Aspects of stratospheric modelling at ECMWF

Agathe Untch
European Centre for Medium Range Weather Forecasts
Shinfield Park, Reading, UK

1. Introduction

ECMWF is planning to introduce soon into operations a version of the model with 50 vertical levels which spans the atmosphere up to 0.1 hPa.

In the process of designing and testing this vertically extended model several problems related with the numerics were encountered in the stratosphere.

A notorious area where numerical problems are most likely to develop is near the strong polar night jets mainly in the southern hemisphere where wind speeds of up to 150 m/s are not uncommon in models and wind gradients are strong. Problems we encountered with numerical noise in this area are discussed in this volume by M. Hortal.

Another area where we found problems related with numerics was, quite surprisingly, the tropical stratosphere. In this paper we will report and discuss mainly aspects related to these problems.

2. Sensitivity of the zonal circulation in the tropical stratosphere to vertical resolution

When plans were made to raise the top of the ECMWF model from 10hPa into the mesosphere at about 0.05 hPa a target for the total number of vertical levels of about 40 to 45 was set for reasons of computational affordability and economy. The current operational model with top at 10 hPa has 31 levels in the vertical of which 26 are located below 100 hPa ensuring a good resolution in the troposphere. Since the tropospheric resolution was, of course, not to be degraded in the new model, only 14 to 19 levels were available to resolve the atmosphere from 100 hPa to 0.05 hPa (about 55 km), too few to have a uniformly good resolution throughout the stratosphere. In order to ensure a smooth transition from the high resolution in the troposphere and resolve the lower stratosphere well, the levels were spaced more closely there than in the upper stratosphere and mesosphere. More precisely, the levels were spaced in such a way that the layer thickness expressed in log(p) was increasing with height quadratically above 100 hPa. Below 100 hPa the distribution of levels was kept the same as in the 31-level model.

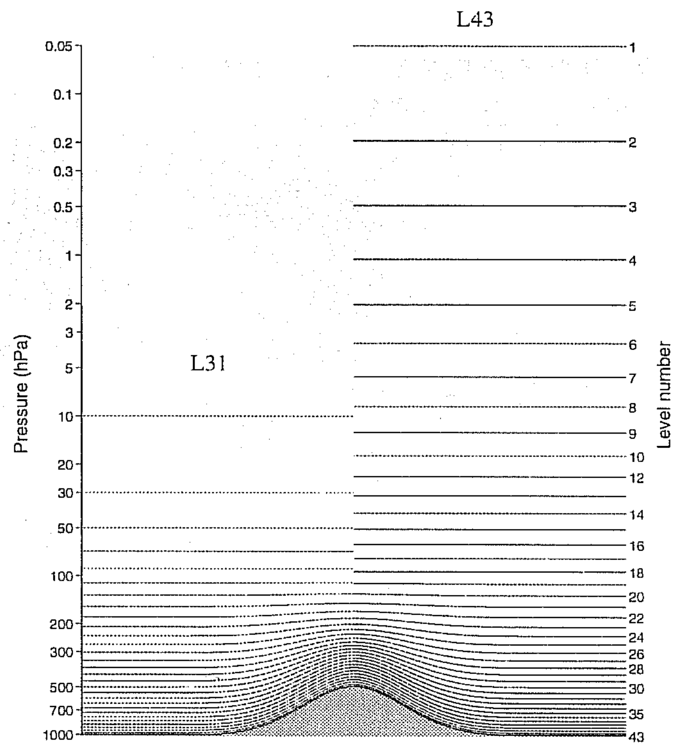

Fig. 1 Distribution of levels in the 43-level version of the ECMWF model compared with the level distribution in the operational 31-level version.

Figure 1 shows the level distribution obtained in this way and compares it to the 31-level distribution. The total number of levels arrived at was 43. Note the substantial increase in resolution between 100 hPa and 10 hPa.

When this 43-level model was used in climate runs a very surprising problem was found in the tropical stratosphere. Figure 2 shows the zonal mean zonal wind after half a year of integrating the model at horizontal resolution T63 with the semi-Lagrangian advection scheme [Ritchie et al., 1995] starting from 1 January 1995 and in figure 3 the verifying analysis provided by the UKMO [Swinbank and O'Neill, 1994] for 30 June 1995 is shown. In the extra-tropical stratosphere the agreement between the model and the analysis is reasonably good, bearing in mind that it is a six months forecast, but there is a striking difference in the tropics. The model has produced a strong westerly jet with a maximum of about 60 m/s at 10hPa and above the westerly jet far too strong easterly winds and a very sharp vertical wind gradient between the two wind regimes. In the verifying analysis for 30 June 1995 there is a weak westerly jet too, because the atmosphere in 1995 was in a westerly phase of the quasi-biennial oscillation (QBO), but the maximum is only about 11 m/s and it is located lower down near 35hPa. The simulated westerly wind is far in excess of what is measured for the zonal mean zonal wind in the tropical stratosphere. In the westerly phase of the QBO wind speeds reach only about 20 m/s [Pawson and Fiorino, 1998; Swinbank and O'Neill, 1994]. Moreover, the westerly jet in the model kept growing, when the integration was continued, and reached a staggering 120 m/s after a year and two months of integration with no

