Vertical discretization for the TKE scheme in ARPEGE/aladin

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CHMI/ONPP LACE 23rd March 2006

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1 Motivation

During early 2005, the RC LACE has decided to put their effort on a development of the turbulent kinetic energy (hereafter just TKE) scheme. The improvement of the vertical diffusion in the operational ALADIN has been recognized as one of the important issues for the short term plans. Knowing that a similar work has been started at Meteo-France for ARPEGE/ARPEGE-climat (P. Marquet and E. Bazile) it seemed to be logical to join the same research stream with them, even with expectation that the final application might be different for ALADIN and for ARPEGE. During the common planning of such action the two key questions has been raised. To know their correct answer is of primary importance for the TKE scheme implementation at the various scales and operational configuration. The questions are:

1. **What is the role of the TKE advection with respect of a model resolution and time-step?** Due to a very local character and short time-scale of turbulence the advection of TKE should be used with a special care in numerical models. When horizontal resolution and time step significantly exceed the characteristic size and time scales of the turbulence, to advect TKE seems to be physically problematic. Ideally the answer of this question should give impression about a threshold resolution and time-step from which it is worth to use TKE as advected field.
2. **What is the role of vertical discretization for a TKE scheme?** There are always various alternatives how to dicretize a given scheme. The best case is of course using such staggering for which just minimal level conversion (half to full or vice versa) of a given amount is needed. This is especially important in the case of turbulence taking into account its very local character and generally unstable behavior in numerical models. Previous implies following questions: Should the staggering be of primary importance for the scheme implementation? Is the performance of a scheme using additional level conversion significantly worse than of the scheme (based on the same scientific assumptions) implemented without any conversion?

The aim of this report is to give answer to the second question. Since the TKE scheme for ARPEGE/ARPEGE-climat has been formulated at half-levels it is especially important for limited area models to know whether it is possible to reformulate it for the full levels. Knowing that the model advection is designed to be applied to full levels quantities, this answer is of primary importance for small scale simulation where use of TKE advection is anticipated.

2 Experimental tool

All the tests presented here were obtained with the ARPEGE/aladin single column model (hereafter as SCM) (Piriou et al., 2002). This version of the full ARPEGE/aladin code is very useful for studies of physical package due to its 1D character.

The SCM experiments were launched exclusively with the second GABLS (GEWEX Atmospheric Boundary Layer Study) experiment profile (Svensson, 2005). This experiment was used for inter-comparison of vertical diffusion schemes from numerous operational or research model (Cuxart at al., 2005) including the operational diffusion scheme of ARPEGE. Logically when the TKE scheme started to be available for ARPEGE/ARPEGE-climat physics the GABLS II experiment became one of its validation tools. The results presented here reflect the state from October 2005. It seems that the forcing of the GABLS II experiment condition still suffers by some minor problems in the used SCM implementation. This can lead to some oscillatory behavior between 26 and 40 hours where the vertical velocity forcing is applied.[1] Since the purpose of this work is mainly to study numerics of the TKE scheme, the version with bugged forcing is considered as sufficient test bed for the tests. Especially knowing that in the 3D model some oscillatory behavior of TKE scheme can be present (imposed probably by other physical parameterizations).

3 Description of the experiment

As mentioned before the SCM version of ARPEGE/ARPEGE-climat TKE scheme is used with the GABLS II experiment data. The scheme is scientifically same as the one from Meso-NH (Cuxart at al., 2000 and The Meso-NH Scientific Documentation, 2001) just implemented with extra care with respect to the numerical stability. In order to avoid unnecessary level conversion it is formulated on half levels. This scheme works well with satisfactory stability. Here after it is referred as the half-levels (HL) scheme.

