

Different aspects of CBR/CLJ

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1 Introduction

In the past, CBR work has been aimed at improving the synoptic scores of Hirlam. Increasing the mixing improves the standard verification scores by reducing constant Hirlam problems like the negative pressure biases in cyclones. These improvement, however, were at the expense of local profiles of the wind and temperature. The daily cycle of the wind and temperature suffer from the increased mixing in stable conditions, causing too high nighttime winds and temperatures. In this study we try to look at the problem of the Hirlam pressure bias from another direction: the surface stress. We also propose one other possible solution for the current tradeoff problem between the synoptic scores and the characteristics of Hirlam under stable conditions.

In the Netherlands we recently have experienced a number of cases where Hirlam 11 km was not performing as well as one would expect. For the wind speed we have found that the extra vertical levels that have been added in the boundary layer in Hirlam 11 km are not causing much difference. Especially in cases with strong shear in the boundary layer we hoped to see some added value of the 9 extra levels. This observation has triggered the research that is presented in this paper.

With the 1-D model we have tried to study the behaviour of different versions of CBR/CLJ (CBR: Cuxart, Bougeault and Redelsberger; CLJ: Cuxart, Lenderink and Jones) systematically in a number of different regimes and with different forcings and vertical resolutions. We have focussed on the behaviour of the wind speed profile. One phenomenon that has been studied is the way the model is (in)capable of producing a low-level jet.

Further, we have looked at the negative pressure bias problem of Hirlam, not from the CBR perspective, but from the surface forcing. The negative pressure bias probably is caused by too little Ekman pumping, caused by a too small ageostrophic wind component. This causes cyclones to become too deep and fill up too slowly. One way to solve this problem is increasing the mixing in the CBR scheme. This causes the wind near the surface to increase, increasing the surface momentum fluxes thereby applying a stronger brake on the model atmosphere. However, this causes too strong mixing which can be seen when model wind profiles are compared to measurements of the Cabauw tower (see De Rooy, 2003).

2 1-D Experiments

To study the impact of the vertical diffusion we have used four different versions of the vertical diffusion scheme. The first version is one of the first releases of CBR that was available in 1999, the one that is incorporated in the 1-D model. This version we will call CBR_dry. The second version is the version that was adjusted by Lenderink (2002) to be conservative and was included in Hirlam version 5.1. In the remainder we will call this version CBR_506. The third version of CBR is the moist version that has not been released yet and which we will call CBR_moist. The last version is the moist version of CBR that also incorporated some changes by Colin Jones. As this version has progressed a long way from the original CBR we will call this version CLJ.

The aspects of the vertical diffusion we study are the version dependence, the vertical resolution dependence and the impact of the height of the lowest model level. Surprisingly, the latter has quite some impact on the wind profiles in the 1-D model.

2.1 Diurnal cycle, the low-level jet

One of the phenomena that is very sensitive to the vertical diffusion is the low-level jet. This wind maximum develops during the evening and night when the turbulence dies down and

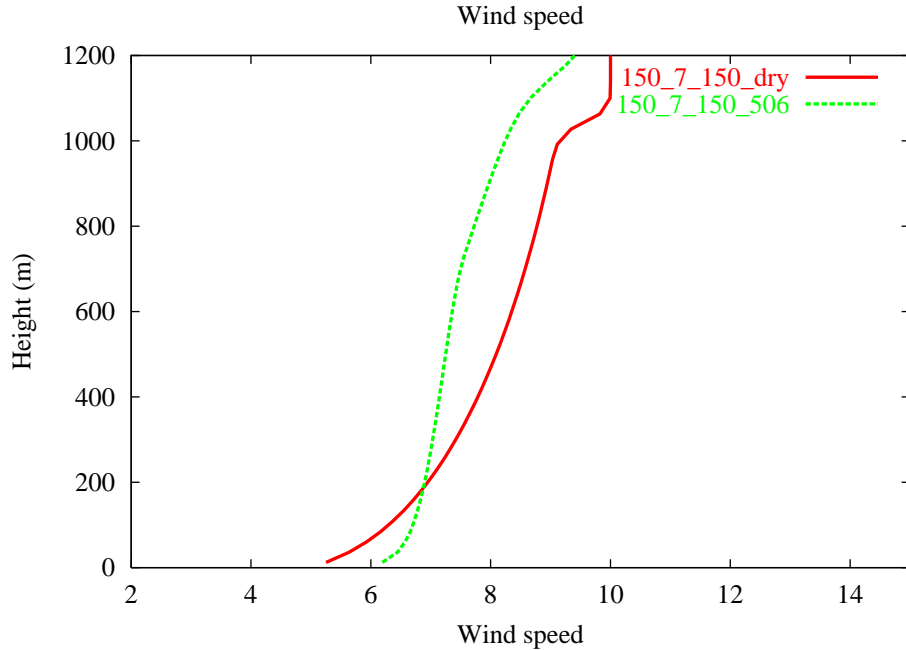


Figure 1: The wind speed profiles at the end of the period with positive sensible heat fluxes with CBR_dry and CBR_506.

the brake on the wind in the day-time boundary layer is removed. Due to the increasing stability near the surface the turbulence dies down completely and the remainder of the day-time boundary layer is decoupled from the surface and does not feel the surface friction any more.

During the day time, the wind in the boundary layer is slowed by the friction of the surface and the equilibrium wind speed will be much lower than the geostrophic wind speed. When the turbulence dies down the new equilibrium wind speed will become the geostrophic wind speed (more precisely the gradient wind), but as the initial wind speed will be much lower, an inertial oscillation will develop. As this oscillation evolves around the equilibrium wind speed, the wind speed will become stronger than the geostrophic wind speed after a couple of hours. The low-level jet should be strongest between 100 and 300 meters above the surface. This is the first level where the decoupling from the surface is complete and where the day-time decrease in wind speed is largest due to the surface friction.

