Orographic forcing in ALADIN

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1. Introduction

As in the early eighties the resolution of the models increased, one of the most spectacular effects was the deterioration of the mean westerly flow at moderate latitudes, especially above the continents. A too strong westerly flow in the northern hemisphere in the winter and a more correct simulation in the southern hemisphere and in the northern hemisphere in the summer suggested a lack of orographic forcing.

Different methods are used to overcome this problem. One method is to increase the orography by adding an envelope (see Wallace et al., 1983). Another one uses a parameterization of the gravity waves generated by the subgrid-scale features. Both methods increase the orographic stress, thus lowering the total momentum.

These two methods are implemented in ALADIN. The envelope is created in configuration 923 (`FENVN=1` in the namelist), the parameterization of gravity waves is treated in the subroutine `ACDRAG`, giving (`PSTRDU`, `PSTRDV`), the additional zonal and meridional stress. The tuning of these effects is as fine as that the slightest change in tuning coefficients gives a much worse result. Nonetheless, the implementation of the two methods are not fully satisfactory :

1. In a number of models, the envelope has been suppressed, but ALADIN still needs it, why ?
2. When air meets a mountain, too much goes over the mountain (giving too much precipitation), too little goes around it.
3. What are the interactions between the different parameterizations (turbulence) ?
4. What happens when going to higher resolution ? ...

To study these problems, we developed a diagnostic tool that calculates the momentum budget over a certain domain. In this budget dynamical terms as well as physical parameterizations are included. So, when going from high to low resolution, there should be a shift from dynamical to physical terms. By doing this we hope to find some shortcomings in the representation of the orographic forcing in ALADIN.

2. The experiments

The chosen domain is the ALPIA domain, centred on the French Alps (45.22° N, 5.90° E). For this domain we have created the complex orography 4 times in 4 different resolutions :

Domain	points	vertical levels	resolution
A	96×96	37	10 km
B	192×192	51	5 km
C	384×384	71	2.5 km
D	768×768	98	1.25 km

A plot of the domain at the different resolutions is shown in Fig. 1.

The resolution in domain D is high enough to handle it as the "perfect" domain where all of the orographic stress is resolved. So, there is no need of a parameterization in this domain. When going to lower resolution (C, B and A), the subgrid-scale orography is not resolved any more and subgrid-scale features should be taken into account. Therefore, we have calculated (following Lott and

Miller, 1995) the variance (μ^2), the anisotropy coefficient (γ^2) and the anisotropy direction (υ) for each gridpoint in these three domains. With :

$$\mu^2 = \frac{1}{4}\left(h(\max) - \overline{h}\right)\left(\overline{h} - h(\min)\right) \qquad \gamma^2 = \frac{K - \sqrt{L^2 + M^2}}{K + \sqrt{L^2 + M^2}} \qquad \upsilon = \frac{1}{2}\arctan(M/L)$$

$$K = \frac{1}{2}\left(\overline{\left(\frac{\partial h}{\partial x}\right)^2} + \overline{\left(\frac{\partial h}{\partial y}\right)^2}\right) \qquad L = \frac{1}{2}\left(\overline{\left(\frac{\partial h}{\partial x}\right)^2} - \overline{\left(\frac{\partial h}{\partial y}\right)^2}\right) \qquad M = \overline{\frac{\partial h}{\partial x}\frac{\partial h}{\partial y}}$$

