Tuning CBR

A.B.C. Tijm

1 Introduction

The pre 6.2 reference Hirlam versions have a positive bias in the wind direction under stable conditions (night and winter conditions), accompanied by too strong near surface winds. In addition there is too little Ekman-pumping, resulting in too fast deepening and too slow filling of cyclones, making the model too active towards the end of the forecast period.

Two ways of dealing with this overactivity have been proposed. The first one is increasing the vertical mixing of momentum under stable conditions, representing the mixing caused by gravity waves, through increasing the mixing coefficient. This is done on top of a larger surface roughness over sea and an increased orographic roughness (see the release notes of Hirlam version 6.2.4). The second proposed solution (Tijm, 2003; Sass and Nielsen, 2004) is a turning of the surface stress towards the geostrophic direction under stable conditions. This causes the wind to turn more to the ageostrophic direction, resulting in more ageostropic wind, a smaller wind direction bias and stronger Ekman-pumping.

The GABLS (GEWEX Atmospheric Boundary Layer Study, see http://turbulencia.uib.es/gabls) intercomparison shows that the vertical mixing of momentum in Hirlam is much too strong, even more so when the updates of Hirlam version 6.2.4 are introduced. This causes the development of a too deep boundary layer in the GABLS stable case, with too strong winds at the surface, a wind profile that has its maximum at the wrong place (too high) and cold air being mixed too deeply. The mixing under stable conditions therefore has to be reduced, but this will re-introduce the old problems.

The turning of the surface stress may prevent the recurrence of the problems in the Hirlam model of the past. Tijm (2003), Sass and Nielsen (2004) and Järvenoja (2004) show that the pressure scores improve as do the wind vector scores when the stress turning is introduced in the Hirlam system. The question, however, is why this surface stress turning is needed. A solid fundamental explanation has so far not been found.

Inspired by the work of Sass and Nielsen (2004) and the GABLS intercomparison, the effect of the stress turning and the formulation of CBR on the wind profiles as well as the wind near the surface are studied. Through a number of experiments, by comparison with high resolution radiosonde data and with standard verification output I try to arrive at a model version that produces good results on the synoptic scale as well as locally in the profiles.

2 1-D Experiments, near surface output

The parameters that are changed in the experiments are the magnitude of the base mixing coefficient under stable conditions (c_h in equation 3.85 in Undén et. al., 2002), the turning of the surface stress direction and an extra mixing contribution for momentum representing the mixing by gravity waves which effectively is an increase of c_m compared to c_h. In the first 1-D experiment we use the settings of Hirlam version 6.2.4, where the surface stress turning is not yet implemented, c_h is 0.2 and the extra mixing for momentum is defined as:

$$c_m = c_h * max(1, min\left[(1 + \gamma Ri) * pfunc, 10\right]) \tag{1}$$

where Ri is the Richardson number and pfunc is:

$$pfunc = max\left(0, \frac{P - 100}{P(nlev) - 100}\right) \tag{2}$$

where P is the pressure (in hPa) and $P(nlev)$ the pressure at the lowest model level. This function is 1 near the surface and drops off to 0 at high levels. The parameter γ is a tuning parameter that determines the strength of the extra mixing under stable conditions. In Hirlam 6.2.4 this parameter has a value of 3.8. This run is called CBR 6.2.4.

In the second 1-D run we use $c_h = 0.1$, $c_m = c_h$ and the turning of the surface stress vector is not applied. In the figures we denote this setting as CBR mix0.

In the third run we use the settings as tested for their operational use by DMI. Here c_h is taken as 0.1, the turning of the stress vector is applied and the γ in equation 1 is reduced to 3.0. In the figures we denote this run as CBR DMI.

The fourth run uses the settings of the DMI-run, but the shape of the extra mixing function is changed drastically. From observations it is clear that the extra mixing through gravity waves is important for Richardson numbers up to 1 (Lenderink, personal communication). Above this number the extra mixing of momentum should fall off to zero again. In CBR 6.2.4, the vertical mixing under stable conditions is much too strong, preventing the buildup of shallow stable layers and destroying phenomena such as the low-level jet, so the extra mixing under stable conditions should be reduced. In the fourth run this is achieved through defining c_m as:

$$c_m = c_h * max(1, min\left[(1 + \gamma Ri * exp(-Ri^2)) * pfunc, 4\right]). \quad (3)$$

We will call this version of CBR in the figures CBR new.

Figure 1 shows the cross isobar angle of the 10-m wind as a function of time for the winter case as described in Sass and Nielsen (2004). In this case the surface roughness is $0.01m$, the latitude 70°N and the date is 20 December, so the 1-D column is cooled at the surface by radiative cooling. The initial temerature and wind profiles are as described in Sass and Nielsen. Figure 1 shows that the cross isobar angle in this experiment depends most strongly on the switching on or off of the extra mixing of momentum under stable conditions. There is a big difference in the cross isobar angle of the 10m wind when c_m is put to c_h for $c_h = 0.1$ (the value found to be best for the GABLS-case, CBR mix0). When the results are compared to Hirlam version 6.2.4 an additional turning of the 10m wind of 20° to 30° can be found. The impact of the turning of the stress vector combined with a

