
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 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 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

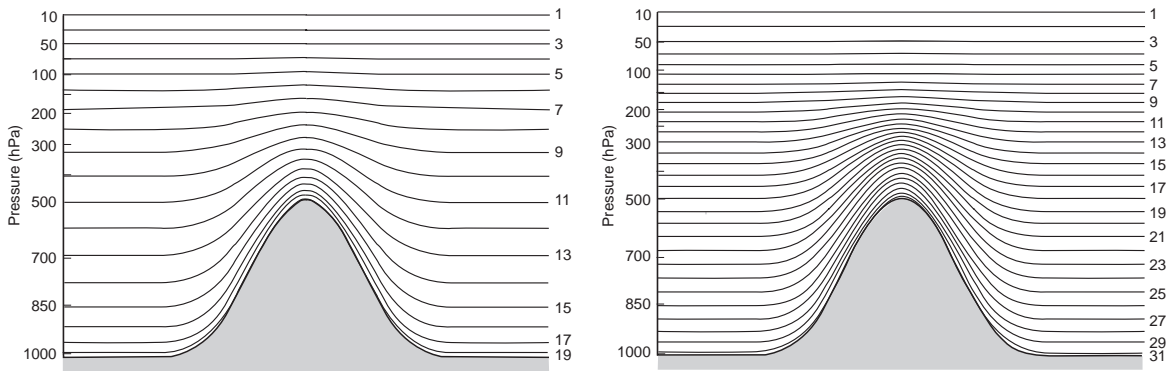


Fig. 1 The 19- and 31- level vertical resolutions

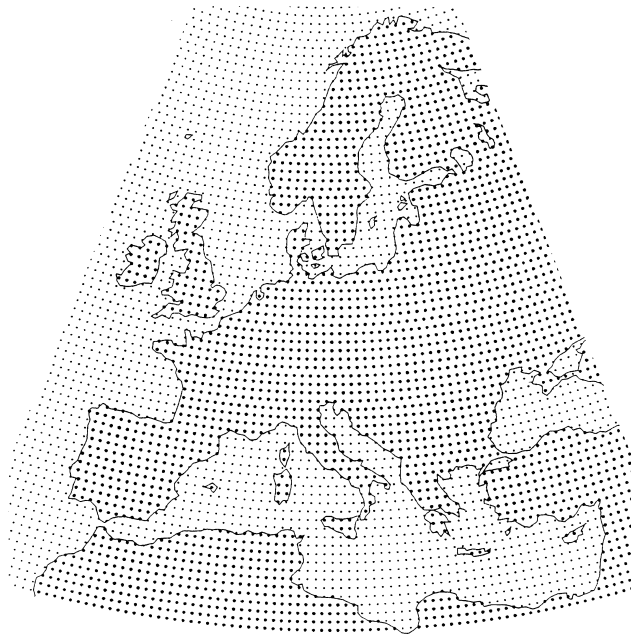


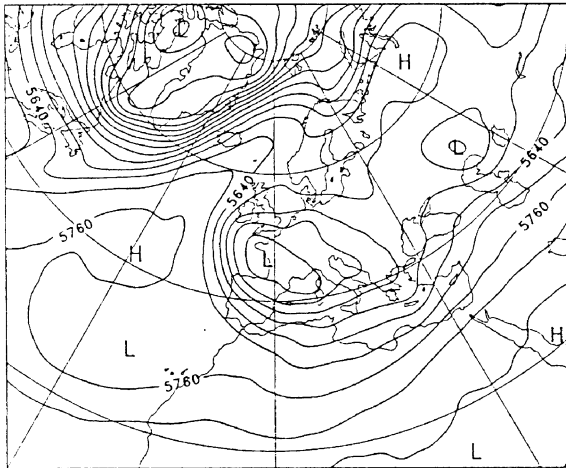
Fig. 2 The reduced grid over Europe for T213 resolution. Heavier dots indicate grid-points treated as land in the model and lighter dots indicate sea points

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.

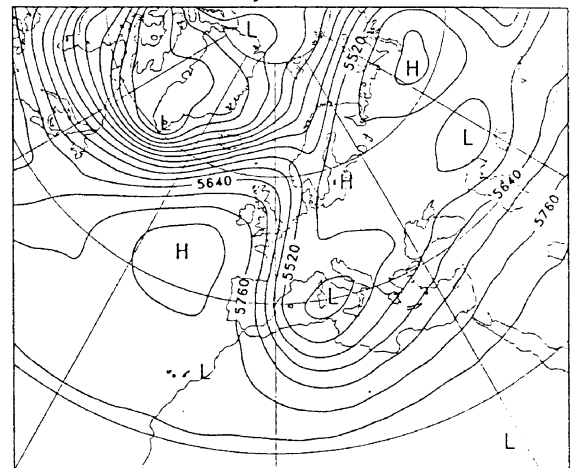
Experimental results providing a completely rigorous comparison between Eulerian and semi-Lagrangian forecasts at T213/L31 resolution are not available. Some parametrization changes were made in the course of development of the semi-Lagrangian version, and it has not been feasible to rerun earlier Eulerian 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 the differences between either of these forecasts and the T106/L19 forecast. This case also serves as an example of a significant improvement in forecast accuracy due to use of the higher resolution.