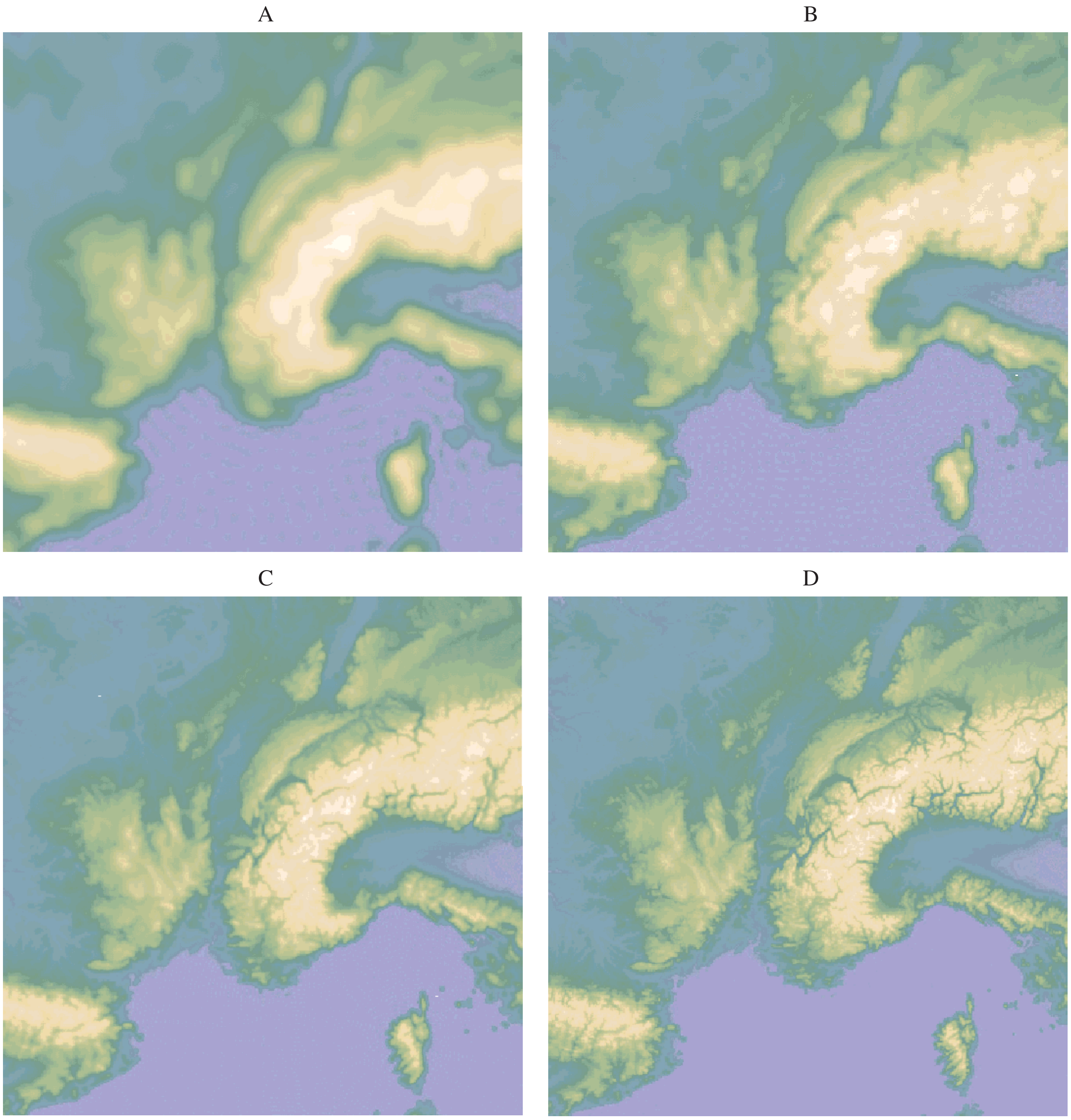

Figure 1 : The ALPIA domains : (A) 10 km resolution , (B) 5 km resolution , (C) 2.5 km resolution, and (D) 1.25 km resolution.

These three subgrid-scale features are needed for the parameterization of gravity waves. It is clear that, ideally, the effects that are not resolved any more should be taken care of by the parameterization.

The envelope was added (following Wallace et al. 1983), increasing the height by twice the standard deviation of the subgrid orography, or : $height = height + \mathrm{FENVN} \times 2\mu$. FENVN is a tuning coefficient, where $\mathrm{FENVN} = 1$ stands for a full envelope and $\mathrm{FENVN} = 0$ stands for no envelope. However, operationally the envelope is created using only 1 times μ. Future tests will also use this value.

