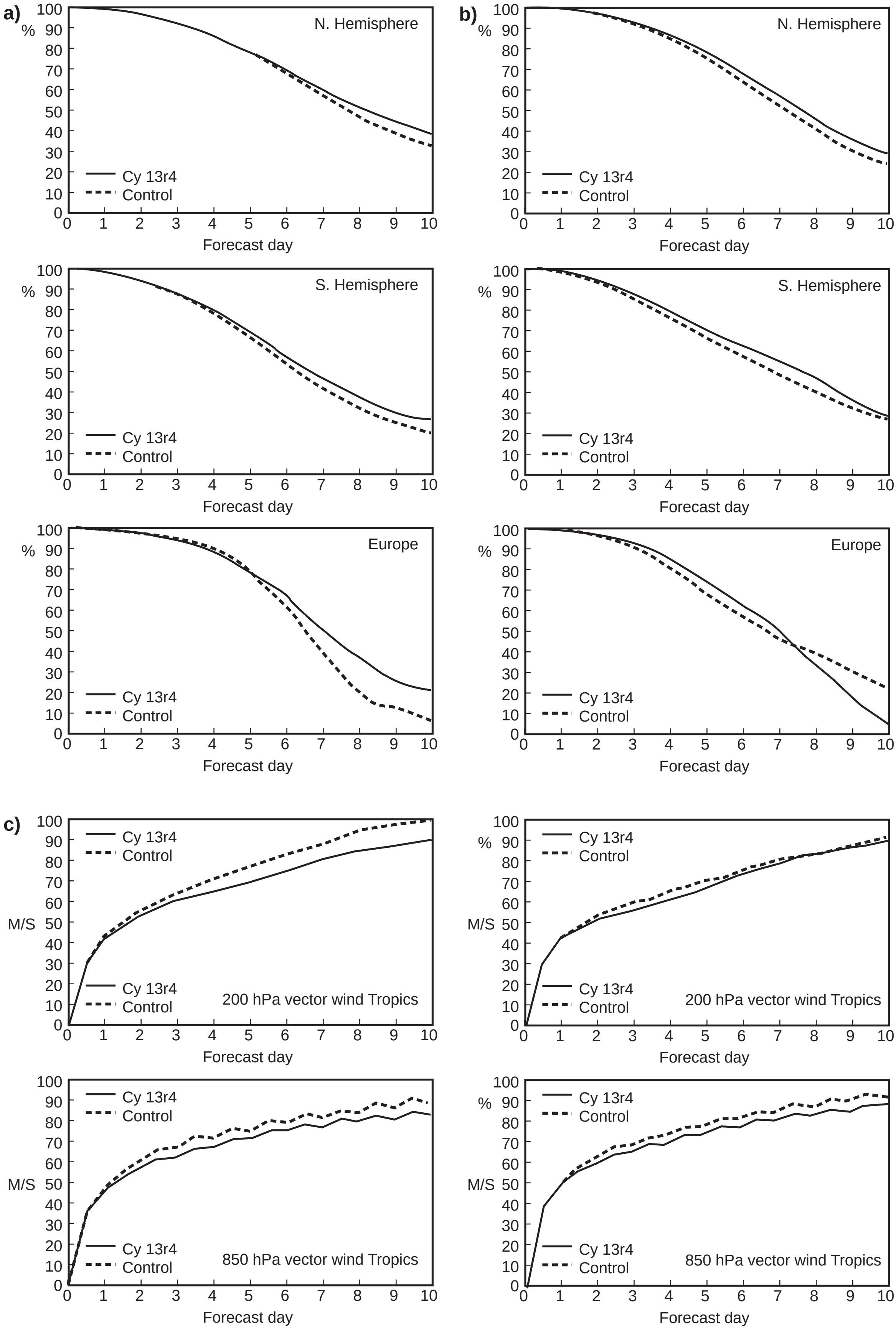

Fig. 4 a) 500 mb height anomaly correlations for the December E-suite (21 forecasts). b) As a) for the June E-suite (20 forecasts). c) Tropical wind RMS scores. LHS from June, RHS from December.