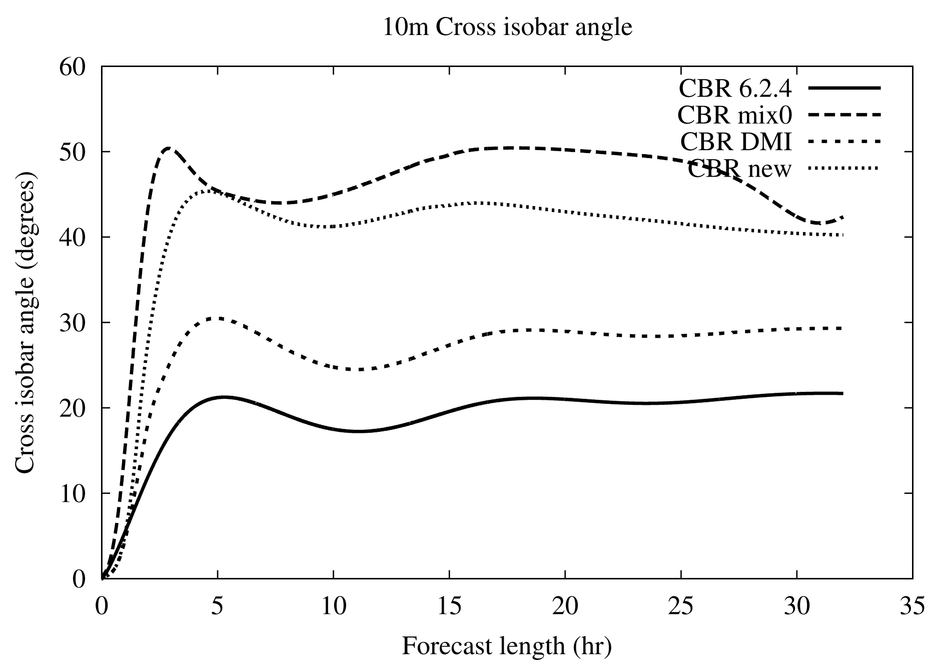

Figure 1: *The cross isobar angle of the wind at 10 meter for different settings in the CBR-scheme (version 6.2.4) and with and without the surface stress turning for the case with a geostrophic wind speed of $10ms^{-1}$ and a roughness of 0.01m at 70°N. The run starts at 20 December, 00 UTC.*

reduction of c_h to 0.1 is much smaller, only around 10°. The cross isobar angle of around 45° with CBR mix0 is probably quite good, because standard verification scores show that the nighttime bias in the wind direction is around 15° to 20°. The new definition of the extra momentum mixing (equation 3, CBR new) combined with the surface stress turning comes closest to the CBR mix0.

The second experiment that has been run is the summer time experiment, again similar to Sass and Nielsen (2004). Here, we use a roughness of 0.35m. This experiment is performed to study the daily cycle of the wind speed and direction.

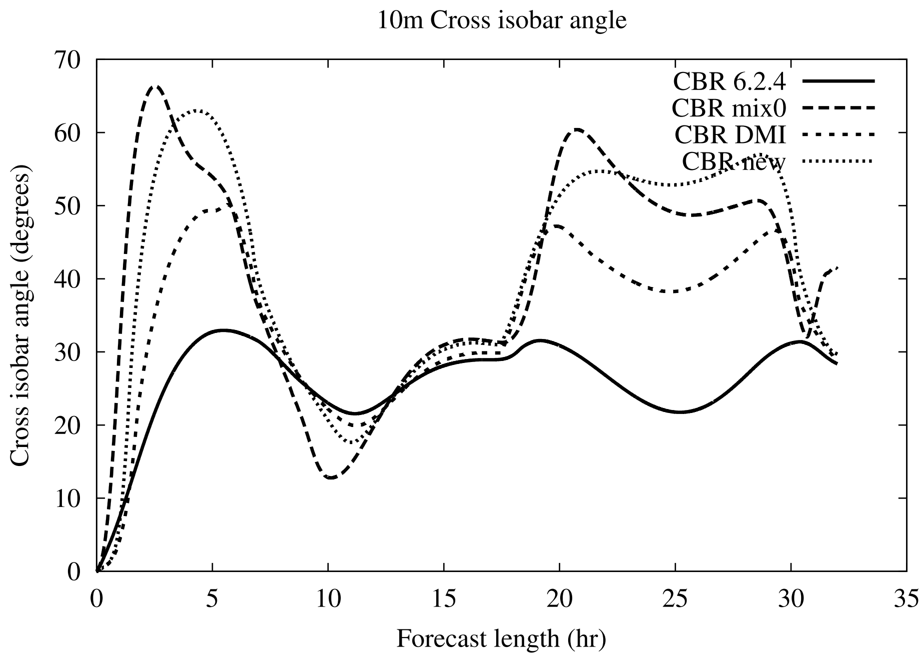

Figure 2: *The cross isobar angle of the wind at 10 meter for different settings in the CBR-scheme (version 6.2.4) and with and without the surface stress turning for the case with a geostrophic wind speed of 10ms^{-1} and a roughness of 0.35m at 45°N. The run starts at 1 July, 00 UTC.*

Figure 2 shows similar differences as figure 1, with CBR mix0 and CBR new giving the largest daily cycles in the wind direction, while CBR 6.2.4 shows almost no daily cycle. For this higher roughness case, CBR DMI also shows a reasonable daily cycle. The most striking feature of figure 2 is the strong daily cycle that Hirlam 1-D can produce when the extra mixing is removed. This shows that fundamentally there is nothing wrong with the CBR-scheme. This is confirmed by the results of the 1D GABLS case, where CBR mix0 reproduces the LES results qualitatively as well as quantitatively in a correct way. The extra mixing, necessary in Hirlam 3D to get a good synoptic behaviour, therefore is the cause for the too weak daily cycle in the wind direction. The wind speed (not shown here) shows similar results.