To study the effects over this complex orography, we chose to use an idealized flow. This flow was constructed using the ACADFA routines, which were used in previous academical studies (see for more information Bubnova, 2000). As the previous studies concentrated on the dynamics, we had to add a small physical part.

The experimental conditions are as follows : the atmosphere is dry, inviscid, in hydrostatic equilibrium and its static stability is given by a constant Brunt-Väisälä frequency $N = 0.01$ s^{-1}. There is a constant reference flow of 24 m/s from the North-West, hence blowing more or less perpendicular on the main mountain ridge. The main flow is in geostrophic equilibrium with a constant Coriolis parameter $f = 0.0001$ s^{-1}. The vertical levels are regularly spaced in z by 867 m for domain A, 619 m for domain B, 433 m for domain C and 306 m for domain D. Finally, the reference values of temperature and density prescribed in the middle of the domain at sea level are : $T_0 = \theta_0 = 300$ K and $\rho_0 = 1$ kg/m^3 .

As the tendency term becomes negligible after 6 hours, the forecast length was set to these 6 hours. We used the two time-level semi-Lagrangian semi-implicit approach with an ALADIN cycle-15 library. A plot (Fig. 2) has been made of the situation after 6 hours.

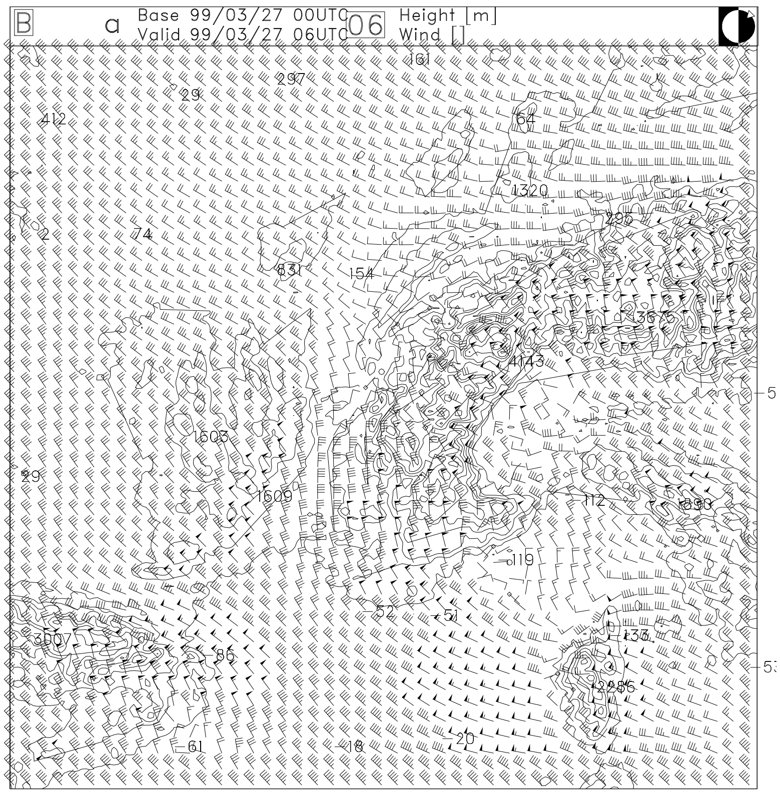

Figure 2 : The situation after 6 hours (domain B).

3. Momentum budgets

As orographic stress reduces the amount of momentum, is seems logic to look at the different components contributing to the total momentum and how they change when going to lower or higher resolutions. The components were integrated inside a box (of which the height changes from 0 to 20.000 m) over the different domains. In this box, the momentum budget should agree to the following balance equation (for the meridional case) :

$$\underbrace{\overline{\frac{\partial(\widetilde{\rho v})}{\partial t}}}_{A}+\underbrace{\overline{\frac{\partial(\widetilde{\rho u v})}{\partial x}}}_{B}+\underbrace{\overline{\frac{\partial(\widetilde{\rho v^2})}{\partial y}}}_{C}+\underbrace{\overline{(\rho v w)_z}}_{D}+\underbrace{\overline{\frac{\partial(\widetilde{p-p_{ref}})}{\partial y}}}_{E}+\underbrace{\overline{\tilde{\rho} f u}}_{F}+\underbrace{\overline{(p-p_{ref})_h\frac{\partial h}{\partial y}}}_{G}+\mathrm{param}..=0,$$

with

$$\tilde{Q}=\int_h^z Q\,dz \quad \text{and} \quad \overline{Q}=\frac{1}{A}\int\int_A Q\,dx\,dy,$$

where h denotes the orography height and z the height of the top. The components stand for the following :