To compare a performance of the HL scheme with a scheme having TKE available on full levels a special test has been created. Supposing that the HL scheme works fine the full-level version was obtained by an added extra conversion of TKE to full-levels. After all the turbulence computation at a given time-step is completed, the TKE and TKE tendency are interpolated from half levels to full levels. Than before the next time-step physics computation the full level TKE is converted back to the half levels. This treatment preserves the advantage of the original stable TKE formulation while making TKE available on full levels. The interpolation used for conversion is rather standard one: To convert from full levels to half a simple averaging is used:

$$TKE_{\tilde{l}} = 0.5(TKE_{l-1} + TKE_l) \quad .$$

The TKE at bounding levels is set to zero: $TKE_{\tilde{0}} = TKE_{\tilde{L}} = 0$. The backward computation from half to full levels uses the obvious weights α (PALPH) and δ (PLNPR):

$$TKE_l = \frac{\delta_l - \alpha_l}{\delta_l} TKE_{\tilde{l}-1} + \frac{\alpha_l}{\delta_l} TKE_{\tilde{l}}$$

The uppermost interpolation is treated asymmetrically as:

$$TKE_1 = \frac{\alpha_1}{\delta_1} TKE_{\tilde{1}} \quad ,$$

the lowest full level then preserves the free atmosphere lower boundary condition for TKE, so it is just:

$$TKE_L = TKE_{\tilde{L}-1}$$

The same conversion (from half to full levels) is applied to the TKE tendencies as well. The computation described above with extra conversions for every time-step is hereafter referred as full level (FL) experiment. (Of course this very basic arrangement should not be considered as formulation of the full level TKE scheme. It is rather special purpose test to show impact of the additional level conversion to the model results.)

The GABLS II experiment with SCM is performed for the low atmosphere (bellow 5 km height). Two levels settings are used with different vertical resolution: 100 levels distribution and so-called 41 levels distribution. The first one describe roughly the 4 km high atmosphere by 100 model levels with resolution varying from 2 meters near the surface and around 100 meters on the top. The second one uses the same level distribution as the operational ARPEGE thus it has just 18 levels bellow 5 km meaningful for this simulation.

As the diagnostic results several fields would be used:

1. The boundary layer height requested by the GABLS II experiment as: the height, where the value of $\sqrt{(uv + vw)^2}$ falls to 95% of its surface value, divided by 0.95.

[1] According recent information, the current version of the SCM GABLS II works fine being freed from the mentioned problem.

2. The TKE itself at various model levels

The first one is a very sensitive diagnostics. It has thus the potential to illustrate the overall scheme performance in one simple curve.

4 Results

Surprisingly the HL and FL schemes are producing very similar results when used with the obvious time-step (i.e. Δt=300s for the L100 experiment and Δt=900s for the L41 one). It is quite well illustrated by figure 1, where the PBL height is displayed as function of time. Here it is evident that the FL formulation tends a bit to smooth the information, which can be sometimes profitable (removing the unrealistic peak at around 22nd hour in L41 experiment) and sometimes not (filling bit the valley at around 42nd hour with the L41 setting). This fact coming from the additional interpolation should not be surprising. What is however surprising is the potential of the FL scheme to remove the short time oscillation. As illustrated by zoomed area between 10th and 22nd hours of integration (figure 2), it is evident that the L100 setting tends to produce $2\Delta t$ waves. The additional interpolation than practically removes those fibrillations. This can be surely considered as extra quality added by the additional interpolation.

As the HL scheme has been designed mainly for the stability reasons the time-step was extended in the further tests. The intention was to see differences in stability of the two compared schemes. As presented by figure 3 the L100 settings starts to exhibit some problems with time-step Δt=900s. Here again the zoomed PBL height as a function of time is shown. Especially the night time with weaker diffusion activity shows a sensitivity to the extended time-step there. It should not be surprising that in this case the oscillations of TKE computed by HL scheme are further amplified by interpolation for the FL formulation (shown in the right part of figure). On the other hand the FL version still seems to have less problems with the fibrillations (left part of the figure 3). Further extension of the time-step leads to an unstable behavior for both compared versions.