The 1-D model should be capable of producing a low-level jet. To force a low-level jet in the 1-D model we prescribe a surface sensible heat flux with a maximum value of 250 Wm^{-2} during the day and a night-time sensible heat flux of 50 Wm^{-2} . The geostrophic wind speed is 10 ms^{-1} and the surface roughness is 15 cm. We start the model at 6 UTC and run for 24 hours. The latitude is 36° .

Figure 1 shows the wind-speed profile at the end of the period with positive sensible heat fluxes, when the decrease in wind speed in the boundary layer is largest. In this quite simple and not very sensitive case, the wind speed profiles differ considerably. Differences of 1 ms^{-1} are no exception. CBR_506 clearly causes more mixing of momentum in the unstable boundary layer than CBR_dry, as the vertical wind speed gradient is much smaller in CBR_506. The increased mixing also causes a stronger near-surface wind. Averaged over the entire profile CBR_506 causes a larger deviation from the geostrophic wind speed than CBR_dry. This may be an important factor in the deepening and filling of low pressure systems.

Figure 2 shows the average wind-speed profile between hours 22 and 23, after about 10 hours of negative sensible heat flux. The CBR_dry profile shows a very well developed low-level jet. The wind speed increases with height very fast and has a maximum at a height

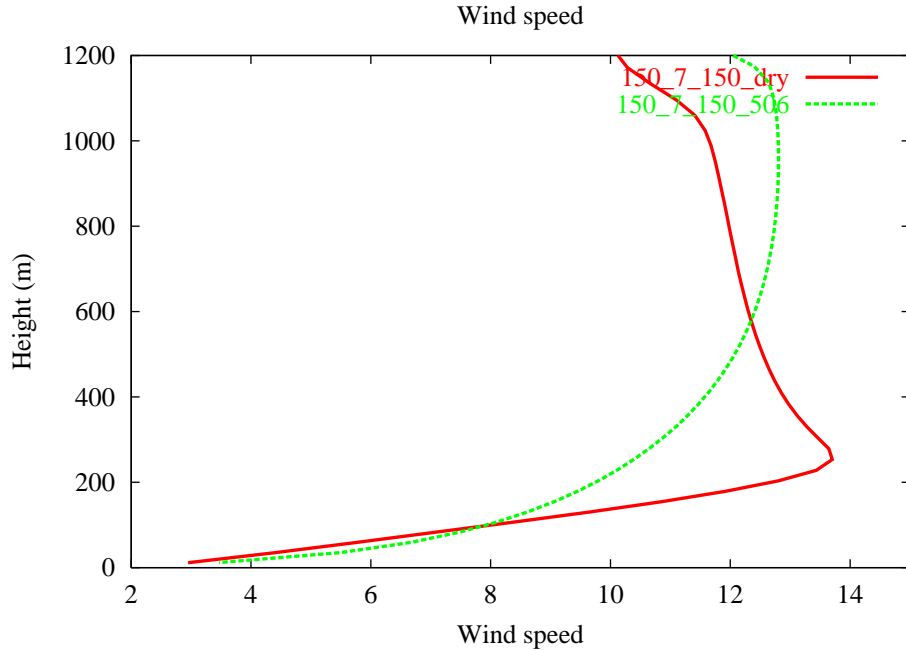


Figure 2: The wind speed profiles at the end of the night with CBR_dry and CBR_506.

of about 250 meters. CBR_506 also has a larger than geostrophic wind speed over a large part of the profile. However, the maximum wind speed below 300 meters is not found with this version of the scheme. The newer version of the scheme clearly has a stronger vertical mixing than the old CBR scheme under stable conditions. This stronger vertical mixing is beneficial for the reduction of the bias in the PMSL. This 1-D case shows that there may be a price to be paid for this stronger mixing. Phenomena such as low level jets do not develop with this stronger mixing. This the case not only in CBR_506, but also in CBR_moist and CLJ. The mixing is stronger in CBR_506 due to the dependence of the length scales on the Richardson number whereas the length scales in CBR_dry only depend on the stability.

2.2 Vertical resolution

To test the dependence of the behaviour of CBR/CLJ as a function of the vertical resolution we ran the 1-D model with 40 and 150 levels, with the lowest level at the same height in both experiments. In this way we are purely looking at the effect of the vertical resolution. We performed four experiments, three with constant surface forcing and one with a daily cycle in the surface forcing. The vertical diffusion scheme that is used in this experiment is CBR_506, the same version as in the current reference Hirlam (6.1.2).

The three experiments with a constant surface forcing (strongly buoyant, neutral and stable) are to check if the equilibrium profiles are similar. To achieve some form of equilibrium we let the model run for 24 hours. Again the geostrophic wind has a strength of 10 ms^{-1} and the 150 levels initial conditions are interpolated from the 40 level input profile, so initial inversion strength etc. are similar. In the unstable case the surface sensible heat flux is 150 Wm^{-2} , in the stable case this flux is -50 Wm^{-2} while in the case with the daily cycle the flux has a day-time maximum of 240 Wm^{-2} and a night-time minimum of -50 Wm^{-2} .

Figure 3 shows that the differences between the different profiles are very small. The largest differences occur in the stable case near the inversion, where the much coarser grid of the 40-level model becomes apparent. Figure 3 shows the wind speed profile after 20 hours in the experiment. The largest differences are about 0.2 ms^{-1} and no systematic differences can be found in this case, or the other cases with a constant surface forcing.