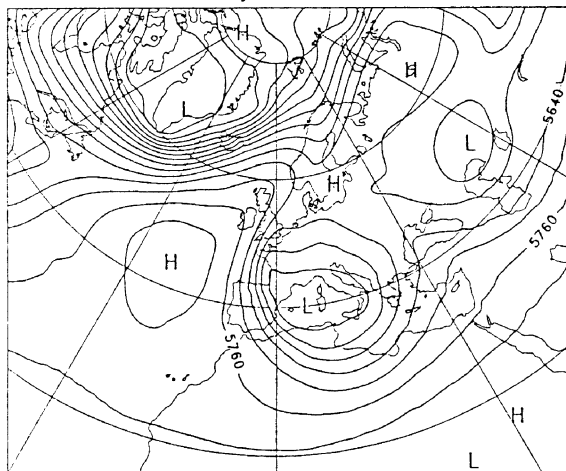
500 hPa Z Verifying analysis



500 hPa Z EUL Day 5 T106L19



500 hPa Z EUL Day 5 T213L31



500 hPa Z SL Day 5 T213L31

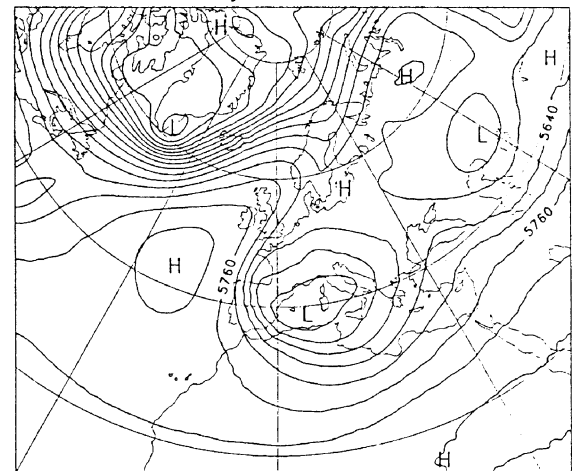


Fig. 3 The analysed 500 hPa height (upper left, contour interval 60m) for 20 April 1990, and day-5 forecasts verifying at this time for: Upper right, T106/L19, Eulerian, $\Delta t=15$ min, lower left, T213/L31, Eulerian, $\Delta t=3$ min, lower right T213/L31, Semi-Lagrangian, $\Delta t=20$ min.

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/LI-9 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 synopticscale 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.