When extra mixing under stable conditions is applied, the daily cycle of the wind speed and wind direction improve considerably when the turning of the surface stress under stable conditions is included. This is shown by the much larger daily cycle of the wind direction for CBR DMI. The decrease of the extra mixing described in equation 3 causes the daily cycle of the wind direction to become more like the one for CBR mix0.

If Hirlam would behave correctly on a synoptic scale for CBR mix0, we would be ready. However, this is not the case. The Ekman pumping and resulting filling of lows would become too weak, making the model too active towards the end of the forecast period. We are therefore seeking a CBR with the least possible extra mixing under stable conditions, with a good daily cycle of the wind, with good profiles and a good behaviour on the synoptic scale.

3 1-D Experiments, profile information

In the previous section we have looked at the near surface characteristics of Hirlam 1D with different settings in the CBR scheme. In this section we look at the behaviour of the profiles. Hirlam 6.2.4 is not capable of reproducing phenomena like low-level jets, phenomena that can be important for wind energy applications, aviation forecasting and the initiation of thunderstorms during the evening and night. This problematic behaviour is caused also by the extra mixing of momentum under stable conditions.

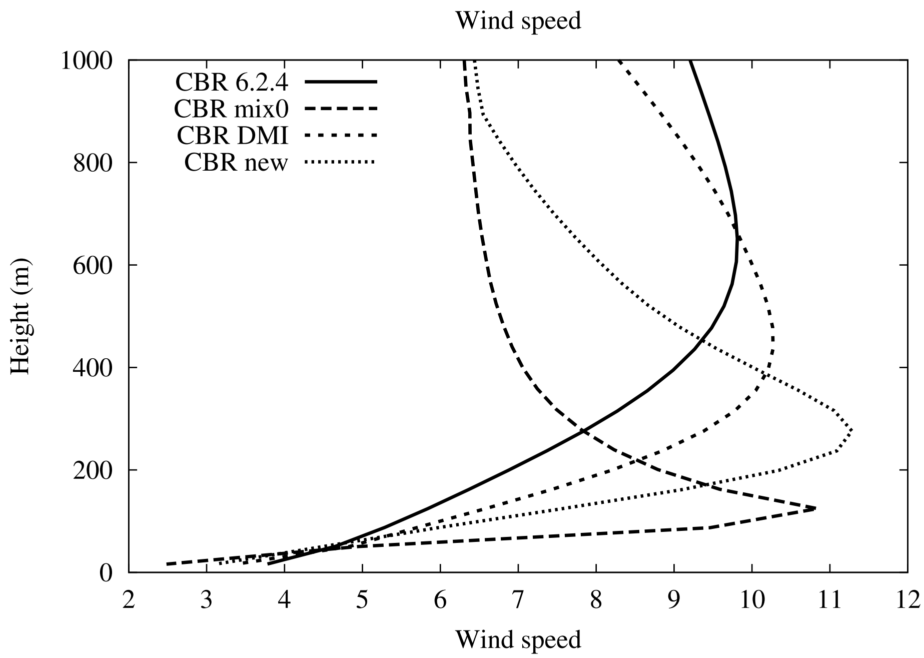

Figure 3: *The wind speed profile at 6 UTC on the second day for the summer case at 45°N starting at 00 UTC on July 1 and with a surface roughness of 0.35m.*

Figure 3 shows the wind speed profiles after 30 hours in the summer experiment with a roughness of 0.35m. In the model this is the end of the night and the changes in behaviour of the different CBR versions are very clear. CBR 6.2.4 shows almost no low-level jet. With some effort a maximum wind speed at a height of 700 meters can be found. The other extreme is CBR without extra mixing, that shows a very pronounced maximum at a level of around 140 meters. At the same level Hirlam 6.2.4 has a wind speed of only 6 m/s, almost 50% weaker than without the extra mixing. The other two versions of CBR lie between the two extremes with CBR DMI looking quite similar to CBR 6.2.4 and CBR new with equation 3 looking more like the CBR mix0.

In addition to giving good near surface and profile behaviour, the tuned CBR scheme must also give good synoptic scores. The last year it has become clear that good dynamic (synoptic) behaviour of Hirlam depends strongly on the Ekman pumping (cross isobar flow) being large enough. In older versions of Hirlam the cross isobar flow is too weak, causing cyclones to deepen too quickly and fill up too slowly. This causes the model to become too active towards the end of the forecast and is (probably partly) responsible for the lack of consistency between subsequent forecasts in some Hirlam versions.

Hirlam 6.2.4, by contrast, is damped much more than previous Hirlam versions. This is achieved through increased roughness of the surface (sea and land) and increased mixing under stable conditions. As shown above, this increased mixing causes wrong profiles under stable conditions, making the Hirlam forecasts less valuable for certain applications. Also, the model is damped too much now, as the momentum flux, averaged over the entire model domain, is considerably lower at the end of the forecast than at the start of the forecast.