The run with the daily cycle (figure 4) shows only marginal larger differences between the two model versions. During the unstable part of the cycle the differences are small, but

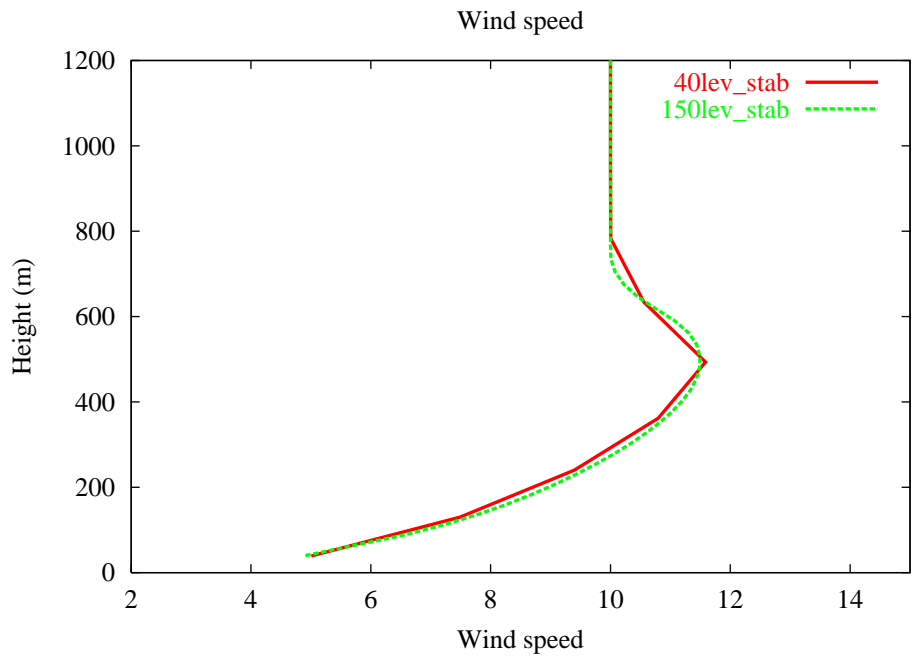


Figure 3: The wind speed profiles between hours 20 and 21 in the experiment in the stable case for the 40 and 150 level runs.

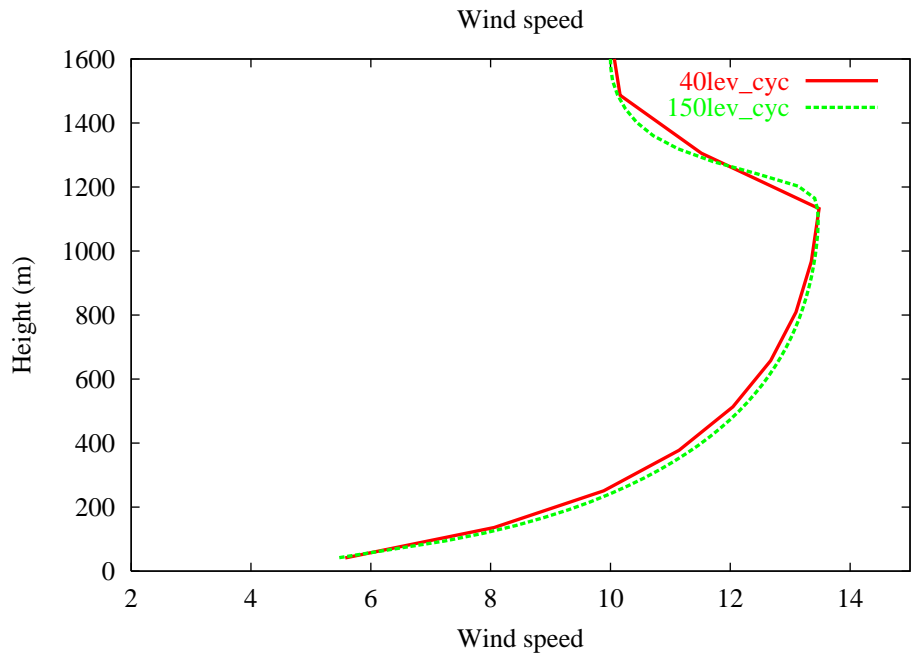


Figure 4: The wind speed profiles between hours 16 and 17 in the experiment in the daily cycle case for the 40 and 150 level runs.

during the stable part the differences are somewhat larger. Nevertheless, the vertical resolution dependence of the CBR/CLJ schemes is very small indeed. The resolution therefore is not a problem in the dry vertical diffusion. With stratocumulus clouds, however, this is not the case (see Tijn and Lenderink, 2003).

3 Height of lowest model level

3.1 1-D study

Surface fluxes of momentum (and heat) and their impact on the model profiles should not differ when the lowest model level lies at a different height. To check if this is the case (or not) we ran the 1-D model with 150 levels, but with the lowest model level at a height of about 12 meter in the first experiment en a height of around 40 meter in the second experiment. The differences in the wind profiles of both experiments are remarkable and may be important.

For both lowest level heights we have again run 4 experiments, similar to the experiments described in section 2.2. All experiments again are performed with CBR_506. We will only show results from the case with a strong surface sensible heat flux of 150 Wm^{-2} .