The similar experiment performed with the L41 levels distribution just confirms previous results. Figures 4 and 5 show the time evolution of TKE for several model level (half or full) counted from the surface. It should not be too surprising that the absolute values of extremes in HL formulation are smoothed by the FL formulation. This has some significance namely at the beginning of turbulence activity period, when the FL scheme significantly smoothes the noise. On the other hand, the effect of interpolation has also some detrimental side effect. As can be seen around 55th hour a small hill is created at 5th level (L5) of the HL scheme. This probably numerical problem is kept separated from the rest of the model, so it dies after some time. This is not the case for the FL formulation, where the interpolation further spreads the hill to the adjacent levels. Although it is dying with around the same time period, the impact of this originally just local instability can be quite significant for some related fields. To illustrate previous the impact to the PBL height is shown on figure 6. Here the FL formulation creates difference bigger than 100% of the reference value. As also presented there, the HL scheme with even longer time-step doesn't seem to amplify the problem in such a way to be visible by PBL height.

Otherwise, once the HL is stable, the FL one keeps the same stability. And vice versa, when the HL formulation shows stability problem it is also problem for the FL scheme. This should not be surprising knowing that the formulation is the same, just the FL is extended by additional interpolation (which is of course absolutely stable in time).

5 Conclusion

To conclude this small exercise. As it has been shown even the simplest FL re-formulation of the HL scheme is not at all detrimental to the model results. Surprisingly some conversion can be even seen as profitable as it is smoothing the $2\Delta t$ oscillations. The tested FL formulation smoothes extremes which can be both positive or negative with respects to the situation. Here a most sophisticated conversion of more conservative components of the TKE would possibly further improve the real full level scheme performance. So far the only negative impact of the additional interpolation is found in its inability to localize an appearing instability. In such case the instability is propagated to the adjacent levels amplifying thus it effect to the other related fields. However, since the aim is to keep time-step short enough to be safe from any instability, it should not matter that much.

Seen from above mentioned results perspective the vertical discretization of the TKE scheme implemented to the atmospheric model is not primarily linked to either full or half levels. If done with some patience a performance of half level or full level scheme should not differ that much.

It should be also said that previous conclusion were obtained in the framework of the specific dry experiment primarily focused to the study of diurnal cycle in turbulence. Due to its stably stratified atmosphere it might be not a difficult case for the vertical interpolation of the TKE. Hence the logical next step of this study should be to reverify the presented conclusions for a simulation with clouds.

6 References

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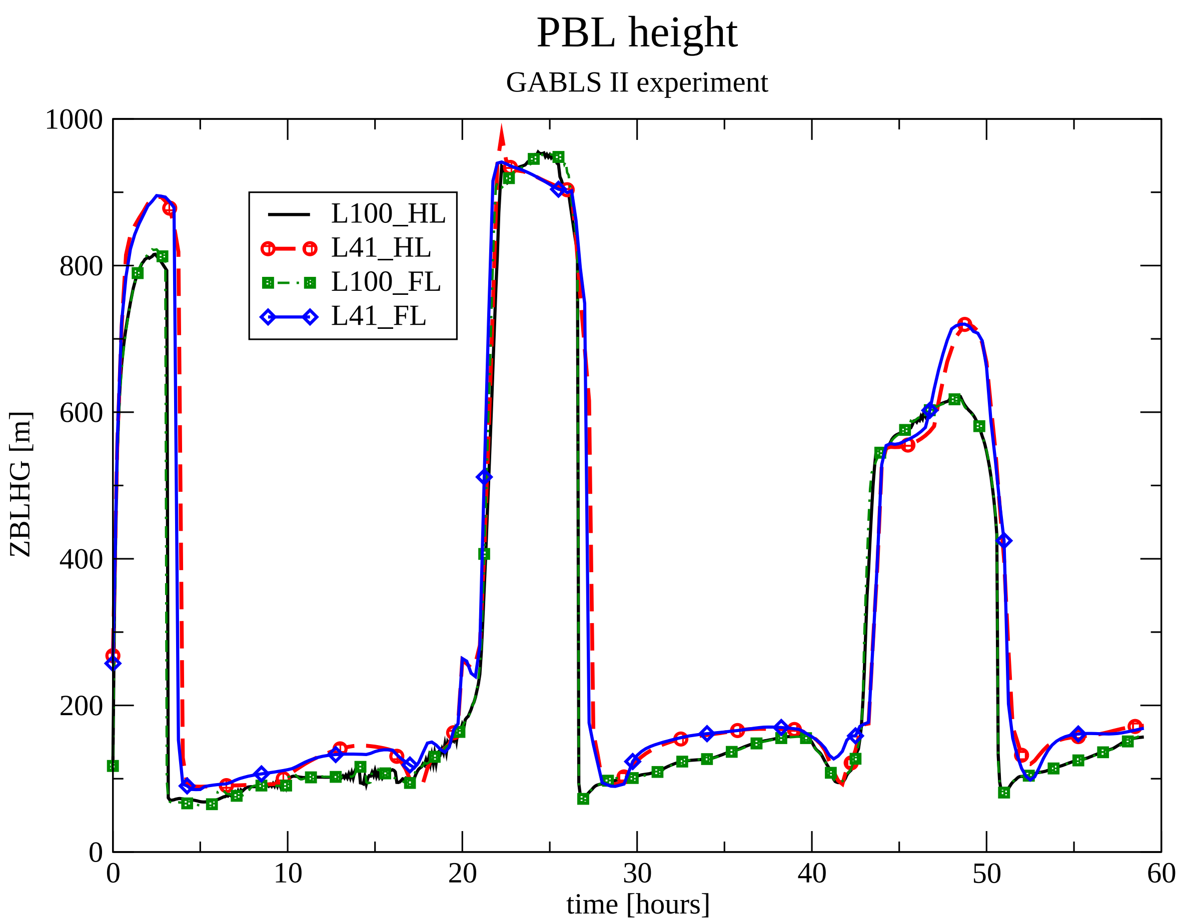