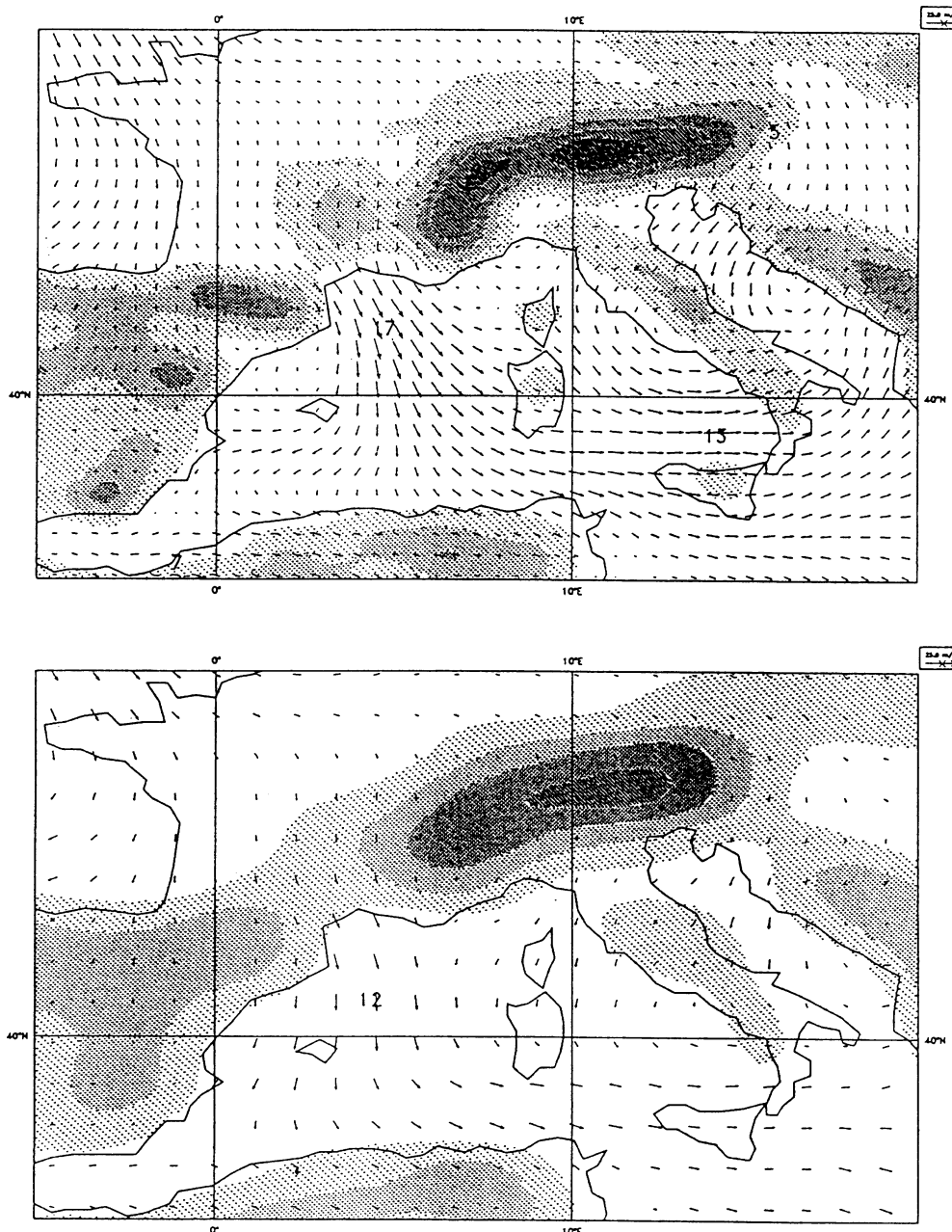


Fig. 4 Day-3 forecasts of 10m wind (m s^{-1}) from 12 UTC 15 April 1991 for T213/L31 (upper) and T106/L19 (lower). Model orographies are indicated by shading.

The increases arise both from the changed horizontal and vertical resolution, and from a change in the parametrization of clouds and radiation (Morcrette et al., 1991) that was introduced operationally at the same time as T213/L31 resolution.

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.

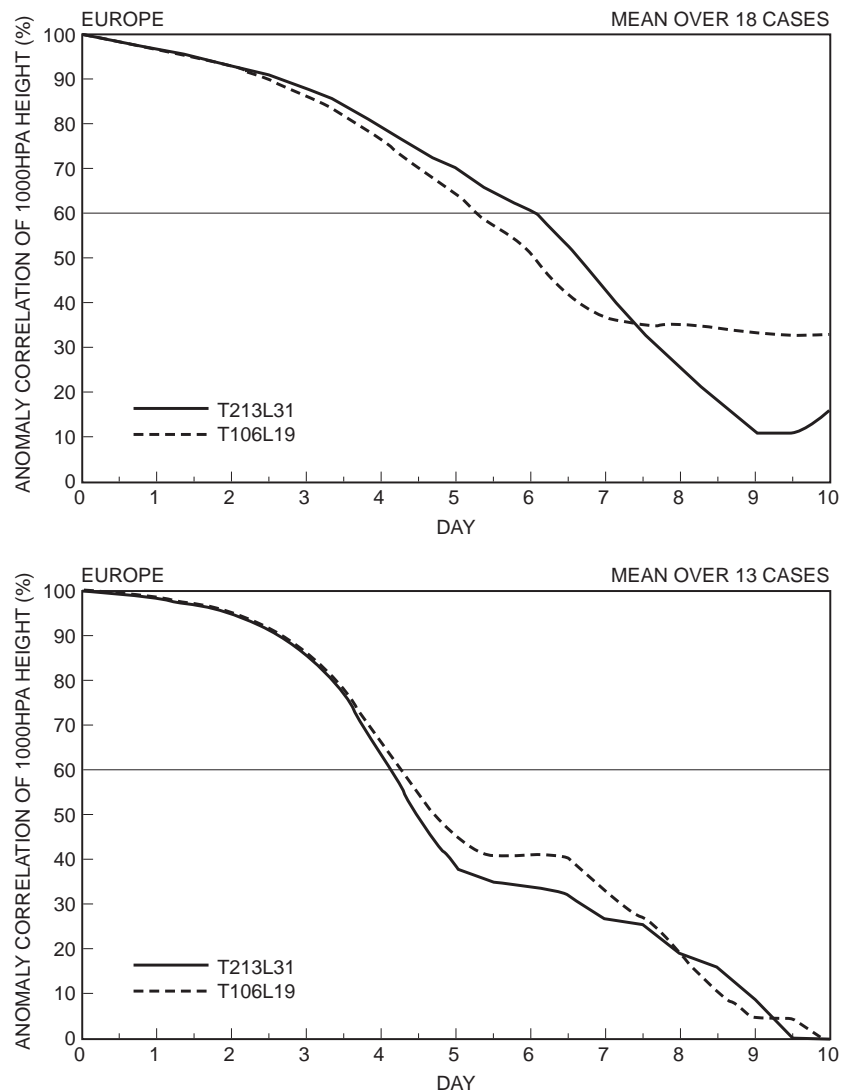


Fig.5 Mean anomaly correlations of 1000 hPa for the European region for the new T213/L31 model (solid lines) and for the operational T106/L19 model (dashed lines) based on the parallel runs carried out in July (upper) and September (lower)

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.

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