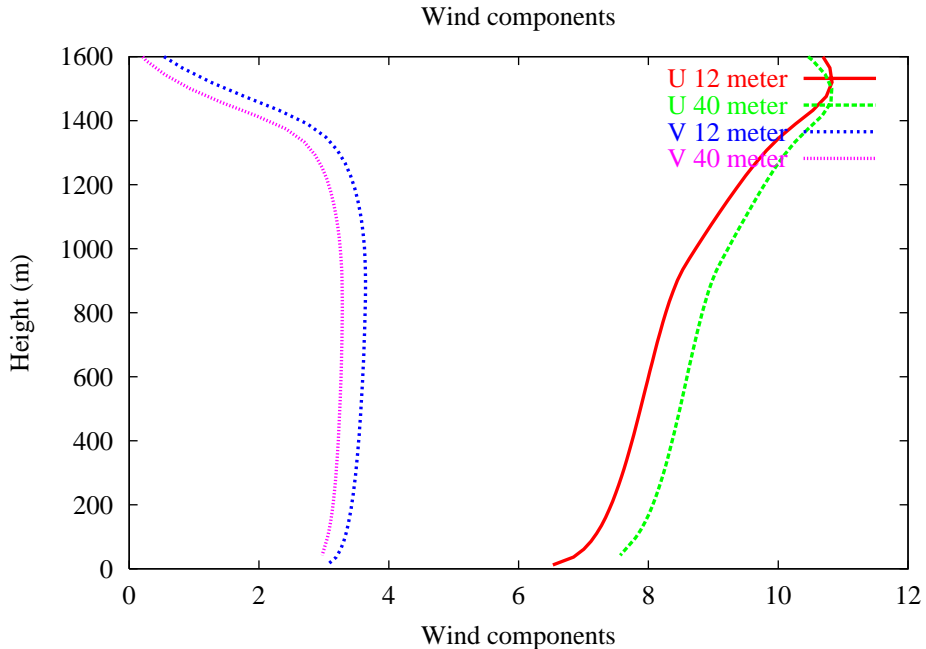


Figure 5: The U- and V-component profiles between hours 16 and 17 in the experiment in the unstable case (sensible heat flux of 150 Wm^{-2}) for the runs with a lowest level at 12 meter and at 40 meter.

Figure 5 shows the wind component profiles for the unstable case with a lowest level at approximately 12 meter and 40 meter. The main differences are a decreased U-component for the 12 meter run (around 0.5 ms^{-1}) and an increase of the V-component, the ageostrophic component. This means that the impact of the surface on the wind profiles becomes larger when the lowest model level is closer to the surface.

Where this difference comes from is not clear yet. Apparently, the relative impact of the surface, expressed in the surface drag, becomes larger when the lowest model level lies closer to the surface. This may be caused by the turning of the wind in the lowest part of the model. In the calculation of the surface stress it is assumed that the wind direction does not change between the surface and the lowest model level. In stable cases this clearly is not the case, but also in unstable cases the wind turns a little to the ageostrophic direction between e.g. 20 and 10 meter. This result may have important consequences for the behaviour of the model itself. The increase of the ageostrophic wind component can be as large as 10%, which can be very important for the behaviour of the 3D model. This increase may decrease the deepening of cyclones and fill them up more rapidly and decrease the negative pressure bias of Hirlam that we find especially in the winter storm season. It may also reduce the tendency of Hirlam to produce too active cyclones towards the end of the forecast period.

The most important conclusion, however, from this experiment is that the surface drag, or the surface momentum flux, is not independent from the height of the lowest model level. In the experiments a prescribed u_* is used, but in the formulation of this parameter a height dependence is included. A part of the difference may be explained by the absence of the turning of the wind in the lowest part of the model. The direction of the surface drag will therefore change when the height of the lowest model level is changed. This effect probably is largest when the vertical profile is stable.

3.2 3-D study

To study the effect of the height of the lowest model level on the Hirlam scores we made a test with Hirlam 6.1.0 where the lowest model level was lowered to about 12 metres (personal communication with Per Unden). We tested the period of 1 to 10 December 1999, a period with a lot of wind and the Danish storm of 3/4 December. The model resolution was 0.2° and the model area consists of a large part of the North Atlantic plus Europe. We will call this run L40 hereafter.

Running with the lowest level at 12 metres is not without a computational cost. The time step had to be reduced to enable the start of the experiment as the model aborts at the first time step in the digital filtering process when a time step of 360 seconds is chosen. With a time step of 180 seconds the model did run, however, with the time constraints on the Hirlam queue at ECMWF that meant that the forecasts could not exceed 24 hours.

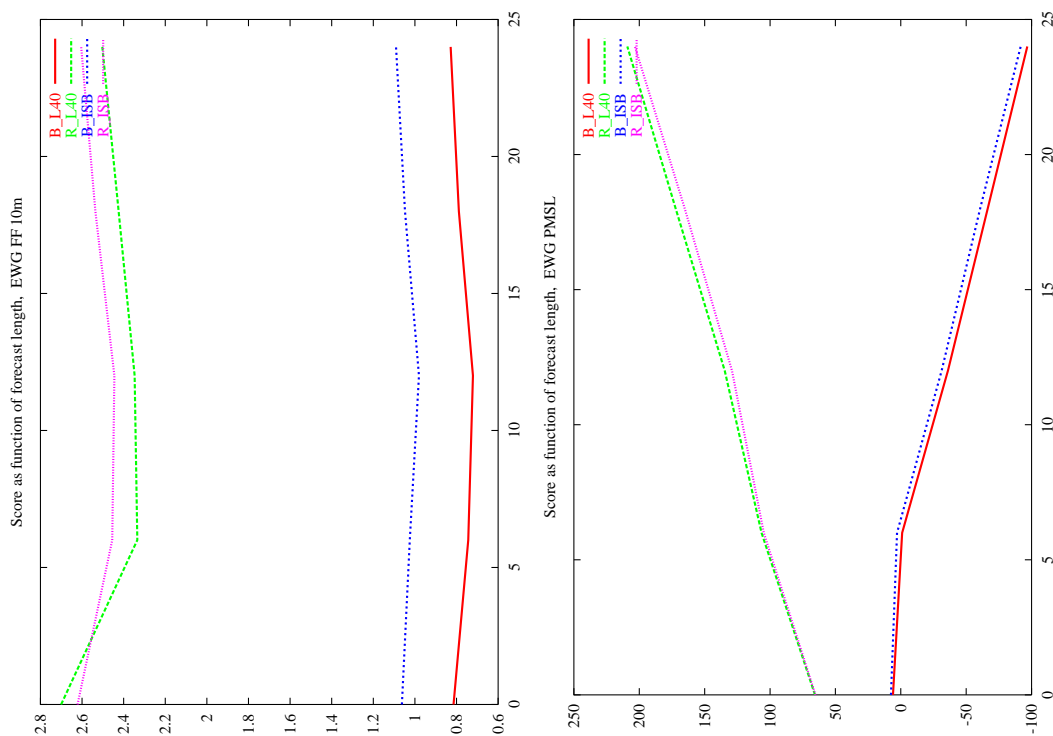


Figure 6: The bias (B) and RMS (R) scores of wind direction (top left, degrees), PMSL (bottom left, Pascal), 10m wind speed (top right, ms^{-1}) and 10m wind vector (bottom right, ms^{-1}) averaged over 1-10 december 1999 for Hirlam 6.1.0 with (DIR) and without (ISB) the turning of the surface wind-stress vector.