- A: Tendency term
- B: Advection term (U-component)
- C: Advection term (V-component)
- D: Vertical flux through the top of the box
- E: Pressure gradient
- F: Coriolis term
- G: pressure drag
- Param: Parameterizations calculated by `ACDRAG` (gravity-wave stress) and `ACDIFUS` (turbulent stress)

The data needed for these integrations are abstracted from the `CPG` subroutine.

4. Tests

Going from high to low resolution

The goal of these tests is to know whether the ACDRAG routine is doing what it is supposed to do : when going from high to low resolution, there should be a shift from dynamical terms to physical terms.

When going from the C domain over the B domain to the A domain we see the following trends (see also Fig. 3) :

- The pressure drag becomes smaller. When going from B to A the decrease in pressure drag is fully compensated by an increase in gravity-wave drag (see Fig. 4). When going from C to B the decrease is partly compensated by the gravity-wave drag and partly by an increase in advection (x direction).
- There is also a steady decrease in pressure gradient (twice of the same magnitude).
- The contribution of the Coriolis effect is the same in the four domains (also D).
- There is a remarkable decrease in vertical flux when going from C to B. This decrease is negligible when going from B to A.
- The higher the resolution, the better the momentum budget is in balance. Domain C is close to being in complete balance.
- At the 2.5 km resolution the parameterization disappears.