The activity of a Hirlam version may be judged from 1D experiments by looking at the cross isobar flow. The cross isobar flow is a good measure for the magnitude of the Ekman pumping. From previous experiences we know that CBR 6.2.4 fills cyclones up too fast, CBR mix0 does it too slowly, while CBR DMI has about the right filling rate, but still the profiles under stable conditions are not correct. With the correctly tuned CBR we are therefore seeking for a cross isobar flow that is less than CBR 6.2.4, much more than CBR mix0 and close to CBR DMI. Here we look at the winter case, again as described in Sass and Nielsen (2004).

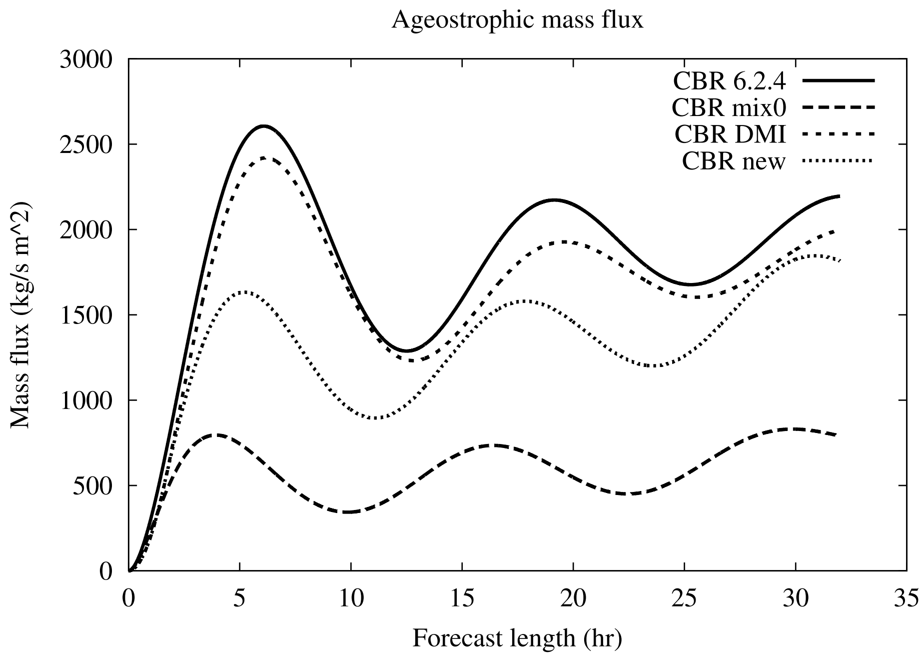

Figure 4: *The cross isobar flow for the winter case at 70° N starting at 00 UTC on December 20 and with a surface roughness of 0.01m.*

Figure 4 shows that CBR 6.2.4 has the largest cross isobar flow while CBR mix0 has the lowest cross isobar flow by far. CBR DMI is quite close to CBR 6.2.4 while CBR new lies somewhere in the middle, with a tendency towards the larger cross isobar flow towards the end of the experiment. All these 1D experiments are performed with the same surface roughness, while different Hirlam 3D versions may also have different surface roughnesses, e.g. over the sea through the Charnock constant or over land though the changes in the vegetation roughness. This means that the dynamical behaviour may differ from these 1D results, also because of the changes in the roughness. From this figure we expect that the CBR 6.2.4 will damp dynamical developments strongest while CBR mix0 will be too active. Note that the CBR DMI and CBR new both incorporate the turning of the surface stress.

4 3D experiments

The 3D experiments focus on three aspects of the behaviour of Hirlam. The first is good synoptic scores through a correct dynamical behaviour. The second is good near surface scores, especially for the wind direction where Hirlam has had a large bias at least in the CBR-era. The third aspect is a better behaviour of the profiles in the lowest km of the model domain. As we can see above, Hirlam 6.2.4 is not capable of producing low-level jets due to the too strong mixing under stable conditions. Two periods have been run, one short period in the summer of 2003 (July 12 - 16), where low-level jets were clearly visible in the

Cabauw measurements. The second period is 1 to 14 January 2004, a period that started with cold wintry weather in the Netherlands and saw a shift to milder and more dynamic conditions in the first week of January.

In the experiments we use a 0.2° version of Hirlam 6.3.3 with standard settings (e.g. 40 levels, IDFI) and with a 6-hour analysis cycle. The model domain is 250 x 250 points centered on North West Europe. ECMWF analyses are used as boundaries. The changes in the physics in the different runs are summed up in table 1.

Table 1: *Coefficients for CBR and the Charnock constants used in the different experiments. The first column gives the experiment name, the second the equation that is used in the enhanced stable mixing calculations, the third the magnitude of* c_h*, the fourth the parameters in the enhanced mixing calculations and the fifth the Charnock constant that is used in the calculation of the roughness over the sea.*

experiment	extra mixing	c_h	γ, max	Charnock
PO8	(eq 1)	0.2	$3.8, 10$	0.025
PO9	(eq 1)	0.1	$3.0, 10$	0.018
P10	(eq 4)	0.1	$3.0, 4$	0.018
P11	(eq 3)	0.1	$3.0, 1.5$	0.018

Experiment 3 has a different shape of the additional stable mixing than is used in PO8 or P11. For $Ri < 1$ it is the same as in the DMI run. For $Ri \geq 1$ the mixing coefficient for momentum is defined as:

$$c_m = c_h * max(1, min\left[(1 + \gamma/Ri) * pfunc, 4\right]) \qquad (4)$$

where γ is 3.0. The maximum c_m with this function is much lower than with the expressions used in the other experiments. This also means that the extra mixing under stable conditions is reduced considerably.