We have compared L40 with a reference run of Hirlam 6.1.0 which we will call ISB hereafter. ISB uses the standard 0.2° timestep of 360 seconds, but is the same as L40 otherwise (except of course for the position of the model levels). Figure 6 shows a few of the scores of this intercomparison. The wind speed RMS decreases a little, probably mainly due to a decrease in the wind speed bias, which is reduced by about 0.25 ms^{-1} . This reduction

in the wind speed bias is not accompanied by a reduction in the PMSL bias and/or RMS. This means that the ageostrophic wind component does not increase when we lower the height of the lowest model level. This is confirmed by the wind direction scores where the bias of the wind direction remains the same and where the RMS even increases.

From this experiment we therefore can conclude that, although the 1-D experiment suggests otherwise, the ageostrophic wind component does not increase with the lowering of the lowest model level. This procedure therefore is not a solution to the problem of the negative pressure bias at the higher latitudes in cyclones in winter.

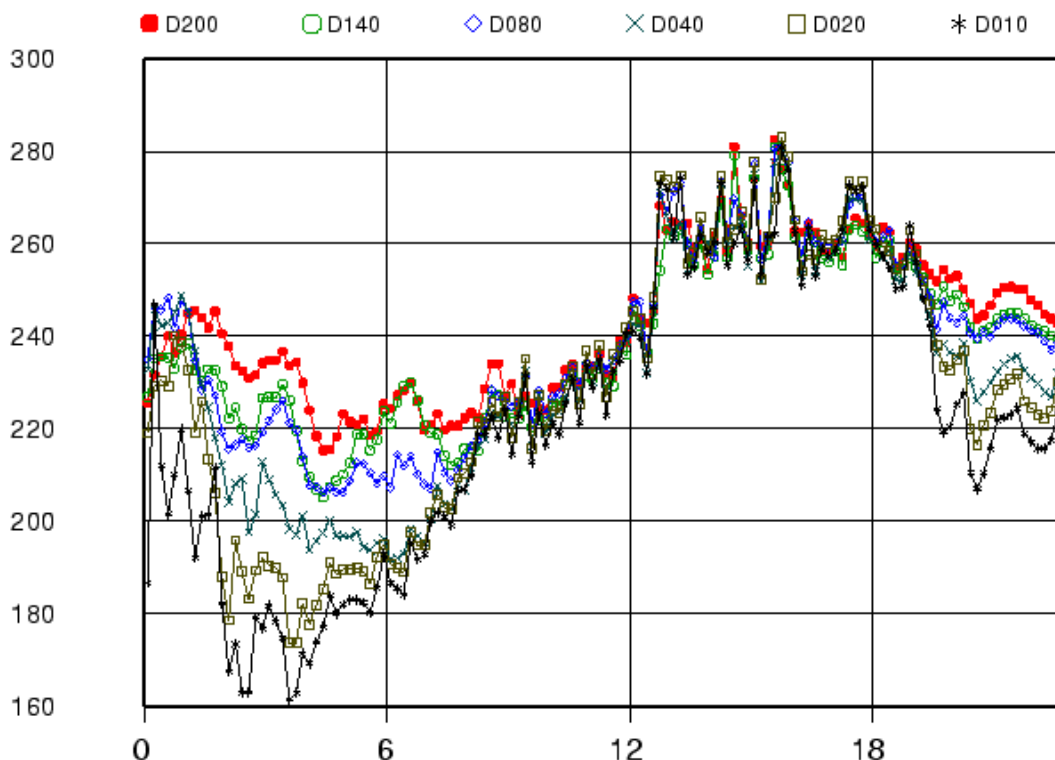


Figure 7: The wind direction at different heights at the Cabauw tower on 21 August 2003.

4 Turning the wind-stress vector

In the previous section we have shown that the height of the lowest model level has a clear impact on the wind profiles. Decreasing the height of the lowest model level increases the ageostrophic wind component in the 1-D model runs, but does nearly nothing in the 3-D runs. Hirlam has a clear wind direction bias with the wind blowing more in the geostrophic direction than in the observations. This can be explained, at least in part, by the absence of the turning of the wind with height in the postprocessing of Hirlam when the 10-m wind is calculated from the wind at the lowest model level. In reality, the wind does turn near the surface (see figure 7). The difference in wind direction near the surface between e.g. 30 and 10 metres will also result in differences in surface stress vectors and may be a cause for the too weak ageostrophic winds in Hirlam.

This last observation gives us the idea that a turning of the surface stress vector may help generate a larger ageostrophic wind component and reduce the wind direction bias in Hirlam. The turning of the wind direction is very clear in figure 7 when you look at the differences between 10 and 20 meter during the nighttime. During the day, the backing of the wind near the surface relative to the winds higher up is (almost) absent. That there is some turning of the wind direction in the real atmosphere between the lowest Hirlam level

(32 meters in the reference version) and the surface therefore is clear, especially under stable conditions. In the model this turning is not taken into account, the wind direction is taken to be constant between the surface and the lowest model level. The surface stress vector therefore will also have a slightly different direction than the wind at the lowest model level.