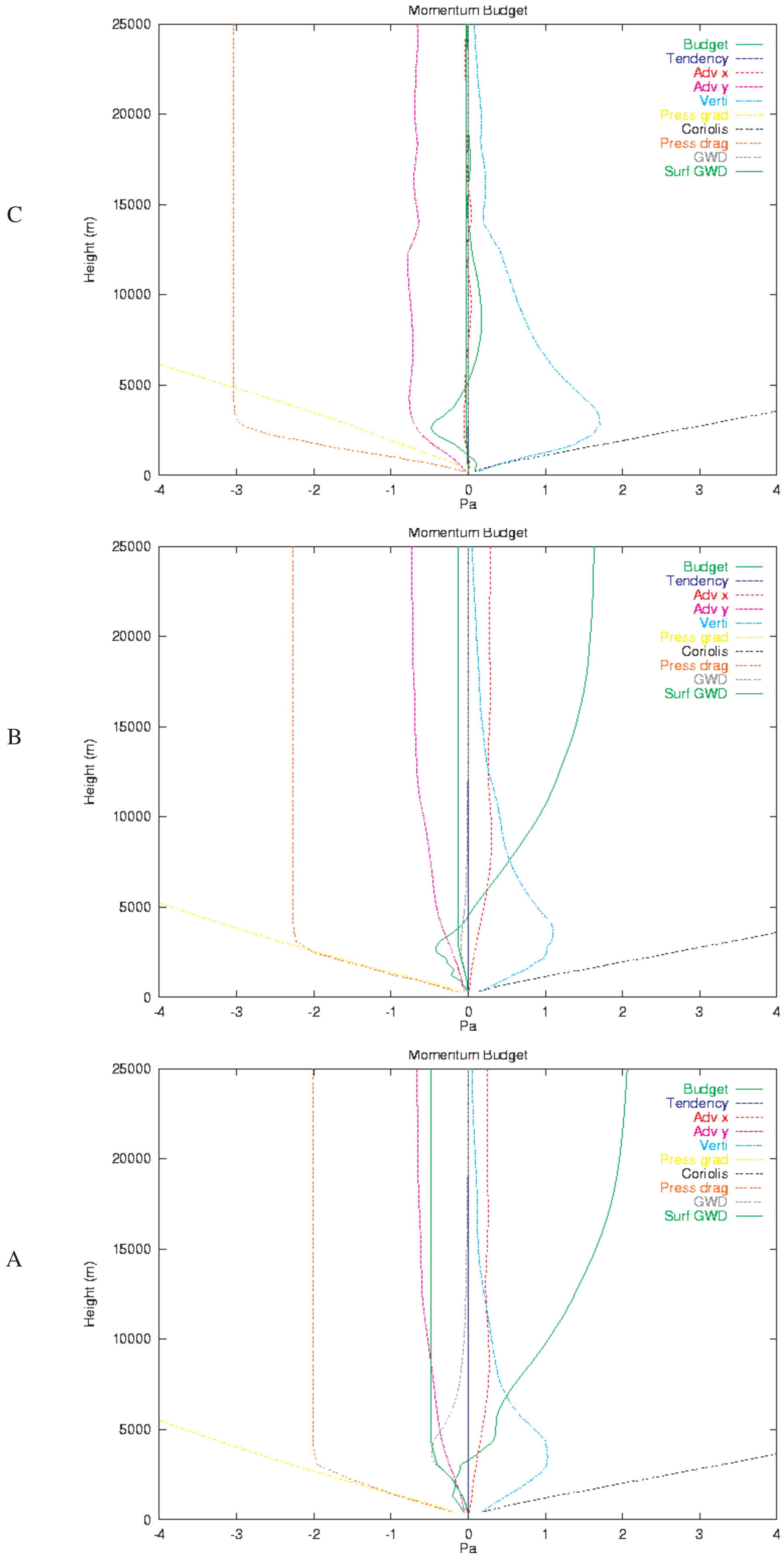

Figure 3 : Momentum budgets, going from high to low resolution : the upper figure is for domain C, in the middle for domain B and the lower figure is for domain A.

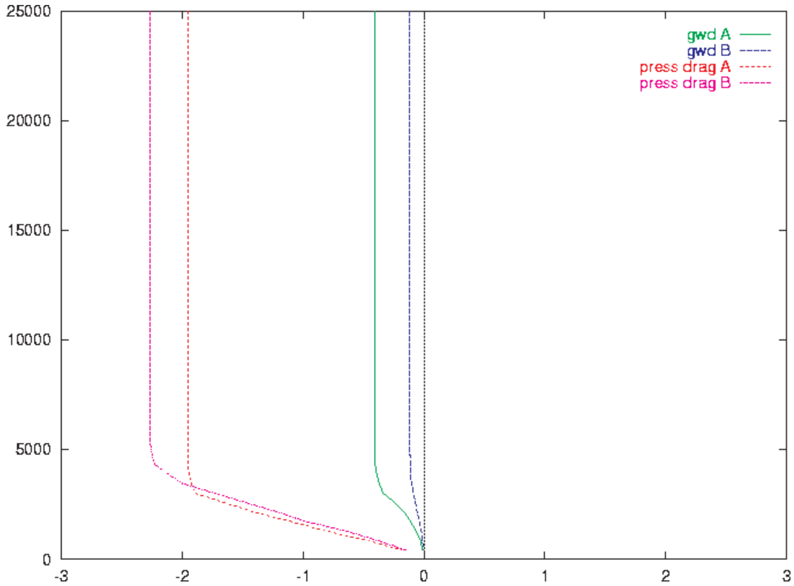

Figure 4 : When going from high to low resolution the decrease in pressure drag is fully compensated by an increase in gravity-wave drag.

Removing the envelope

Removing the envelope has always been a problem in ALADIN. ALADIN still needs it while other models can work without it. So let's see what changes in the momentum budget when we remove the envelope.

Removing the envelope actually means removing high peaks and lowering valleys. Hence it is clear that the pressure drag should decrease. An other general (logical) trend in the budget terms is that a lot of activity will take place at lower altitude. Finally, when we compare the budget it is clear that the simulation with the envelope is better than without it (the budget at lower altitude is closer to zero, see Fig. 5).