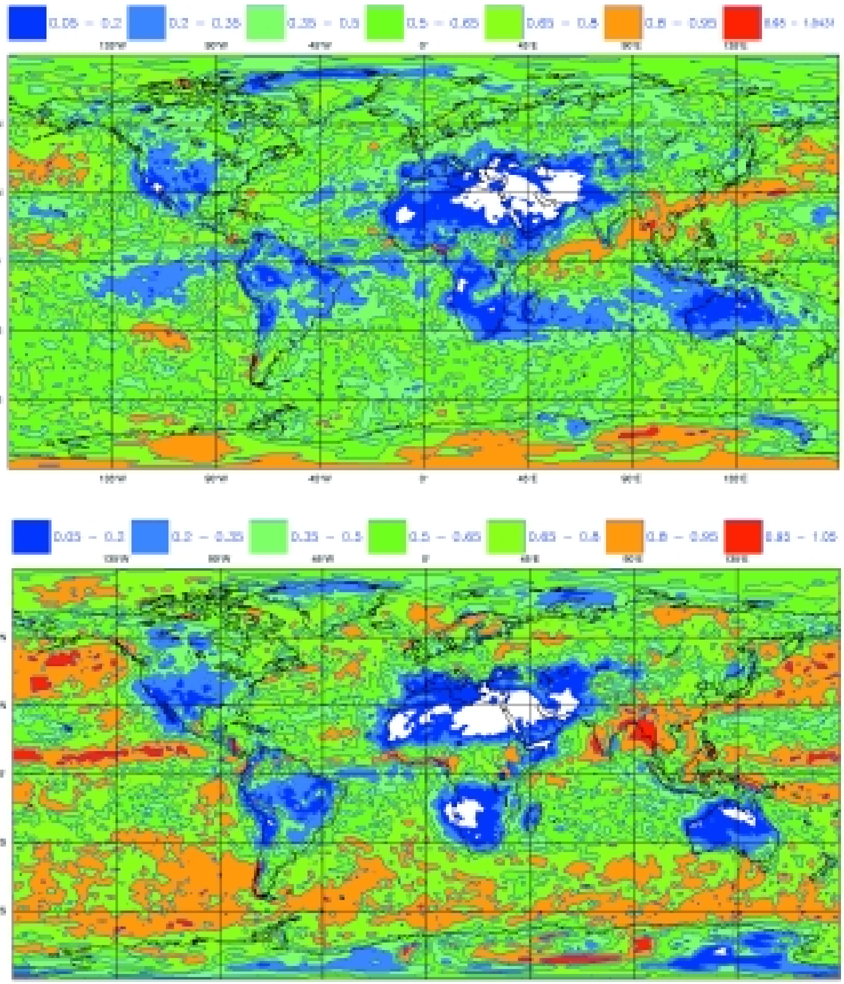

Fig. 5 Upper: Total cloud cover averaged over all (D+5) operational forecasts for the June period (1/6/94-20/6/94). Lower: As above but for the new cycle.