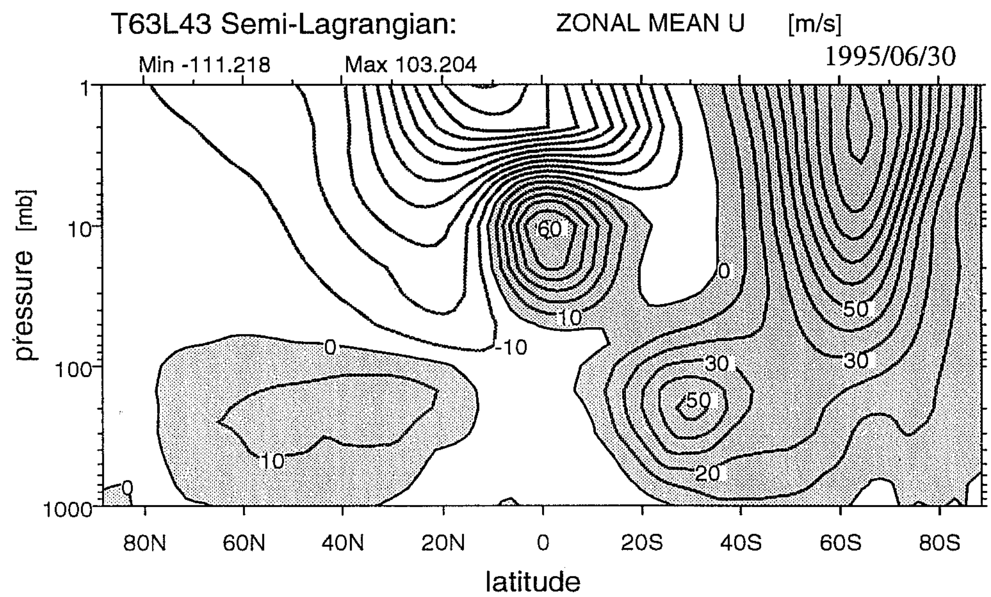

Figure 2. Zonal mean zonal wind generated by the 43-level model after 180 days of integration starting 1 January 1995. Westerly winds are shaded.

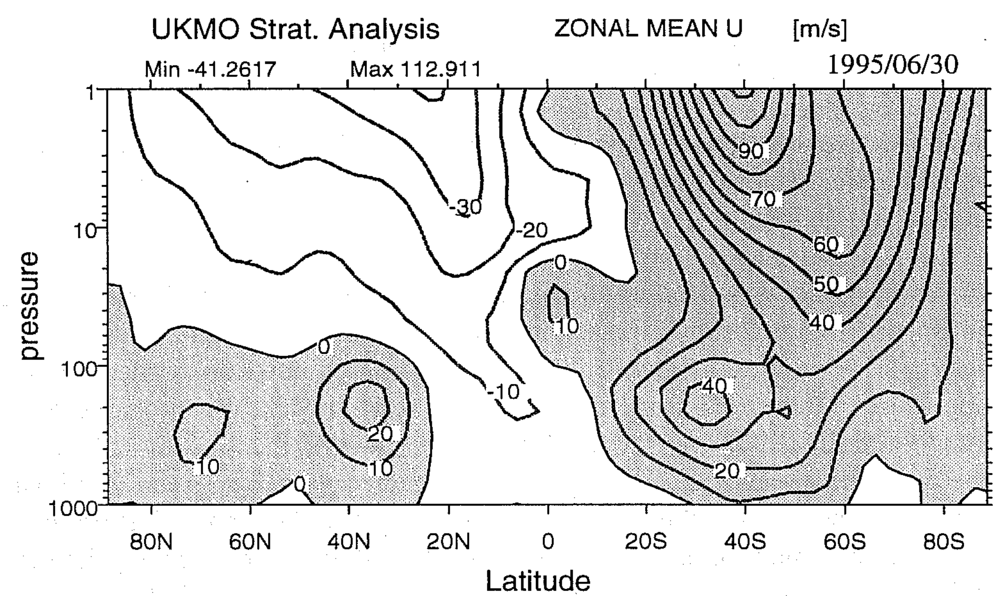

Figure 3. UKMO analysis for 30 June 1995. Westerly winds are shaded.

sign of slowing down the growth. The maximum of the jet remained at 10hPa and did not move downwards as is the case for the westerly and easterly wind regimes in the QBO. See figure 6 for a picture of the QBO as analysed by UKMO [Swinbank and O'Neill, 1994].

To our knowledge no other general circulation model (GCM) has experienced a similar problem with far too strong westerly winds in the tropical stratosphere. On the contrary, current GCM's have not been successful in simulating the QBO so far, mainly because they have difficulties generating westerly winds in the tropical middle stratosphere. In view of this, our problem with too strong westerlies in this region of the atmosphere seemed even more surprising.

A clue as to what might cause the problem came from the Holton-Lindzen theory of the QBO [Holton and Lindzen, 1972]. According to this theory the eastward and westward acceleration in the QBO is provided by eastward moving equatorial waves (mainly Kelvin waves) and westward moving equatorial waves (mainly mixed Rossby gravity waves), respectively. These waves are generated in the upper troposphere, propagate up into the stratosphere where they break and deposit their momentum in such a way as to produce an oscillation in the mean zonal flow over the equator. For a detailed explanation of this mechanism see for example Andrews et. al (1987).