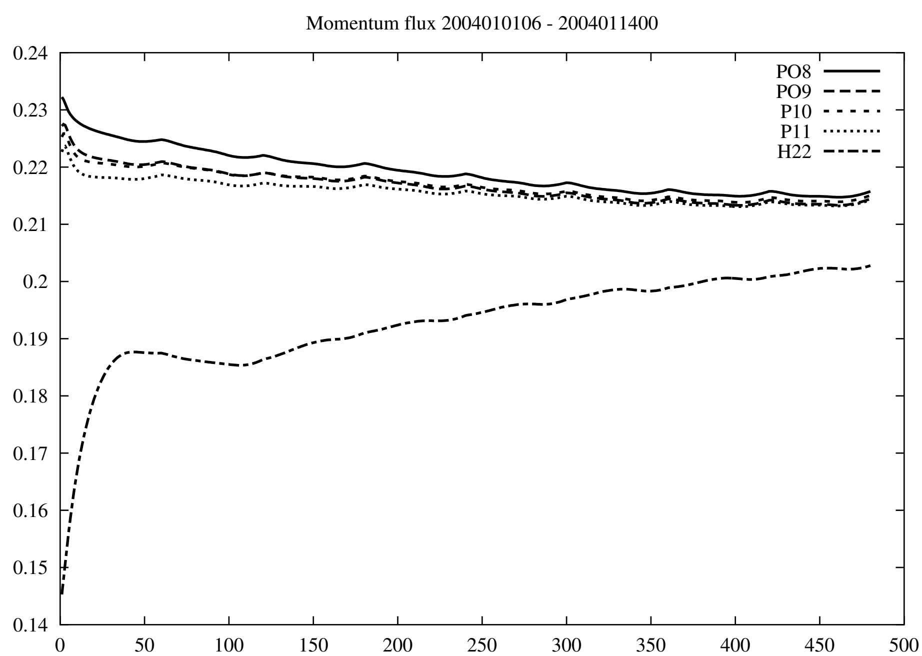

Figure 5: *The model area average momentum flux averaged over 56 forecasts from 01-01-2004 to 14-01-2004 for the four experiments and Hirlam 5.0.6 (H22).*

One way of looking at the dynamics of Hirlam is through the surface momentum flux. Average statistics are calculated for every time step of the forecast and by averaging every individual time step over a large number of forecasts you can get a good idea about the dynamical activity of a model. The current operational KNMI version of Hirlam (version 5.0.6) clearly shows an increase in momentum flux during the forecast period (see figure 5). Disregarding the spinup, the surface momentum flux increases from around 0.185 to 0.203, an increase of 10%. This increase is caused by the cyclones becoming too deep and the highs remaining too high. The resulting increases in the pressure gradients cause the increasing momentum flux. Figure 5 also shows that the experiments with the more recent version of Hirlam shows a slight decrease in the momentum flux. This is also conform the experiences with Hirlam version 6.2.2 (plus some adjustments that were included in Hirlam in version 6.2.4) at KNMI which shows a model that is damped too much.

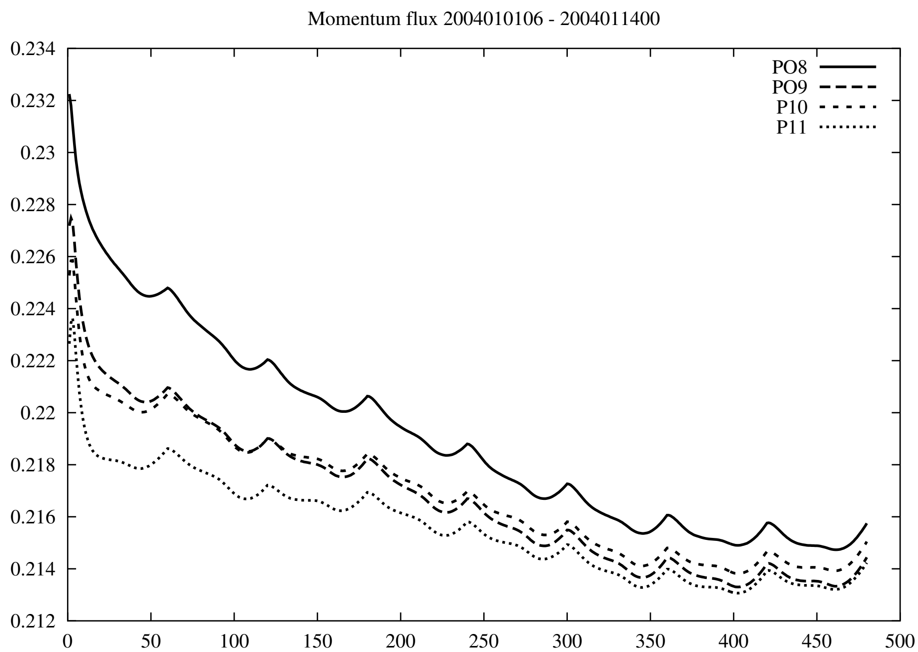

Figure 6: *The model area average momentum flux averaged over 56 forecasts from 01-01-2004 to 14-01-2004 for the four experiments and Hirlam 5.0.6.*