To test this hypothesis we have adjusted the direction of the wind-stress vector in CBR. As the surface stress is implicitly included in the reference version of Hirlam, we also made the source term for momentum explicit, to enable a simple testing of the turning of the wind-stress vector. In the first experiment we have turned the wind-stress vector 20° clockwise, so the force exerted on the wind is turned more into the direction of the pressure gradient. The turning of the stress vector by 20° is quite rigorous, but as we are interested only in the effects of this turning, the magnitude (within limits) is not very important. We take the 40 level Hirlam version for this experiment and force the surface fluxes with the daily cycle as described in section 2.2.

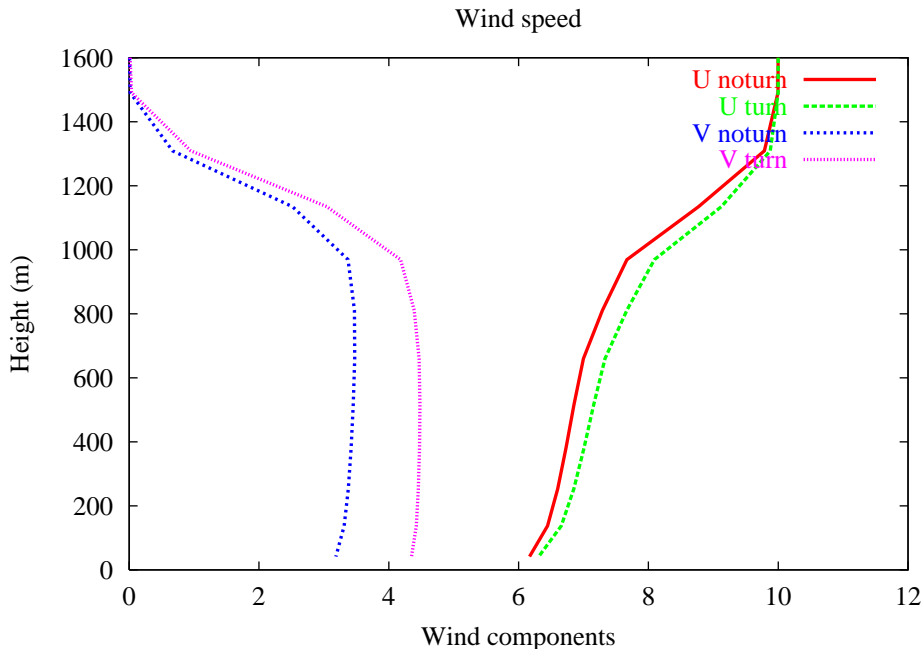


Figure 8: Profile of the wind components for the run with (turn) and without (noturn) turning of the surface stress vector after 10.5 hours in the experiments.

Figure 8 shows the wind components at the end of the period with positive sensible heat fluxes. The main difference between the two wind profiles is the strong increase in the V-component of the wind (ageostrophic) in the experiment with a 20° turning of the wind-stress vector. Apparently, this change results in the desired effect. The wind direction (not shown here) turns by about 8° in unstable conditions. Under stable conditions the wind veers an extra 10 to 12 degrees. As the increase of the ageostrophic wind component by 20 to 30 percent is quite radical, and may be way too much, we test the impact of the turning of the wind-stress vector by 10 degrees in a 3D experiment.

4.1 3D experiment

In the 3D experiment we turn the surface stress vector by 10 degrees, as an increase of the ageostrophic wind component by around 25% as found in the 1D experiment is too much. We run Hirlam 6.1.0 on a resolution of 0.2° over the North Atlantic and Western Europe for the period of 1 to 10 December 1999, including the Danish storm. The experiment is performed on a grid of 306 by 250 points. ECMWF analyses are used as boundaries and we use 29 and 30 november as spinup days.