If the strong westerly acceleration in the model at 10hPa is produced by upward propagating Kelvin waves too, then there must be a problem with the representation of these waves in the model. Kelvin waves measured in the atmosphere have vertical wavelengths of about 6 to 10 km [Andrews et. al, 1987]. If the Kelvin waves generated by the model near the tropopause are of similarly short vertical wavelengths they can be resolved well with the 43-level resolution only in the lower stratosphere and increasingly less well as they propagate upward because the spacing between the levels increases through the stratosphere from 1.2 km near 100 hPa to 2.5 km at 10 hPa and to 5 km at 1 hPa. The shorter Kelvin waves cannot be resolved properly in the vertical when they approach 10 hPa and the model must 'break' them here somehow and 'absorb' their momentum into the mean flow. If this sketchy picture of how the model generates the strong westerly jet is close to what really happens, then a significant increase in vertical resolution around 10 hPa should prevent the formation of this erroneous westerly jet.

To test this hypothesis, we created a new vertical resolution with a total of 50 levels and spaced the levels this time so as to have a uniform resolution of 1.5 km through most of the stratosphere. Figure 4 shows the variation of the layer thickness with pressure for the new 50-level resolution (L50) and compares it to that of the 43-level resolution (L43). The symbols on the curves mark the positions of the individual levels. The distribution of levels in the troposphere (below 100 hPa) is identical in the two resolutions and very similar in the lower stratosphere up to 50hPa. From 50hPa to 5hPa the spacing in L50 is constant at 1.5 km and increases above 5 hPa towards the top first gradually but then increasingly faster to save on the number of levels. For the same reason the top full level was lowered from 0.05 hPa to 0.1 hPa in the new model.

With this new vertical resolution we repeated the six months climate integration from 1 January 1995 and this time the strong westerly jet at 10 hPa did not develop. The maximum of the simulated westerly winds in the tropics on 30 June 1995 was located near 40 hPa and had a magnitude of only 7.5 m/s, in good agreement with the UKMO analysis for 30 June 1995 shown in figure 3.

Encouraged by this result we extended the integration for several years and the model generated an oscillation in the zonal wind of the tropical stratosphere not unlike the QBO. Figure 5 shows the evolution in time of the zonal mean zonal wind near the equator (at 0.93N) over 6 years obtained with the 50-level model integrated with the semi-Lagrangian advection scheme at horizontal resolution T63 and figure 6 shows for comparison the evolution of the tropical wind at 1.25N from January 1993 to September 1998 as analysed by UKMO [Swinbank and O'Neill, 1994]. Note that the model integration starts in January 1995 and extends into the future (to the

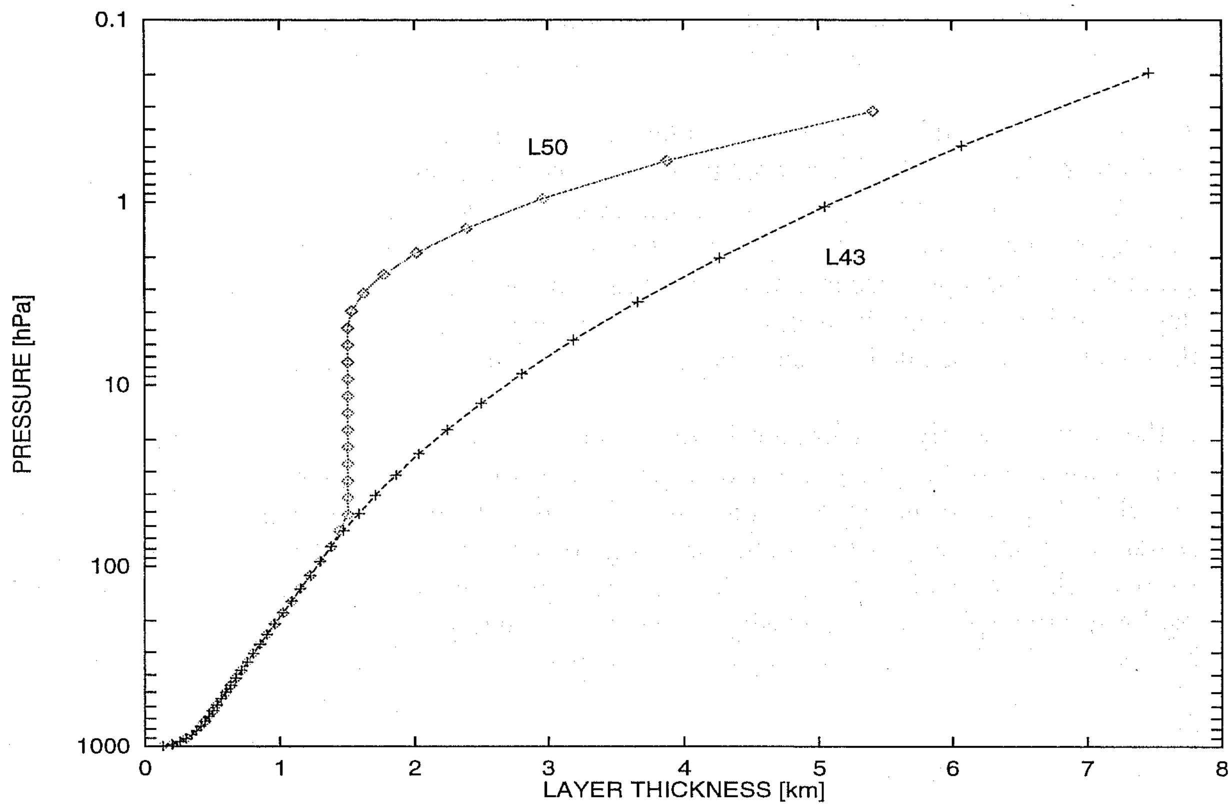

Figure 4. Variation of the layer thickness with pressure for the 43-level distribution (labeled L43) and for the 50-level distribution (labeled L50).

end of 2000), so only the first 3 years and 9 months of the run can be compared directly to the analysis. The model was forced with the observed sea surface temperature (SST) for the first two years (1995 and 1996), for 1997 and all following years the observed SST of 1996 had been used.