Zooming in on the new experiments, figure 6 shows that all four experiments experience a decrease in the momentum flux during the forecast. The largest decrease is found in experiment PO8, which is the reference version of Hirlam (6.3.3), measured as the difference between the first local minimum around time step 50 and the last minimum around time step 470. The experiment with the DMI-settings has the second largest decrease while experiment P10 has a decrease that is a little smaller. Experiment P11 is damped the least with a decrease of the surface momentum flux of only 2%. The last experiment therefore has the best behaviour of the four experiments, with experiment P10 coming second. Note that the absolute value of the surface momentum flux is smaller in experiments PO9, P10 and P11 due to the decrease in the roughness over sea. Note also that the spinup is almost absent in the new Hirlam version, as can be seen clearly from the comparison with figure 5.

Good dynamical behaviour off course is not the only important characteristic of a model. Good verification scores are also important. Here only the verification scores are shown in plots where considerable differences can be found between the different experiments. In a table we will give the score of the forecast parameters with smaller differences.

The first verification figure shows the bias of the 10m wind direction. This bias was the reason for the research involving the stress vector adjustment and the pressure bias. Figure 7 shows that the bias is reduced considerably through the reduction of the mixing under stable

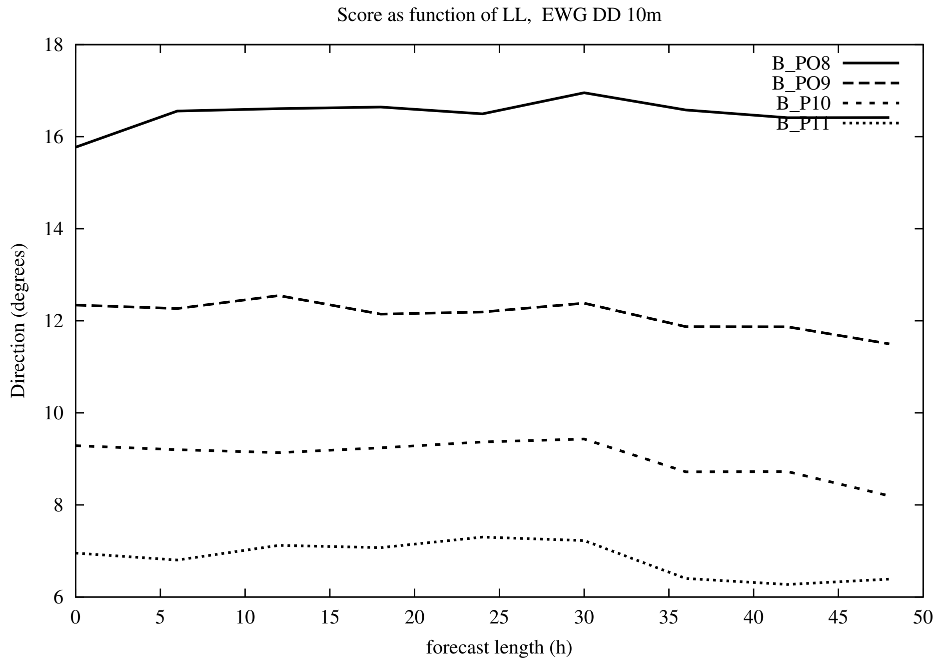

Figure 7: *The 10m wind direction bias for the EWGLAM stations averaged over 56 forecasts from 01-01-2004 to 14-01-2004 for the four experiments.*

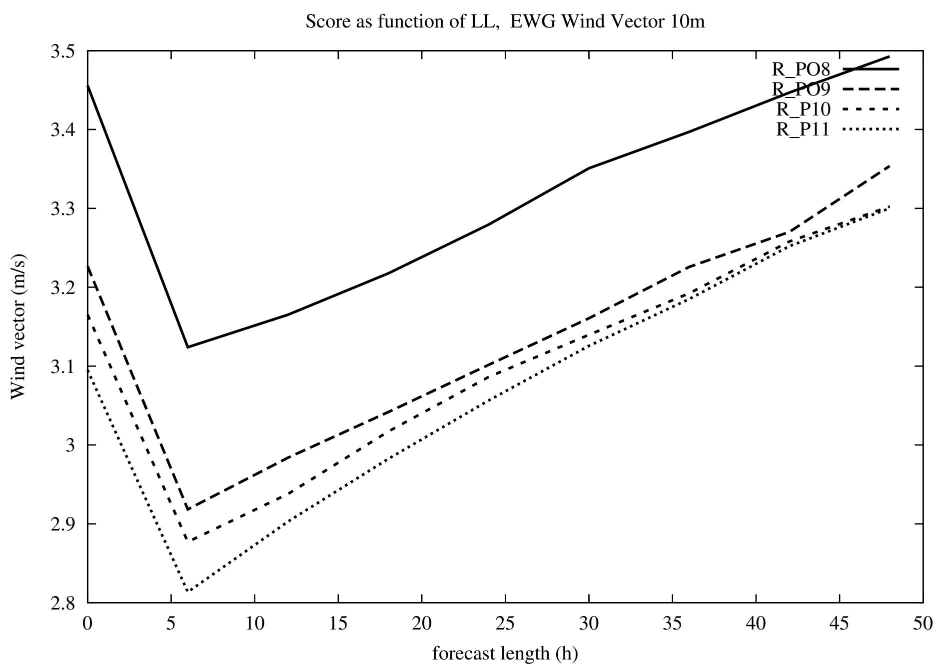

Figure 8: *The 10m wind vector RMS for the EWGLAM stations averaged over 56 forecasts from 01-01-2004 to 14-01-2004 for the four experiments.*