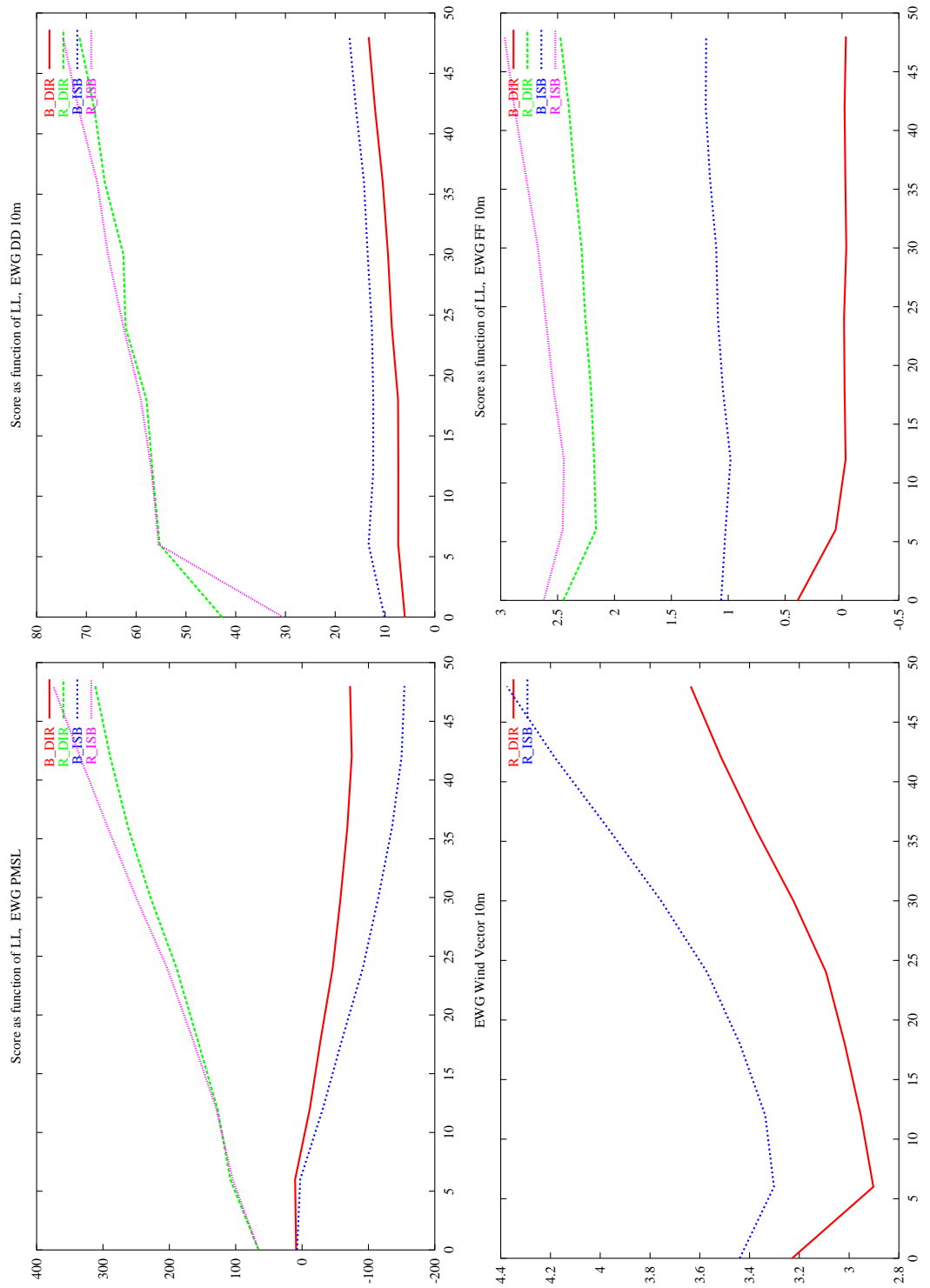


Figure 9: The bias (B) and RMS (R) scores of wind direction (top left, degrees), PMSL (bottom left, Pascal), 10m wind speed (top right, ms^{-1}) and 10m wind vector (bottom right, ms^{-1}) averaged over 1-10 december 1999 for Hirlam 6.1.0 with (DIR) and without (ISB) the turning of the surface wind-stress vector.

The experiments are performed with the aim to reduce the negative pressure bias of Hirlam in the winter storm season. Figure 9 shows the surface verification scores of the experiment (DIR) compared to a run with the same model version, but without the turning

of the surface wind-stress vector (ISB). The differences between the two runs are quite large. The negative bias in the PMSL is reduced by about 50% after 48 hours. This also results in a decrease in the RMS of the PMSL. The pressure scores therefore are improved a lot by the turning of the surface wind-stress vector.

These kind of improvements in PMSL scores were also found in experiments when the mixing in stable conditions was increased (e.g. Jones et al, 2003). However, as often has been the case with improved PMSL scores that were caused by changes in CBR, these improvements were accompanied by worse scores for the 10m wind. The problem with improving the scores through tuning CBR is that more mixing is needed to increase the surface stress, which in turn increases the ageostrophic wind component. The increased mixing increases the 10m wind speed bias and the RMS for the wind speed. Figure 9 shows that by turning the wind-stress vector, the wind speed bias is reduced considerably. In this experiment the wind speed bias has become zero, and stays there, whereas until now the 10m wind speed bias had the tendency to increase with forecast time. The improved PMSL is accompanied by an improved score for the 10m wind speed, something that cannot be achieved by tuning CBR.

The improved scores for PMSL are caused by the turning of the wind vector to the ageostrophic direction. This can be seen in the decrease of the 10m wind direction bias. The larger ageostrophic component causes a slower deepening and quicker filling up of the cyclones in the model. Inspection of a few PMSL maps during this period also shows that the maximum pressure in high pressure areas is a little lower. The entire pressure distribution therefore is flattened somewhat by the turning of the surface wind-stress vector. The decrease in the wind speed bias is not a direct effect of the fiddling with the stress vector. In the 1D experiment (figure8) the wind speed increases a little. This was due to the fact that the surface stress in the direction of the wind decreases a little by turning the surface stress vector and not changing the magnitude of the surface stress. The decrease of the wind speed bias is caused by a decrease of the surface pressure gradients, as the vertical diffusion scheme has remained the same.

The last score we show in figure 9 is the RMS of the 10m wind vector. This parameter has improved very much, so much that we gain almost 24 hours in the forecast, compared to the scores of the experiment with no turning of the wind-stress vector. The large improvements are caused by the cumulative effect of an improvement in the RMS of the wind direction as well as the RMS of the wind speed.

The positive scores are not only found near the surface. Higher up in the atmosphere (see figure 10) most scores also have improved at most levels after 48 hours. The geopotential clearly has improved through the entire atmosphere. The bias has been removed for the main part, while the RMS (and the standard deviation that is not shown here) also have been reduced. Again, the increased ageostrophic wind component seems to have reduced a long standing Hirlam problem.

The wind speed is the only score where deterioration can be found. Especially the absolute value of the bias of the wind speed has increased. Also this bias jumps from a positive value in the reference Hirlam to a negative value in the experiment with the turning of the surface wind-stress vector. The increase in the wind speed bias is accompanied by a decrease in the wind speed RMS, except for the highest verification level. This means that the standard deviation is reduced at most levels.

The wind vector also has improved considerably through the entire atmosphere. This improvement is much larger than the improvement in the wind speed, so it is caused by an improvement in the wind direction also. The last scores shown here are the temperature profiles. The bias and RMS for this parameter are better also, although the improvement is smaller than in the other parameters. Only the scores near the surface have been degraded a little.