The simulated oscillation in the tropical zonal wind has all the main characteristics of the analysed QBO. Alternating regimes of westerly and easterly winds are generated near 10 hPa and move downward with time to almost the tropical tropopause where they are dissipated. The period of the oscillation is close to the observed period of about 26 months in average but is less regular in the model than in the analysis. The westerly phases are weaker than the easterly phase, as is the case for the QBO, but they are too weak reaching only about half the magnitude of about 15 m/s of the analysed winds.

Near 5 hPa the model generated a second oscillation in the tropical wind with a period of half a year reminiscent of the semi-annual oscillation (SAO) observed near the tropical stratopause (at 1hPa in figure 6). The amplitude of this oscillation is strongly modulated by the phase of the QBO-like oscillation, in agreement with the analysed SAO. Since the simulated semi-annual oscillation is located too low (at 5 hPa instead of at 1 hPa) there is a strong easterly bias at 1 hPa and also, there is not a clear separation between the QBO-like and SAO-like oscillation in the model.

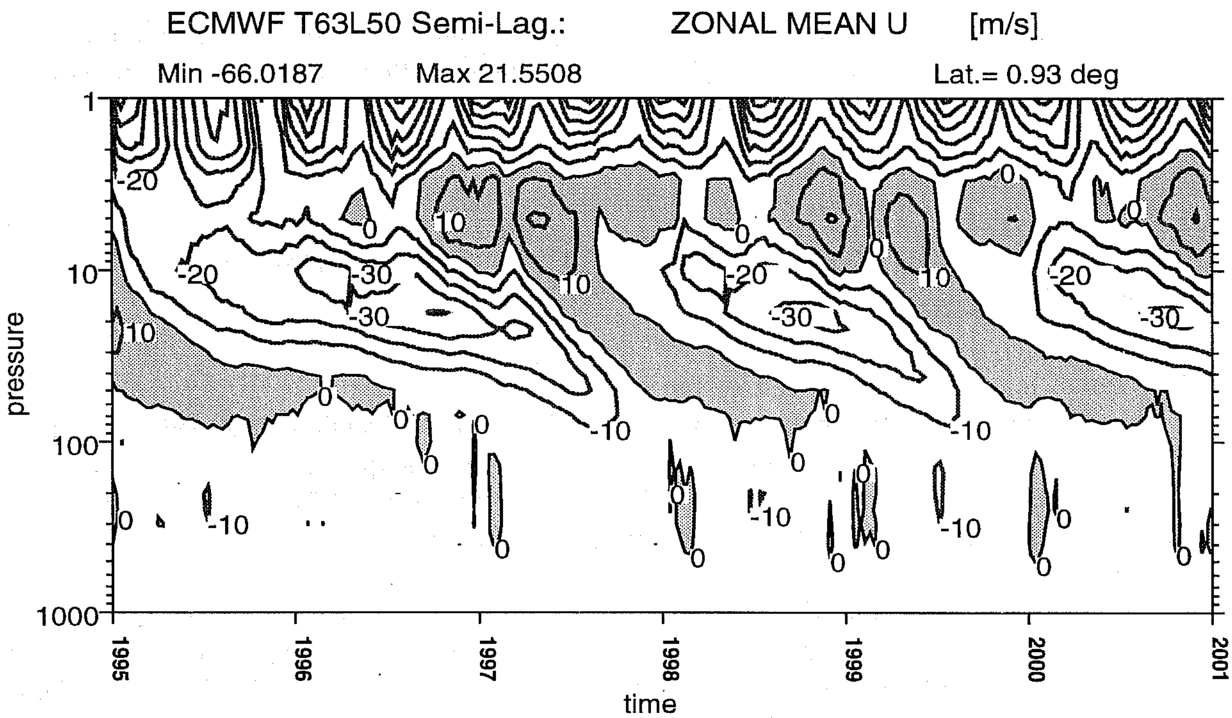

Figure 5. Time-height section of the zonal mean zonal wind at 0.93N from a model run with 50 levels at horizontal resolution T63 with the semi-Lagrangian advection scheme. Westerly winds are shaded.