Figure 1: *The time evolution of the PBL height. The L100 stands for the high resolution experiment while L41 represents the operational ARPEGE level distribution. The HL and FL stand for half-level and full-level experiments respectively. The usual time-steps are used here: Δt=300s in case of L100 settings and Δt=900s for the L41 case.*

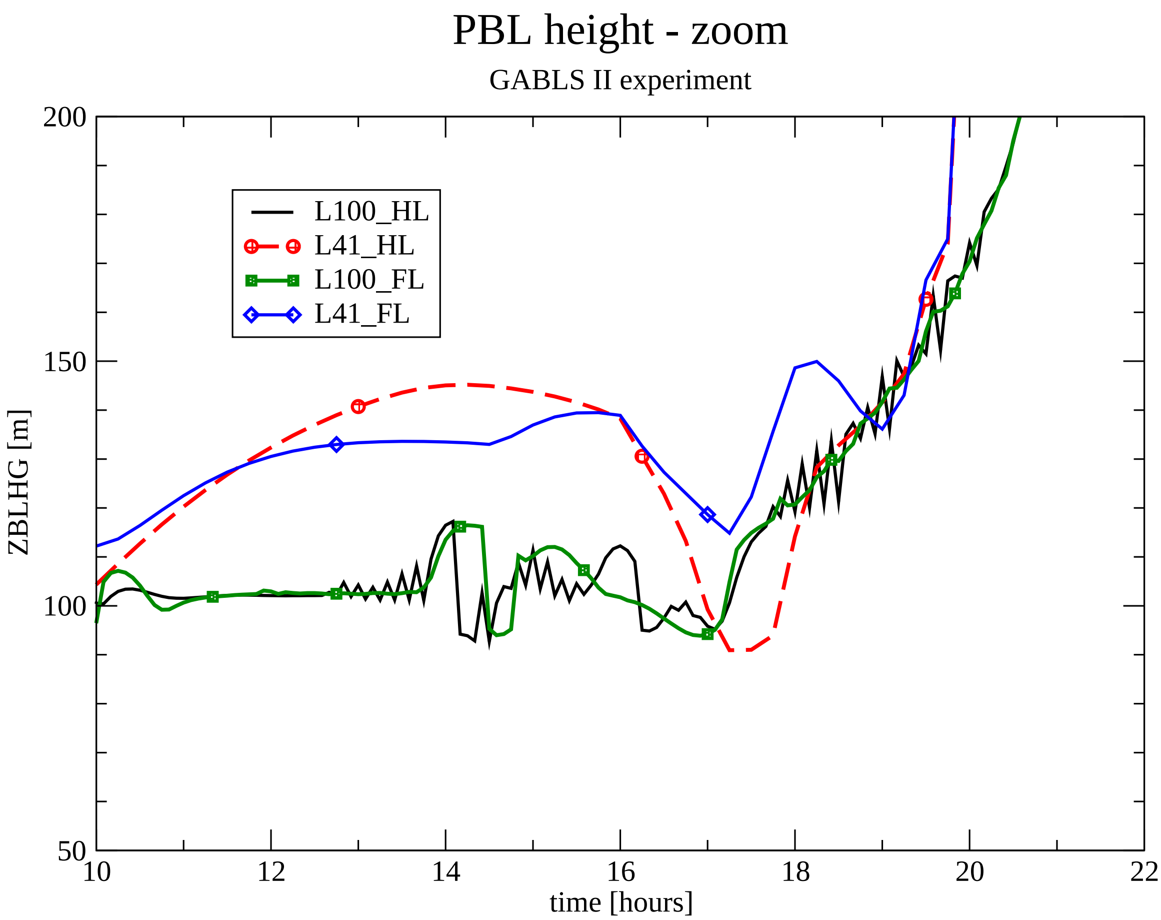

Figure 2: *The time evolution of the PBL height zoomed to the period between hours 10 and 22 of simulations. All the experiments description keep the same meaning as in previous figure 1.*