conditions together with the turning of the surface stress vector. The largest reduction is achieved in P11, where the mixing coefficient under stable conditions is reduced the most. Still, some of the bias (around 6°) remains while the roughness over land in the model will be larger than the roughness around the observation stations. The wind deviates from the geostrophic direction more over rougher terrain, which means that the model should have a negative wind direction bias over land. That this is not the case may mean that the roughness over land still is too small. This conclusion is confirmed by the wind speed bias that is still positive in all runs over land (see table 2).

The second verification figure shown here is the 10m wind vector scores (figure 8). This score is also improved significantly when P10 and P11 are compared with PO8. This figure shows that the large extra mixing under stable conditions is not necessary for good synoptic scores and good wind vector scores. With only small extra mixing and with the aid of the surface stress turning the verification scores remain very good. The improvement of this score is achieved primarily over land because the scores over the sea (Northern North Sea) do not show this improvement. This probably also means that we are heading in the right direction with the adjustments over land, but that we have not yet reached the best possible settings with the model.

Table 2: *+48h verification scores of a few parameters for the EWGLAM stations for the period 01-01-2004 to 14-01-2004.*

experiment	Bias				RMS			
	PMSL	ff10m	T2m	Td2m	PMSL	ff10m	T2m	Td2m
PO8	**-23**	0.52	**-0.34**	**-0.43**	249	2.21	3.16	3.29
PO9	-36	**0.50**	-0.71	-0.52	241	**2.18**	3.21	3.34
P10	-30	0.54	-0.78	-0.56	249	2.19	**3.12**	**3.25**
P11	-42	0.53	-0.84	-0.58	**236**	2.19	3.17	3.27

Table 2 shows that the verification scores for the other parameters do not differ very much. Experiment PO8 has the best scores when looking at the bias, but this may be caused by the extra mixing under stable conditions that masks errors that are made in e.g. the surface fluxes. Removing the extra mixing under stable conditions may therefore help in the study and improvement of the surface fluxes and near surface parameters.

The second experiment that was performed was a short summer period with low-level jets over the Netherlands. The currently operational KNMI-Hirlam as well as the current reference Hirlam are not capable of reproducing low-level jets adequately. Low-level jets are important because they can be the cause for moisture convergence, triggering convection, they are important for aviation forecasting and not forecasting low-level jets reduces the usefulnes of Hirlam output for e.g. the forecasting of the potential energy supply from wind.

Figure 9 shows the +30h forecast of the temperature profiles at De Bilt at 06 UTC on July 14, 2003 and the +48 forecast of the wind profiles at the same location at 00 UTC on July 15, 2003. Both profiles clearly show the effect of reducing the extra mixing under stable conditions. The temperatures are lower in P10 and P11 than in the other two experiments up to about 300 m. This is caused by the shallower cooled layer in these last two experiments. The experiment with the smallest extra mixing under stable conditions (P11) has the highest temperatures above this level, the remnants of the PBL of the previous day. The formulation of the stable mixing in PO8 and PO9 causes the cooled surface air to mix higher up, increasing the near surface temperature, decreasing the temperature higher up and overall increasing the heat release by the surface during the night. The increased mixing also stabilizes the remainder of the PBL of the previous day (between 970 and 920 hPa) more than P11 does.

The effect of decreasing the mixing under stable conditions has the largest impact on the momentum flux. For the temperature the only change is the decrease of c_h from 0.2 to 0.1, while for the wind the extra mixing through the calculation of c_m (the Richardson term) is affected also. The right hand side of figure 9 shows the impact of the decrease of c_m on the wind speed profile. The largest difference occurs between the runs P10 and P11, where the maximum wind speed increases by 2 ms^{-1}. This maximum is found at a height of about 400 meters while at around 200 meters the wind speed is around 11 ms^{-1}.

The observed (radiosounding) wind speed at this level is almost 15 ms^{-1} and the ra-