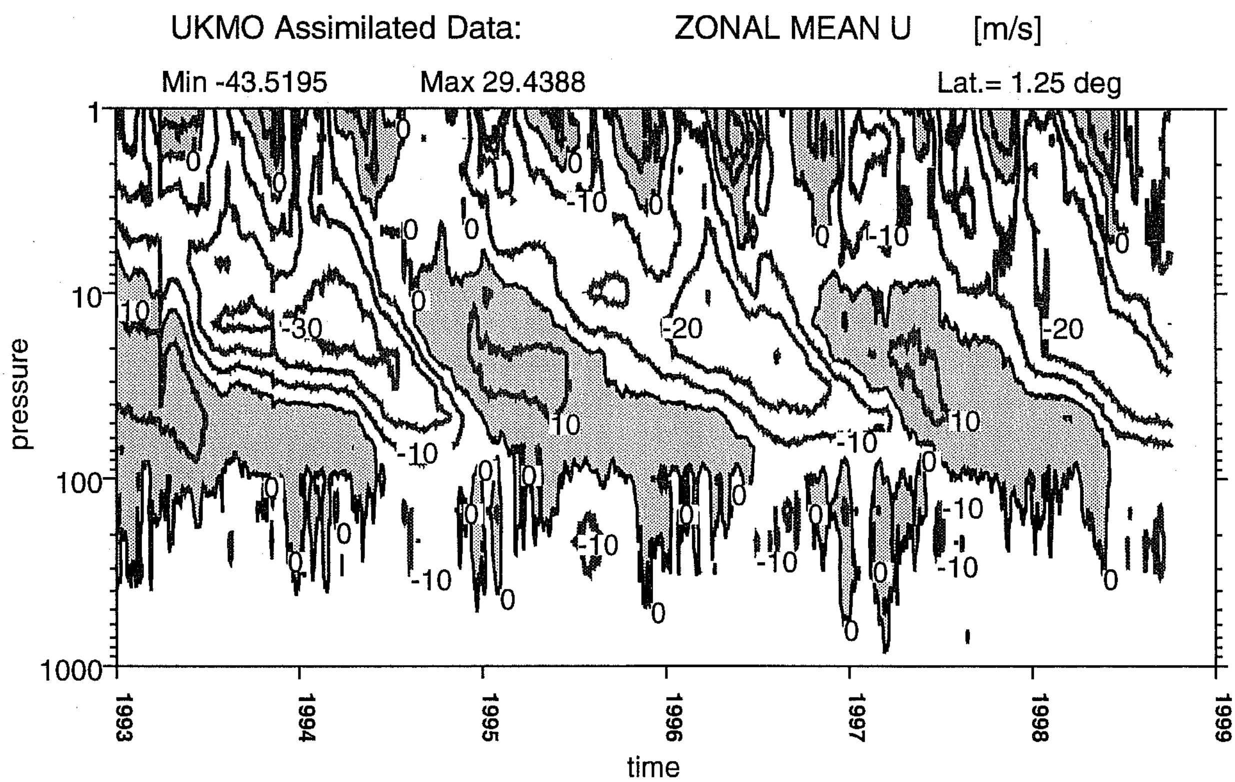

Figure 6. Time-height section of the zonal mean zonal wind at 1.25N from the UKMO analysis. Westerly winds are shaded.

In spite of these shortcomings, this is a surprisingly good simulation of the zonal circulation in the tropical stratosphere. To our knowledge, it has been the first time such a realistic QBO-like oscillation has been obtained with a vertical resolution in the stratosphere which is affordable at present by full state of the art GCM's.

3. Sensitivity of the zonal circulation in the tropical stratosphere to the advection scheme

The model integrations discussed so far had all been run with the semi-Lagrangian advection scheme more precisely, the three-time-level, fully-interpolating version described in Ritchie et al. (1995) with a time step of 30 minutes. With Eulerian advection quite different results for the wind in the tropical stratosphere were obtained. The time step used in all Eulerian runs discussed here was 7.5 minutes and the horizontal resolution T63, the same as in the semi-Lagrangian runs.

With the 43-level model and Eulerian advection [Ritchie et al., 1995] the very strong westerly jet at 10 hPa obtained with the semi-Lagrangian scheme did not develop, but neither showed the Eulerian scheme with the 50-level model any potential for generating a QBO-like oscillation as had been obtained with the semi-Lagrangian scheme.

Panel b) in figure 7 shows the time evolution of the zonal wind at 0.93N over a period of one year obtained with the 50-level model and the Eulerian advection scheme. In panel a) the evolution of the tropical wind during the first year of the climate run with the semi-Lagrangian scheme shown in figure 5 is reproduced to aid the comparison. Both runs were started on 1 January 1995 from the same initial conditions. In the Eulerian run the westerly winds disappear much quicker than in the semi-Lagrangian run or in the analysis (see figure 6) and are replaced by weak easterly winds which persist for the remainder of the run. An integration of only one year is too short to establish wether the Eulerian scheme generates a QBO-like oscillation or not, but the fact that the westerlies of the initial condition are maintained only for a few months does not look promising at all

The Eulerian scheme shows less tendency to generate westerly winds than the semi-Lagrangian scheme, suggesting a difference in the representation of the relevant eastward moving equatorial waves which are transporting westerly momentum into the stratosphere.