If we want the budget to move closer to zero, we must compensate the decrease in pressure drag by increasing the gravity-wave drag. Now, in the subroutine ACDRAG the nonlinear effect of blocked flow is included. This effect separates the flow in a part that goes over the mountain and a part that goes around it. The separation is arbitrarily chosen by a tuning parameter `GWDCD` which is by default set to 6. By increasing this value and hence increasing the part of the flow going around the mountain and thus increasing the stress, we can compensate for the removal of the envelope and keep our budget in balance.

We did this test for domain A, where the influence of the parameterization is high. We increased the value for `GWDCD` from 6 over (a very unrealistic) 60 to 100. The results are shown in Fig. 6. One can see clearly that by increasing `GWDCD` the momentum budget becomes better in balance, especially in the lower layers.

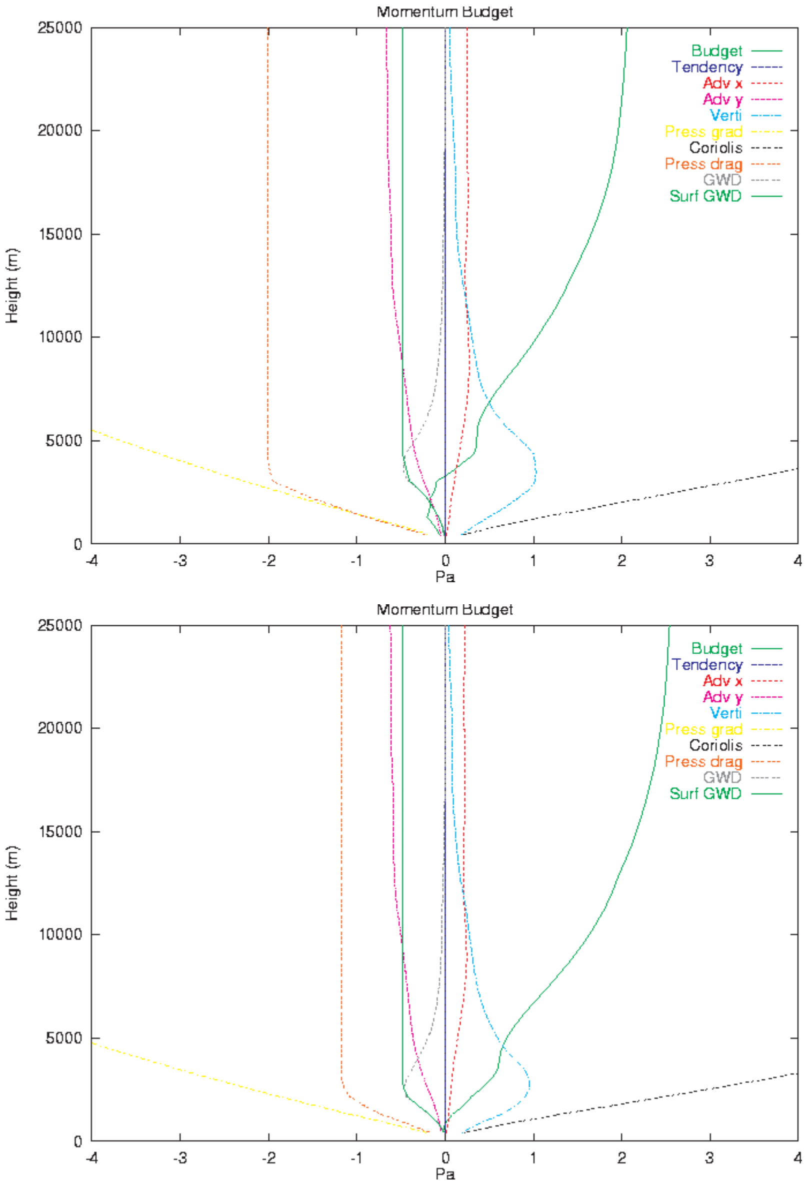

Figure 5 : Upper figure: momentum budget with envelope, lower figure: without envelope (both with GWDCD = 6).