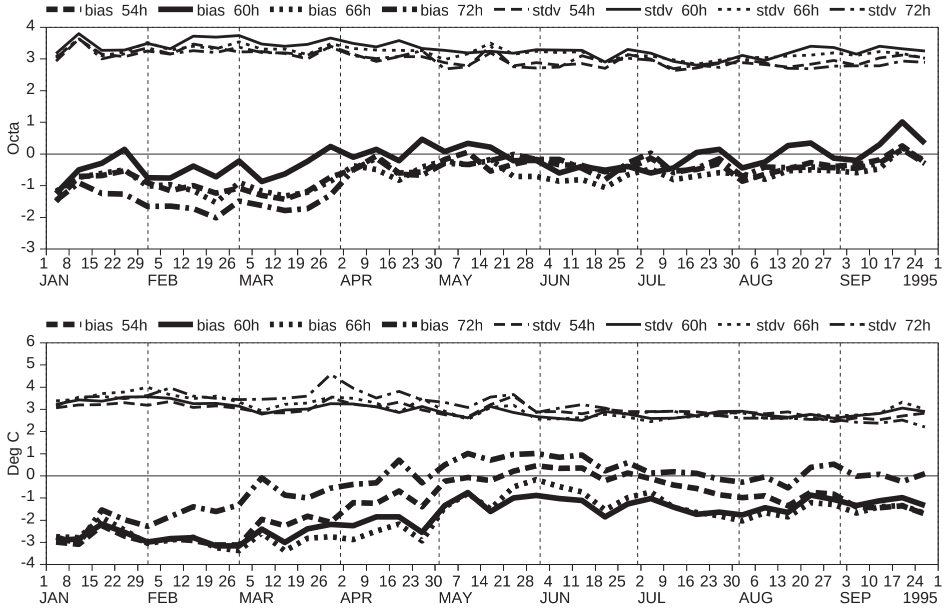

Fig. 6 A weekly time series of the biases of forecast cloud cover and two-metre temperature as calculated against European SYNOP reports.

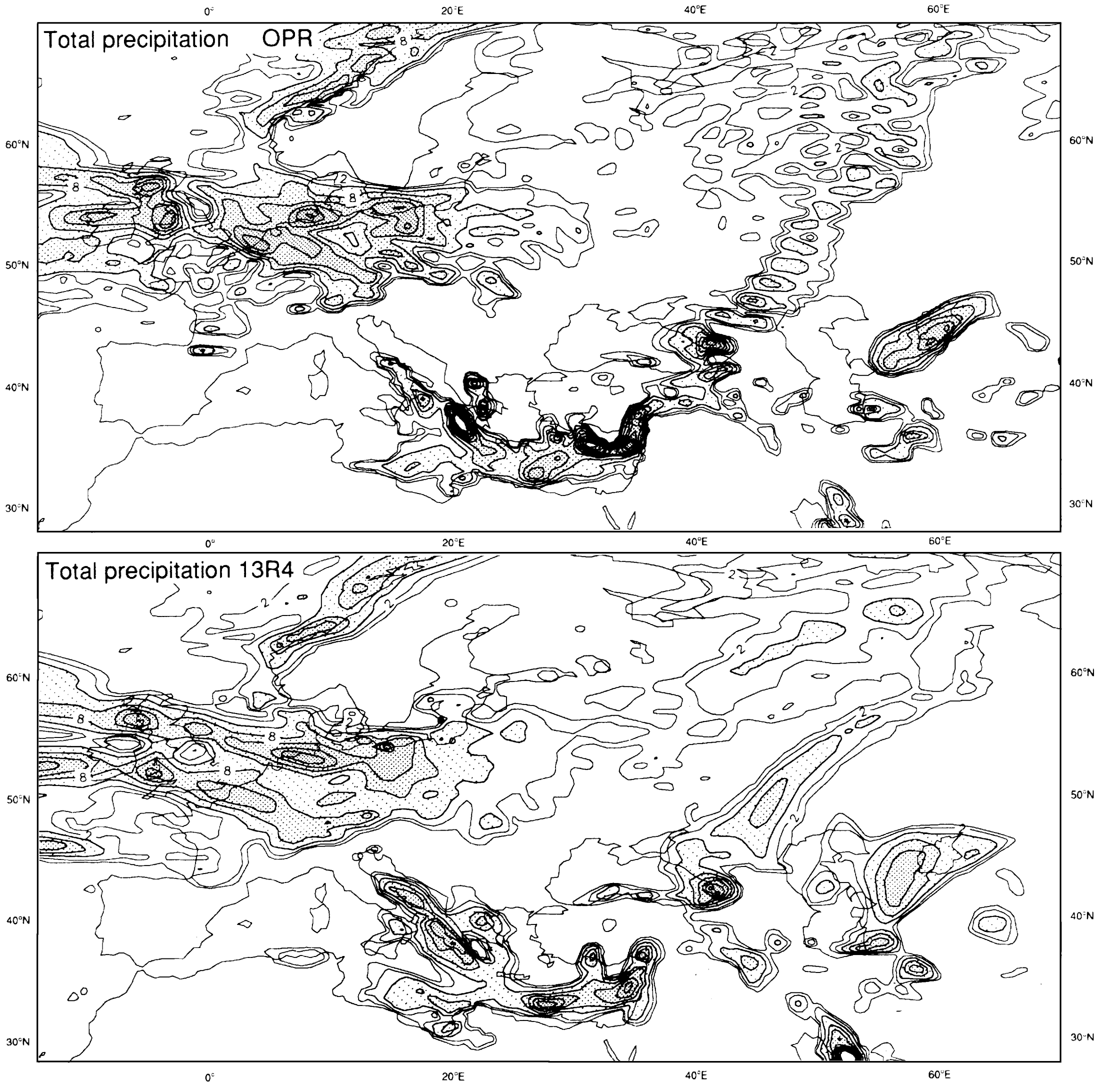

Fig. 7 Forecast model 24 hr precipitation fields for the 48-72 hr forecast. Upper: Operations - initial date 5/11/94. Lower: New cycle.