Panel c) of figure 7 shows the evolution of the equatorial wind obtained with an alternative version of the semi-Lagrangian scheme which avoids interpolation in the vertical [Ritchie, 1991]. The property of this scheme which is of interest in this context is the fact that in the stratosphere, where vertical velocities are small, the vertical advection is in fact Eulerian, only the horizontal advection is semi-Lagrangian. To see this consider the general advection equation (eq. 2.1 in [Hortal, 1998, this volume]) written in the following form:

$$\frac{d_H X}{dt} + (\dot{\eta}^*)\frac{\partial X}{\partial \eta} = R - (\dot{\eta} - \dot{\eta}^*)\frac{\partial X}{\partial \eta}$$

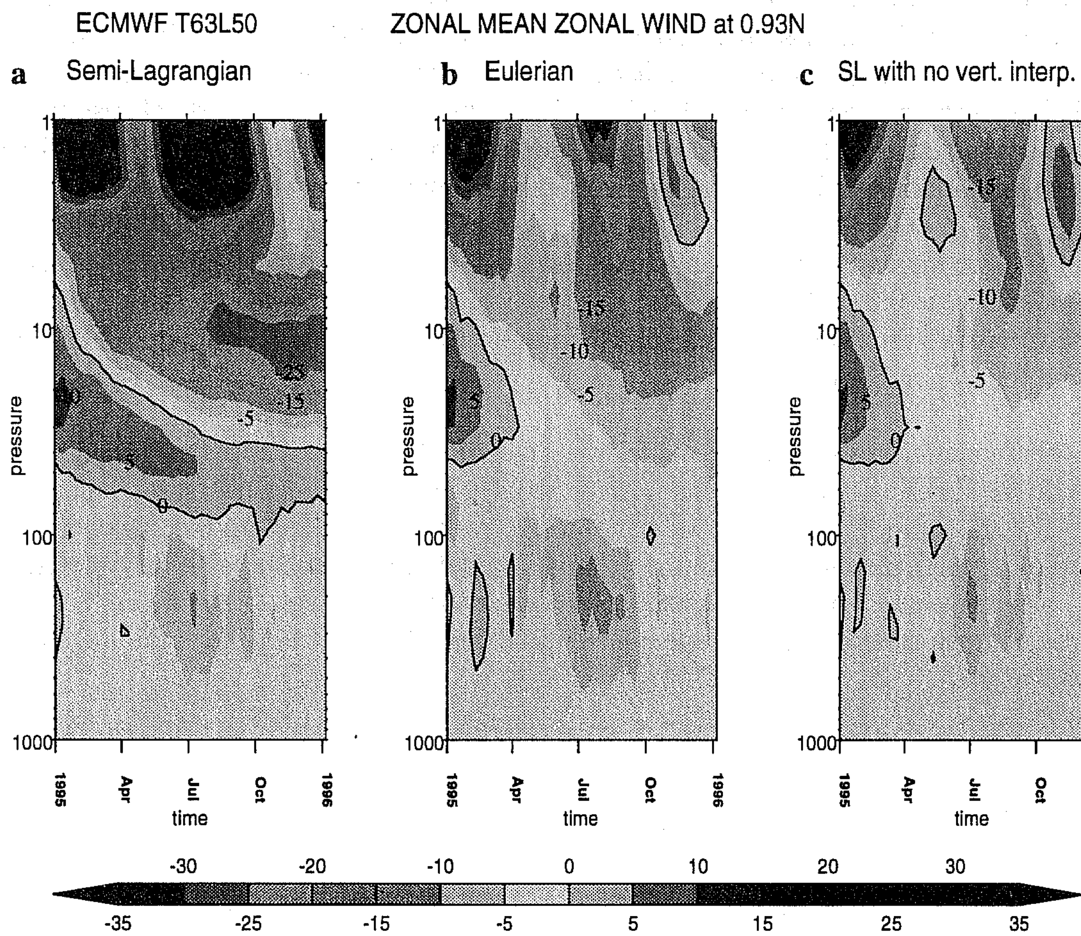

Figure 7. Time-height sections of the zonal mean zonal wind at 0.93N from runs with the 50-level model at T63 with the fully-interpolating semi-Lagrangian scheme (a), the Eulerian scheme (b), and the semi-Lagrangian scheme with no interpolation in the vertical (c).

The first term on the left-hand side of contains the partial time derivative of X plus the horizontal advection operator and $\dot{\eta}^*$ is a vertical velocity defined in such a way that the departure point of the trajectory lies exactly on a model level, so no interpolation in the vertical is needed to evaluate X at $t - \Delta t$ at the departure point. The price one has to pay is the additional vertical advection term on the right-hand side of the above equation which is treated in an Eulerian way. The model level from which the modified trajectory originates is chosen to be the level closest to the true departure point. When the true vertical velocity $\dot{\eta}$ is small, the true departure point is close to the arrival level, so $\dot{\eta}^*$ is chosen to be zero in this case and the vertical advection is purely Eulerian.

The westerlies obtained with this modified semi-Lagrangian scheme are very similar to the westerlies of the Eulerian integration, showing that the accuracy of the vertical advection plays a key role in a successful simulation of a QBO-like oscillation with a vertical resolution of 1.5 km in the stratosphere (50-level model).

The fact that the two different numerical schemes for the vertical advection give significantly different answers indicates that the vertical resolution of the 50-level model in the stratosphere is near the lower limit required for resolving the equatorial waves relevant for the QBO and simulating their upward propagation and breaking correctly. Increasing the vertical resolution should show a convergence of the two schemes, hopefully towards the result of the semi-Lagrangian scheme since at L50 this in better agreement with the analysis.

To test this, we increased the vertical resolution in the stratosphere to 1 km and also raised the top full model level to 0.01 hPa to check the influence of the position of the model top on the results. The new vertical resolution has 72 levels. Figure 8 shows the variation of the layer thickness with pressure for L72 and L50.