5. Conclusions

Some preliminary conclusions concerning the change in resolution :

1. The gravity-wave drag parameterization disappears at 2.5 km resolution.
2. When going from 5 to 10 km resolution, the decrease in pressure stress is fully compensated by the increase in gravity-wave drag. So, the parameterization does what it is required to do (when a change in resolution is concerned).

Conclusions concerning the removal of the envelope :

As we can see from the momentum budgets, when installing an envelope the vertical flux is increased and spread over a larger vertical range. So when we want to remove the envelope, the parameterization should compensate for the loss of volume. As the scheme in its current form is not able to do this, we might have to think about a semi-envelope (where there is still a barrier effect, but the volume is suppressed).

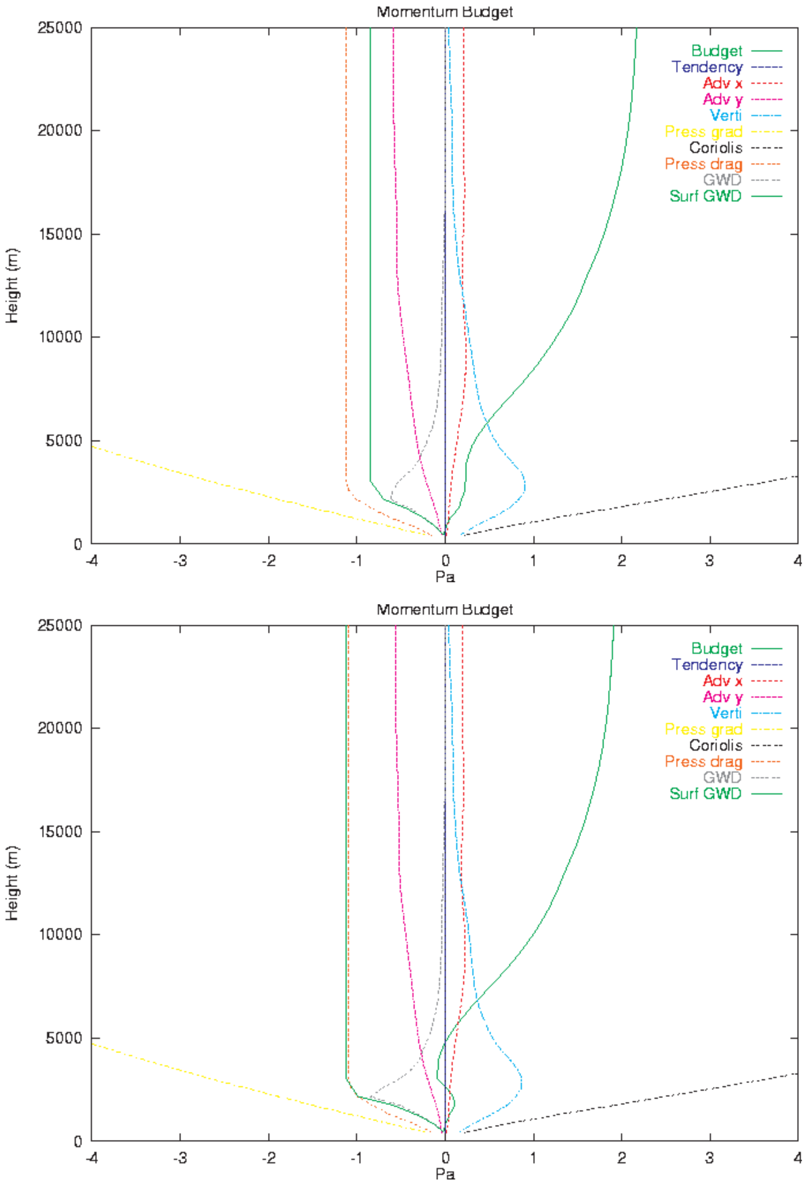

Figure 6 : Momentum budget without envelope and : upper figure : `GWDCD` = 60, lower figure : `GWDCD` = 100.

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