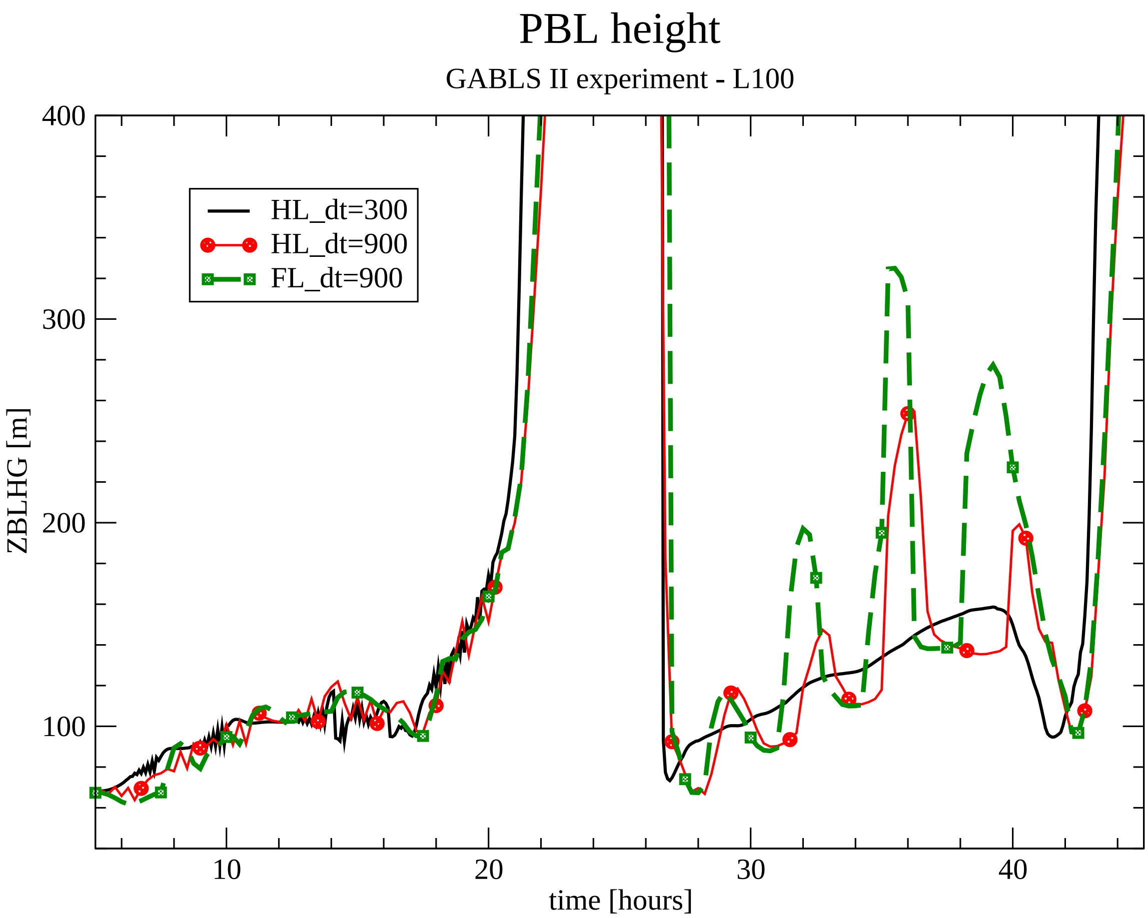

Figure 3: *The time evolution of the PBL height zoomed to the period between hours 5 and 45 of high resolution (L100) simulations. The reference HL run keeps original time-step* Δt*=300s while for the other runs the time-step is pushed to* Δt*=900s.*