Summary of results

Prior to operational testing, two periods of approximately three weeks each (initial dates 1/6/94 and 6/12/94) were run with the full IFS. A selection of results follows which is chosen to illustrate the benefits of the new cycle in a variety of ways. Fig. 4 shows objective scores for the two E-suites referred to above, and it is encouraging to note improvements in skill for all areas. For the June period the comparison is made against the modified operations that included the soil moisture analysis described in the ECMWF newsletter (No. 69).

The new cycle has major impacts directly on the forecast cloud distribution and amount, and indirectly on near-surface parameters such as two-metre temperature. Although these are predominantly from the cloud changes, the other changes also contribute quite significantly.

Fig. 5 compares the total cloud cover for the mean of the twenty five-day forecasts made with the model operational in June 1994 (with the diagnostic cloud scheme) with the total cloud cover for the new cycle. Immediately apparent is the increased cloudiness particularly in the midlatitude storm tracks. There is also more cloud over the subtropical oceans (excessively so) and less over the subtropical desert areas. Although there is some improvement in the marine stratocumulus areas, these do not extend close to the coasts.

The impact of the new cycle on the cloud cover and two-metre temperature forecasts for Europe is shown in Fig. 6 which compares several forecast ranges against SYNOP observations.

Previous negative cloud biases of more than one okta before April 1995 have been reduced by about 50%, while the large daytime warm biases discussed in the previous newsletter have been substantially alleviated.

As an example of the impact of the reduced numerical ‘noise’ discussed earlier, Fig. 7 compares the 48 72 hr forecast precipitation fields (reflecting the smoother vertical velocities).

Operational experience since April 1995 has supported the above examples and the impacts both on skill scores and weather parameters have been generally good. This experience has also confirmed the improvements in precipitation distribution and amount particularly in the vicinity of mountain regions.

Such a major model change will inevitably exhibit new problems as well as solving or alleviating pre existing ones. However, the current model should provide an effective foundation for further development and refinement in the next few years.

Annex

Meteorologically relevant model changes:

- prognostic cloud scheme
- smoothed mean orography
- new sub-grid scale orography parametrization
- zenith-angle dependent ocean surface albedo
- fully interpolating semi-Lagrangian scheme
- averaging of the RHS of all equations along the trajectories using linear interpolation at the departure points for these terms
- advective form of the Coriolis terms
- quasi-monotone cubic interpolation in the horizontal for the (t-Dt) terms of all the equations and likewise in the vertical for moisture (q)
- use of (RT) rather than T as spectral variable
- grid-point specific humidity
- modified reduced Gaussian grid

Martin Miller, Mariano Hortal, Christian Jakob

References

Baines, P G and T N Palmer, 1990: Rationale for a new physically based parametrization of sub-grid scale orographic effects. ECMWF Tech Memo 169.

Bermejo, R and A Staniforth, 1992: The conversion of semi Lagrangian advection schemes to quasi-monotone schemes. *Mon Wea Rev,* 1**20,** 2622-2632.

Hortal, M, 1994: Recent studies of semi-Lagrangian advection at ECMWF. ECMWF Tech Memo 204.

Jakob, C, 1994: The impact of the new cloud scheme on ECMWF’s integrated forecasting system (IFS), Proceedings of ECMWF/GEWEX workshop on modelling, validation and assimilation of clouds, ECMWF, November 1994.

Lott, F and M Miller, 1995: A new sub-grid scale orographic drag parametrization: its formulation and testing. Submitted to QJRMS.

Tiedtke, M, 1993: Representation of clouds in large-scale models. *Mon Wea Rev,* **121,** 3040-3061.