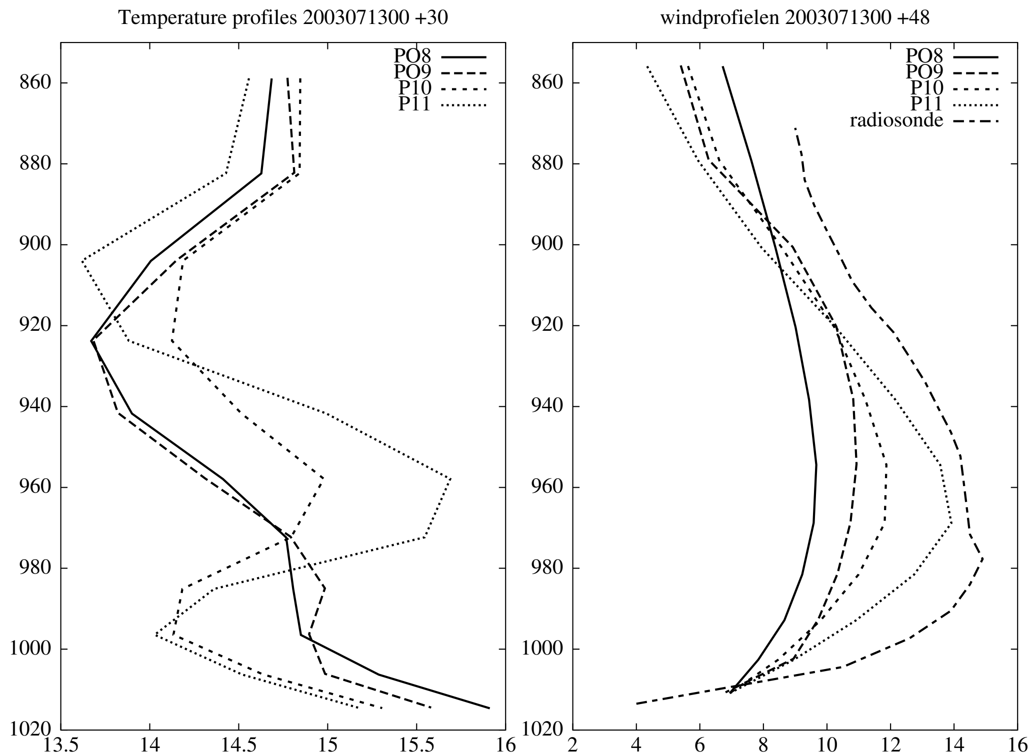

Figure 9: *The +30h temperature profiles (left, °C) and the +48h wind profiles (right, ms^{-1}) at De Bilt as a function of pressure for the run starting at 13 July, 2003, 00 UTC.*

diosounding shows a much larger gradient between the near-surface wind and the first few observation points than all experiments. The adjustment in P11 therefore goes in the right direction, but it still is far from the observed wind speed and profiles. What is clear from this experiment is that the changes in the vertical diffusion are heading the right way to resolve the deficiencies that can be seen in the profiles of the lowest km of the atmosphere when looking at high resolution radiosoundings or observations from sites like Cabauw. Figure 3 shows that CBR also is capable of producing gradients similar to the one in the radiosounding in figure 9, but for this the extra mixing under stable conditions has to be switched off completely. Note that the standard verification is not capable of showing the deficiencies in the lowest km because the temp-verification only is performed at certain pressure levels with the first one at 1000 hPa and the next one at 925 hPa.

5 Conclusions and discussion

In this article a version of CBR is described that produces good synoptic scores, better near surface winds (smaller bias in wind direction) and better profiles in the lowest km of the model domain. The results of this study, however, have to be seen as a step in the right direction and not the end point of the evolution of the dry CBR scheme, because the profiles still are not good enough to be compared favourably with the observations.

The CBR scheme is capable of producing correct wind profiles and near surface wind directions, if the extra mixing under stable conditions is removed completely. The 1D results and comparison studies like GABLS show that the settings in CBR mix0 probably are the correct ones for homogeneous terrains. From 3D experiences we know that with these settings the model becomes too active and pressure biases can become large.

So far this overactivity has been solved by increasing the mixing under stable conditions. By doing this, however, the model output becomes less useful in the lowest km of the model domain. Low-level jets (and probably other features under stable conditions) are not resolved resulting in a negative nighttime wind speed bias at a height of 100 to 200 meters that can be as large as 50% of the observed wind speed.

The synoptic scale problems of Hirlam may have two causes. The first one is the fact that CBR still is defined in dry variables. In cyclones the temperature profile usually is moist adiabatic, which the dry-CBR will see as a stable environment. This may be the most important reason for a underestimation of the vertical diffusion in cyclones, causing them to become too active. A moist version of CBR may solve this problem. The second reason may be that the orographic drag parameterization was not efficient enough to have a large impact on cyclones, or that this impact has been minimized because it was overwhelmed by the modifications in the stable mixing of CBR. It may therefore be interesting to see what the orographic drag parameterization does in a Hirlam version with reduced or zero enhanced mixing under stable conditions.

For the near surface winds the turning of the surface stress is not necessary. CBR is capable of producing the correct winds near the surface and in the lowest km. However, as long as enhanced mixing under stable conditions is used or necessary in CBR, the turning of the surface stress will also be necessary to get better scores for the near surface winds.

With all the proposed adjustments, the model still has a positive bias in the wind speed and the wind direction. To arrive at a bias that is 0 or even slightly negative (observations are usually performed on locations with a lower roughness than the Hirlam grid box average) the surface or vegetation roughness may also have to be increased even more than is done in Hirlam 6.2.4.

Another source for the overactivity of Hirlam without the stable mixing enhancement may be a too large latent and sensible heat flux over the ocean, especially when the winds are not strong. Makin (2003) proposes a Charnock parameter that is not constant, but varies as a function of the wind speed. For relatively light winds the Makin (2003) proposal results in a reduction of the Charnock parameter (and the fluxes) by a factor of 3 compared to the current reference Hirlam. For strong winds the Makin proposal is almost equal to the current reference Hirlam. A reduced evaporation for weak winds may lead to less erroneous fog formation over the sea and less energy content of the entire model, while for strong winds the good dynamic behaviour of the current reference Hirlam is retained. The impact of the Makin Charnock proposal will be the subject of future studies.

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