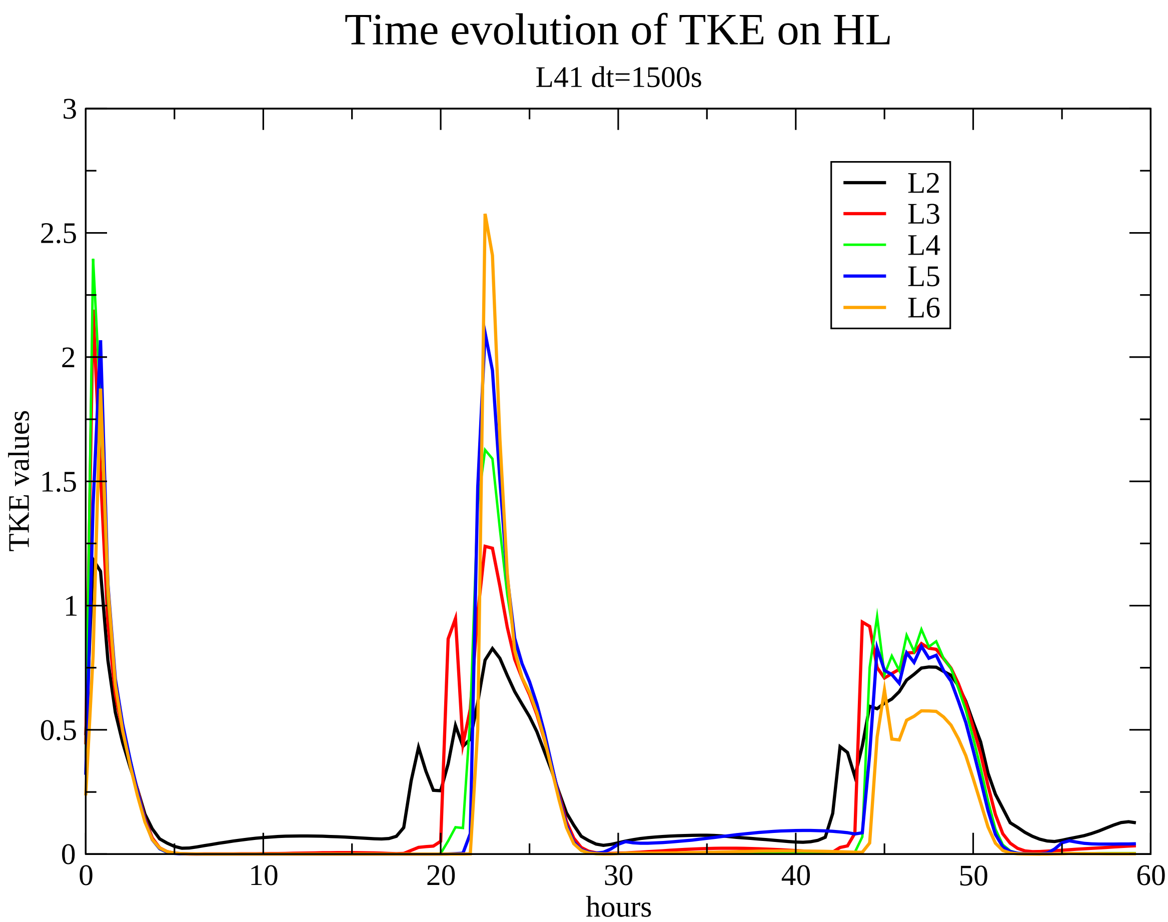

Figure 4: *The time evolution of the TKE at various half levels (numbered from the bottom). The low resolution HL (L41) setting is used with rather long time-step* Δt*=1500 s.*