With this increased resolution the model was integrated for six months from 1 January 1995 at T63 with the Eulerian advection scheme and the fully interpolating semi-Lagrangian scheme. The results are shown in figure 9 and compared to the results obtained with the 50-level model. The westerlies in the Eulerian run with the 72-level model are quite similar to the westerlies of the semi-Lagrangian runs, but still decrease a bit faster then in the semi-Lagrangian runs. With the semi-Lagrangian scheme the westerlies have not changed significantly with the increase in vertical resolution.

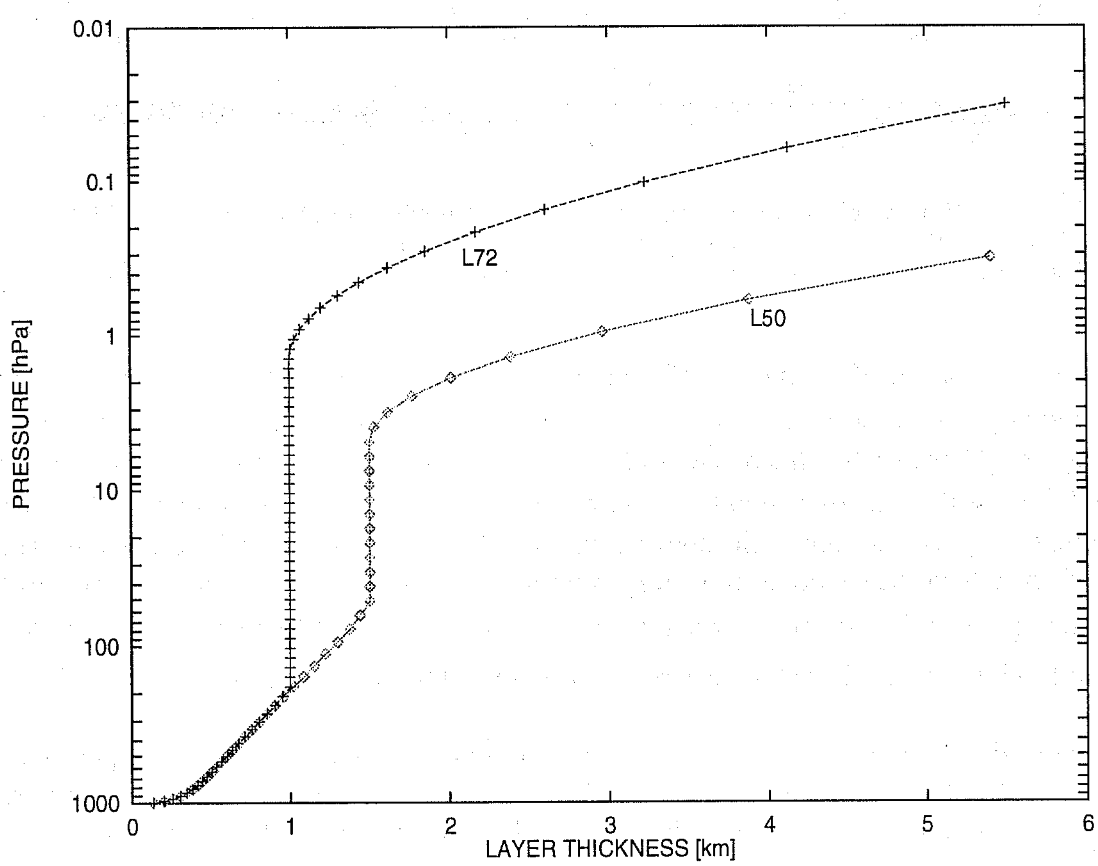

Figure 8. Variation of the layer thickness with pressure for L72 and L50.