5 Conclusions

From the 1D experiments it is clear that the newest versions of CBR/CLJ are not capable of representing the structure of stable (nighttime) vertical profiles very well. Too strong mixing

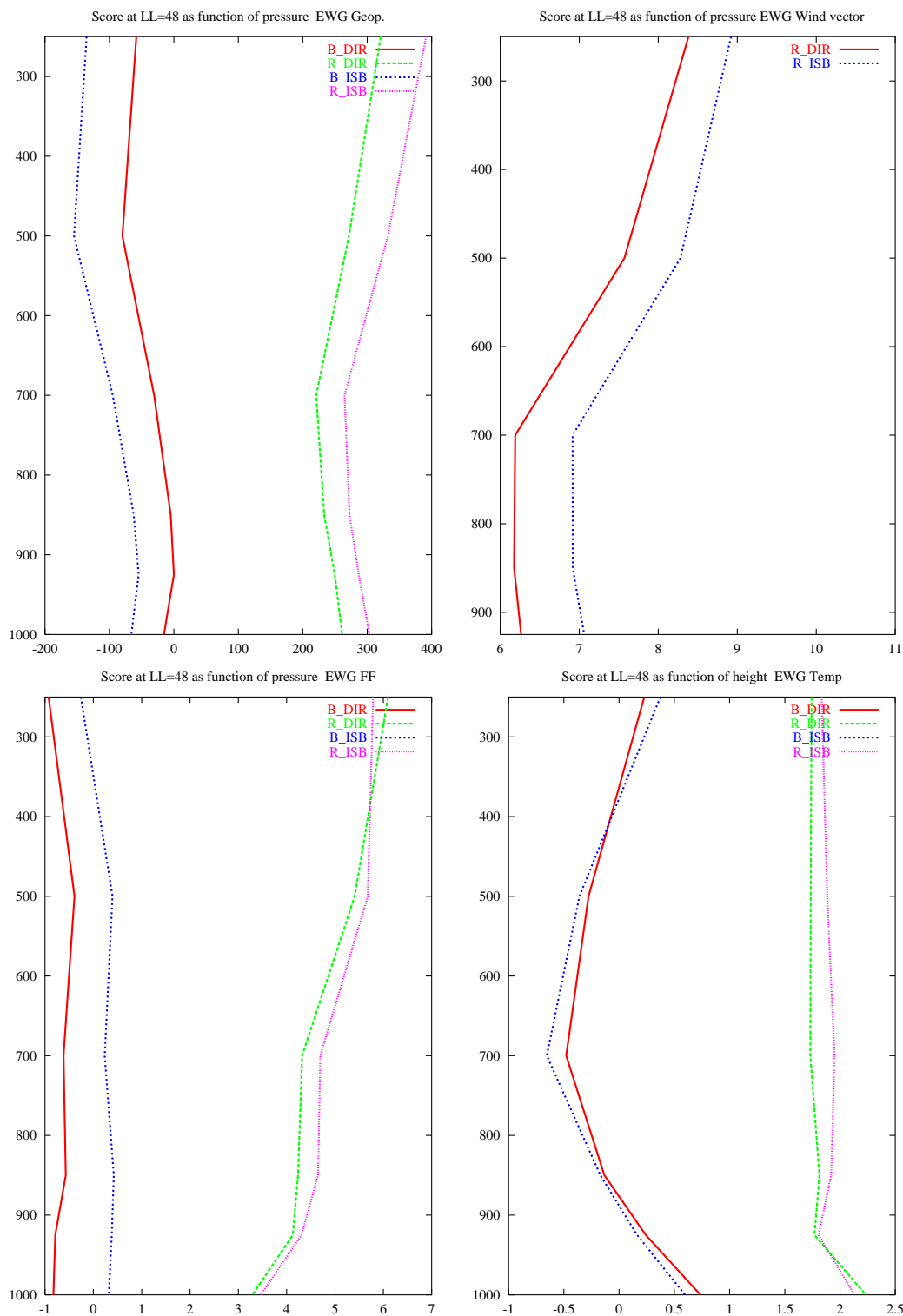


Figure 10: The upper air bias (B) and RMS (R) scores of geopotential (top left, gm), wind speed (bottom left, ms^{-1}), wind vector (top right, ms^{-1}) and temperature (bottom right, K) averaged over 1-10 december 1999 for Hirlam 6.1.0 with (DIR) and without (ISB) the turning of the surface wind-stress vector as a function of pressure and after 48 hours in the forecast.

under stable conditions is the reason for this behaviour. This has a strong impact on the capability of Hirlam to model flows like low-level jets, density currents (sea breezes, katabatic flows) and cold outflow ahead of e.g. cold fronts. At least a part of the underestimation of the strength of these phenomena comes from the too strong mixing in the current CBR versions.

The impact of the vertical resolution on the profiles of the wind and/or temperature is not very large, so for most processes the vertical resolution is not very important. For moist processes, however, the vertical resolution is very important and insufficient at the moment.

The height of lowest model level has a relatively large impact (5% decrease of geostrophic wind component, 10% increase of ageostrophic wind component). This may have large impact on life cycle of low pressure systems. Where this difference comes from is not clear yet. It may have to do with the turning of the wind in the lowest part of the atmosphere, that will be taken into account when the lowest model level lies closer to the surface. This will cause a shift in the direction of the surface stress, causing the difference in the ageostrophic component.

The observation made above has led to the testing of turning the surface wind stress vector to generate a larger ageostrophic wind component. Turning this vector by 20° causes the wind speed to increase by about 5 percent while the ageostrophic wind component increases with about 25% in the 1-D model. As this is a bit extreme we tried a turning of the surface stress vector of 10 degrees in a 3D experiment. This resulted in major improvements in the scores for PMSL and the wind. The PMSL scores were improved considerably due to the increased ageostrophic wind component that reduced the PMSL bias by 50%. The wind speed bias improved (decreased) due to a smaller pressure gradient. The turning of the wind stress vector therefore is a powerful tuning mechanism for Hirlam.

A moist version of CBR (more mixing in moist layers), that has less mixing under stable conditions, together with increased surface drag (De Rooy, 2003) may solve a lot of Hirlams problems.

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