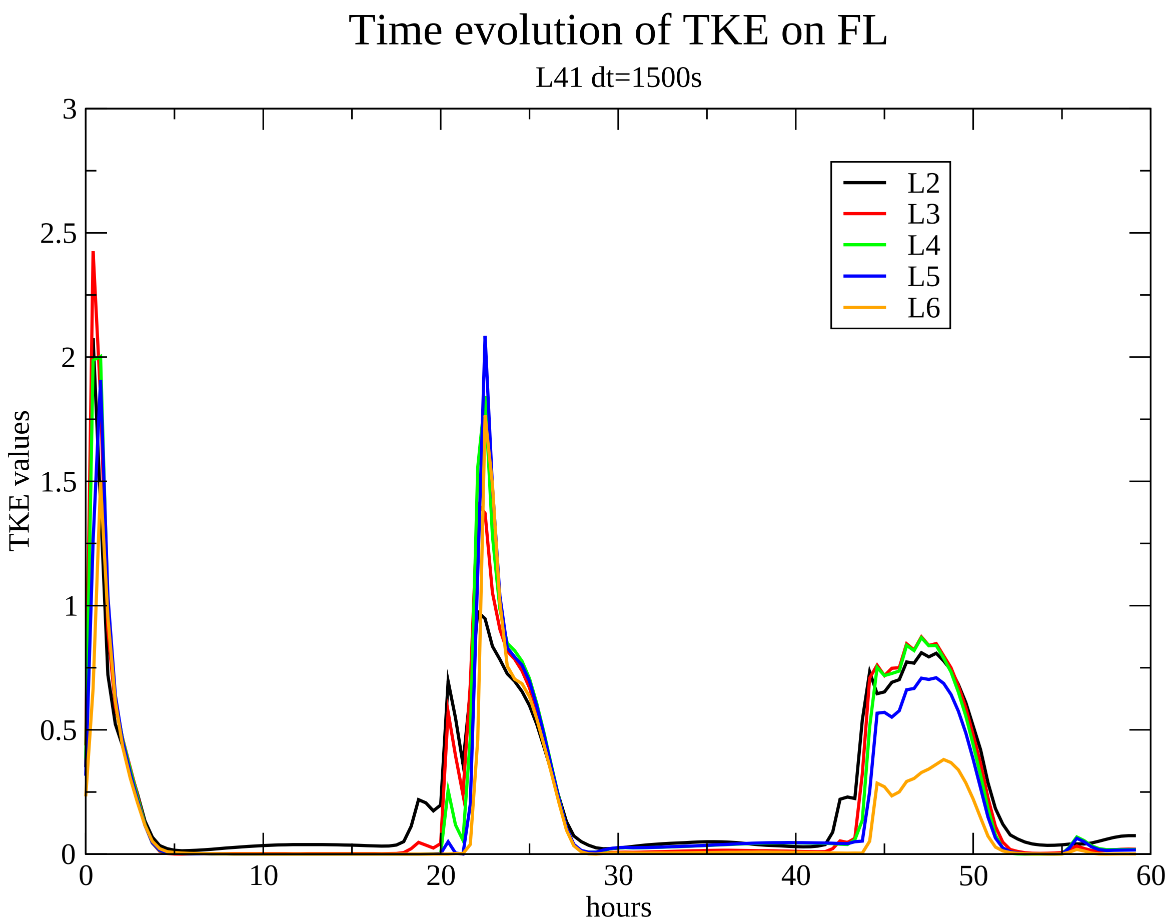

Figure 5: *The time evolution of the TKE at various full levels (numbered from the bottom). The low resolution FL (L41) setting is used with rather long time-step* Δt*=1500 s.*