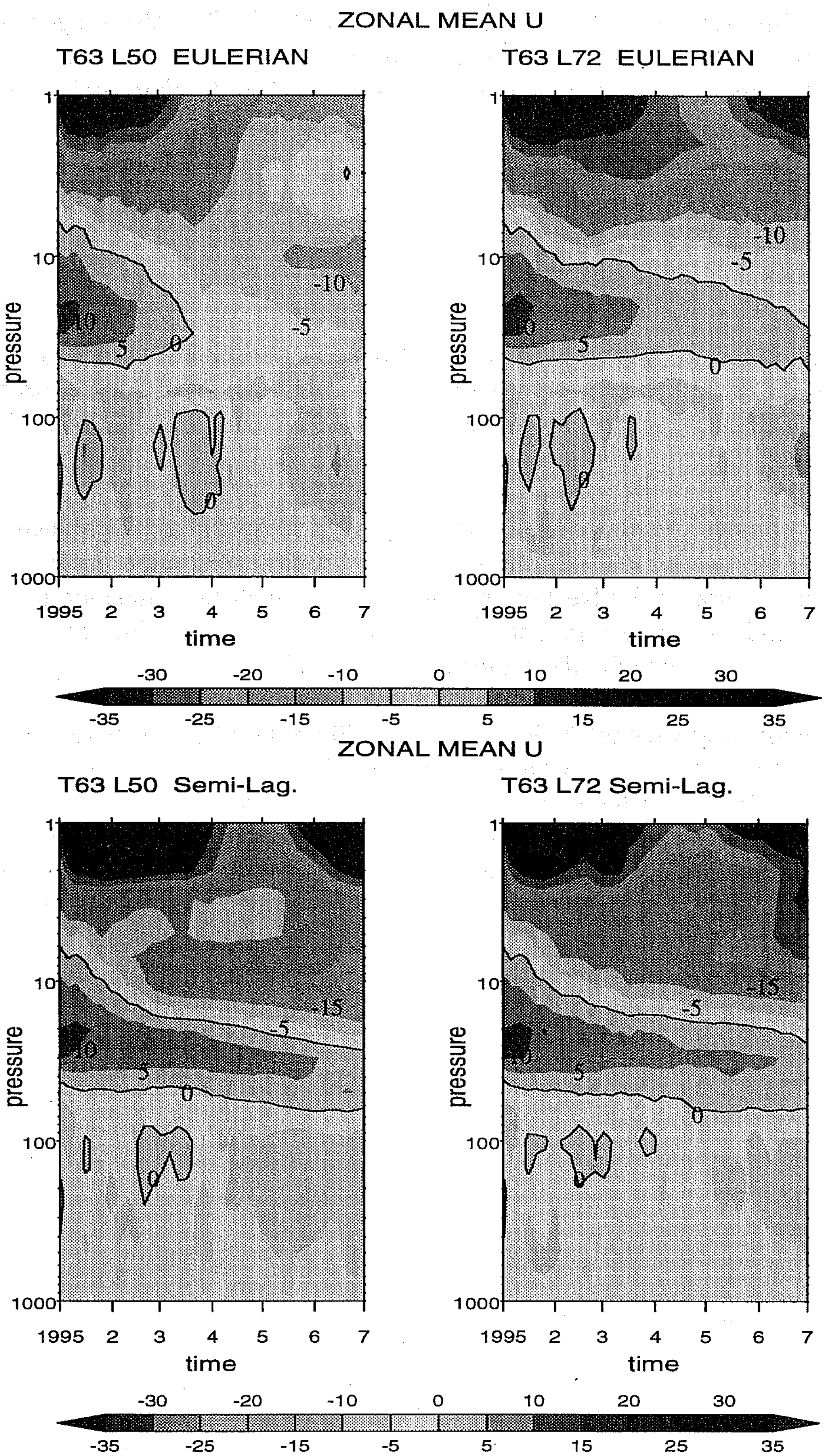

Figure 9. Zonal wind at 0.93N from runs with the Eulerian advection scheme (top two panels) and with the semi-Lagrangian advection scheme (bottom two panels) at L50 (left) and L72 (right).

These results demonstrate the higher accuracy of the semi-Lagrangian vertical advection compared with the Eulerian vertical advection as used at ECMWF. They also suggest that the vertical resolution of the 50-level model in the stratosphere is adequate in conjunction with the semi-Lagrangian advection for modelling the wind in the tropical stratosphere realistically and that the results are already converged with respect to vertical resolution.

4. Conclusions

A problem with excessive westerly winds in the tropical stratosphere at 10 hPa found in long runs with the 43-level model in connection with semi-Lagrangian advection has been reported and traced back to inadequate vertical resolution in the middle stratosphere with the 43-level distribution.

With the 50-level model where the levels in the middle stratosphere are distributed uniformly with a spacing of 1.5 km the erroneously strong westerly jet did not develop. Instead the model integrated with semi-Lagrangian advection, produced quite a realistic simulation of the QBO in the tropical zonal wind and also a semi-annual oscillation, but the later is located to low down in the stratosphere at 5hPa instead of at the stratopause.

Eulerian advection at vertical resolutions L43 and L50 produced very different zonal circulations in the tropical stratosphere from what had been obtained with the semi-Lagrangian scheme at these resolutions. With L43 the strong westerly jet did not develop and with L50 the Eulerian scheme did not show any potential for simulating a QBO-like oscillation. A vertical resolution of at least 1 km is required for the Eulerian advection scheme as used at ECMWF to give similar results to those obtained with the semi-Lagrangian scheme with L50 (vertical spacing of 1.5 km).

With the semi-Lagrangian scheme an increase in vertical resolution from 1.5km to 1km did not change the results significantly, showing that with this scheme the vertical resolution of L50 gives already converged results.

Acknowledgments. The author wishes to thank M. Hortal for helpful discussions during the development of the 50-level model and the UK Meteorological Office for making available the stratospheric analysis used in this study.

References

Andrews, D. G., J. R. Holton, and C. B. Loevy (1987): Middle Atmosphere Dynamics, Academic Press, Inc. San Diego, California.

Holton, J. R., and R. S. Lindzen (1972): An updated theory of the quasi-biennial cycle of the tropical stratosphere, J. Atmos. Sci., 29, 1076-1080.

Hortal, M. (1998): Aspects of the numerics at ECMWF. This volume.

Pawson, S., and M. Fiorino (1998): A comparison of reanalyses in the tropical stratosphere. Part 2: The qasi-biennial oscillation, Clim. Dyn., 14, 645-658.

Ritchie, H., (1991): Application of the semi-Lagrangian method to a multilevel spectral primitive-equation model. Quart. J. Roy. Meteor. Soc., 117, 91-106.

Ritchie H., C. Temperton, A. J. Simmons, M. Hortal, T. Davies, D. Dent., M. Hamrud (1995): Implementation of the semi-Lagrangian method in a high-resolution version of the ECMWF forecast model. Mon. Wea. Rev., 123, 489-514.

Swinbank, R., and A. O'Neill (1994): A stratosphere-troposphere data assimilation system, Mon. Wea. Rev., 122, 686-702.