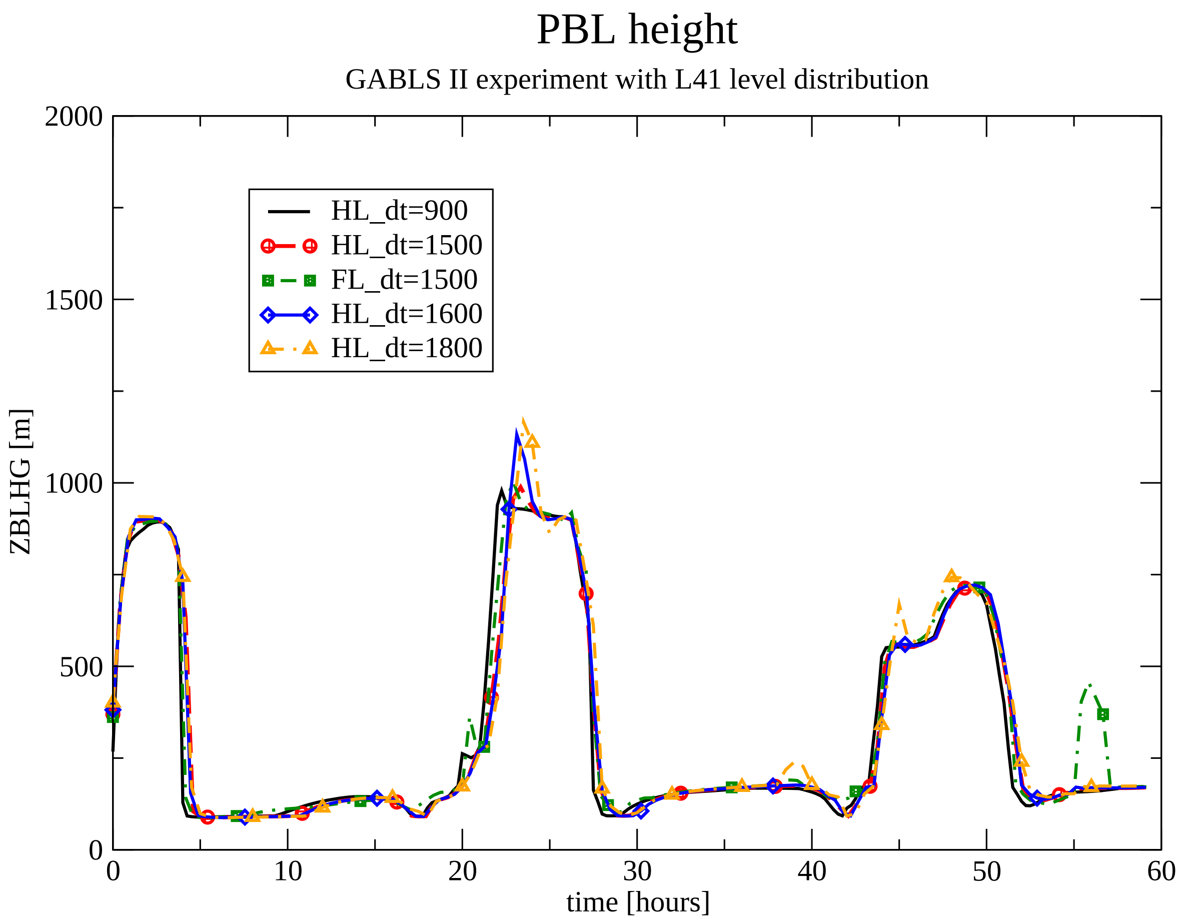

Figure 6: *The time evolution of the PBL height as computed with the low resolution (L41) settings for various time-steps and formulations of the TKE scheme (HL/FL).*