Status of work on the turbulence modelling in the CBR scheme: instability with high u_* values

Geert Lenderink, Enrique Sánchez and Joan Cuxart
KNMI, de Bilt; INM Madrid

1 Short overview

This note describes work that has been done at KNMI and INM to improve on the representation of turbulent mixing in the CBR scheme. The CBR scheme is a TKE-l scheme with a prognostic equation for the turbulent kinetic energy and a diagnostic length scale. From previous experimentation, it became clear that the CBR reference version was mixing too much in neutral conditions. This reason for this is that the present reference CBR scheme does not discriminate sufficiently between neutral and convective situations. The reference scheme is tuned to convective situations, and hence overestimates mixing for neutral conditions. In particular, for winds this leads to too high surface winds (and surface stress) and too small vertical wind gradients in the boundary layer. This is perhaps best illustrated in a detailed comparison with Cabauw tower data for the month July 1996 (see e.g., de Rooy, HIRLAM Newsletter 35). Also predictions at the FMI for January 2000 (Jarvenoja) showed a positive bias in the mean sea level pressure in Scandinavia, apparently resulting from the excessive surface stress in the reference scheme.

To improve the representation of mixing, Lenderink and Rooy (HIRLAM Newsletter 36) tried a different mixing length approach embedded in the CBR scheme and compared results with Cabauw data. This approach (called in the following CBR_KNMI) uses a formulation in which stability (for neutral to convective situations) is embedded in a integral sense into the length scale formulation (see Newsletter 36). Results were promising, and improved both results for winds in comparison with the Cabauw tower data and the pressure bias in the January simulation performed at FMI. However, the scheme turned out to be rather unstable, in particular for winter months.

A turbulence meeting at DMI was organized in early December 2000 to discuss these findings, and to organize work that has to be done in order to improve the turbulence scheme (see Cuxart et al. HIRLAM Newsletter 37, p 7-9). It was felt by all participants that this work has highest priority. It was concluded to concentrate at the following points:

- Solve the instability in CBR_KNMI.
- Improve mixing in the CBR reference version.
- Continue testing with Cabauw tower data (concentrating on the turbulent mixing) and the FMI runs (concentrating on the more traditional scores).

Since then, a lot of work has been done on these points. The instability in CBR_KNMI has been solved (as described below). The reference version of CBR has been updated with a Richardson dependency in the mixing K for momentum (in the following this scheme is denoted CBR_INM). Both testing with the Cabauw tower data and the testing at FMI have been continued. At present the following verification is available:

- CBR_INM: July 1996 (Cabauw); Jan 2000 (FMI)
- CBR_KNMI: July 1996 / 2000, Feb. 2000 (Cabauw); Jan 2000 (FMI)

In a rather late stage, it turned out the CBR_INM revealed similar instabilities as CBR_KNMI, though in a lesser degree. This is the reason that the verification for Feb. 2000 (Cabauw) is not yet available. The reason for the instability is described below, followed by some tests based on idealized and reference simulations (convective, neutral with shear), in a single column version of HIRLAM. Results of the verification done so far are very encouraging: both new versions improve both the traditional scores (except RMS surface pressure) and wind characteristics at the Cabauw site considerably (for details see papers by others in this Newsletter).

2 Instability

In model prediction of HIRLAM the model turned out to be unstable over mountains, in particular with strong winds during winter months. The reason turned out to be related to the explicit computation of the momentum stress. This explicit formulation works as follows: given the winds at the previous (n-1) time step, in the surface flux routine (SLFLUXO) the surface stress u_* is computed. This stress enter the turbulence scheme, and in used as a boundary **flux** condition in the implicit solver of the turbulence scheme. The advantage of such a approach is that it enables a modular approach in which the surface flux routine and the turbulence scheme can be treated completely independently. Unfortunately, this approach turned out to be unstable; the reason for that can be understood (intuitively) as follows. Given strong winds and high surface stresses strongly curved profiles near the surface occur. (Note that HIRLAM uses rather high roughness lengths over mountains in order to get sufficient drag and to compensate for the absence of gravity wave drag.) In that case the explicit flux boundary condition does not guarantee that the wind velocity goes to zero at the surface; in some cases overshoots occur and the surface wind is directed opposite to the winds at higher altitudes. In that case, the scheme becomes numerically unstable, mainly because the surface "drag" starts to accelerate the model.

A natural solution to this problem is to go over to a **no-slip** boundary condition, and to compute the surface momentum flux implicitly in the diffusion solver of the turbulence scheme. This requires the exchange coefficient (K) at the solver which is computed in the surface flux routine. In many models the surface flux routine and the turbulent diffusion scheme are therefore strongly intertwined, which contrasts with the modular approach of HIRLAM. We adopted a simple work-around which completely retains the modularity of HIRLAM. In this approach the surface exchange coefficient is reconstructed in the turbulence scheme from the surface stress and the wind speed velocity at lowest model level (nlev) at the previous timestep (n-1) by:

$$K_{surf} = \frac{u_*^2 z_{nlev}}{V_{nlev}^{n-1}}$$

with z_{nlev} the height of the first model level. It turned out the flux computed implicitly now in the diffusion solver closely matches with the explicit flux, with differences in the order of a few percent only.

In the INM version of the implicitation idea, a sligthly different approach was used. Surface momentum flux was recalculated inside turbulence routine from u_*:

$$\overline{w'u'}_{surf} = -u_*^2 \frac{u_{nlev}^{n+1}}{V_{nlev}}; \overline{w'v'}_{surf} = -u_*^2 \frac{v_{nlev}^{n+1}}{V_{nlev}}$$

Doing this, now coefficients used in the solver for fluxes can be computed now at all levels, surface level included, making scheme completely implicit. Nevertheless, this modification is very close to KNMI formula.

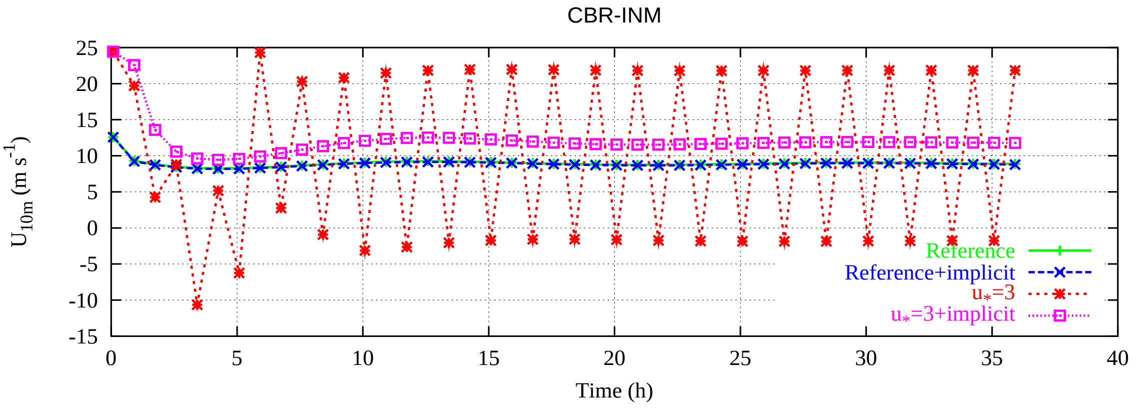
Results in a single column model for both new CBR versions with their approach to implicitation are presented in next section.

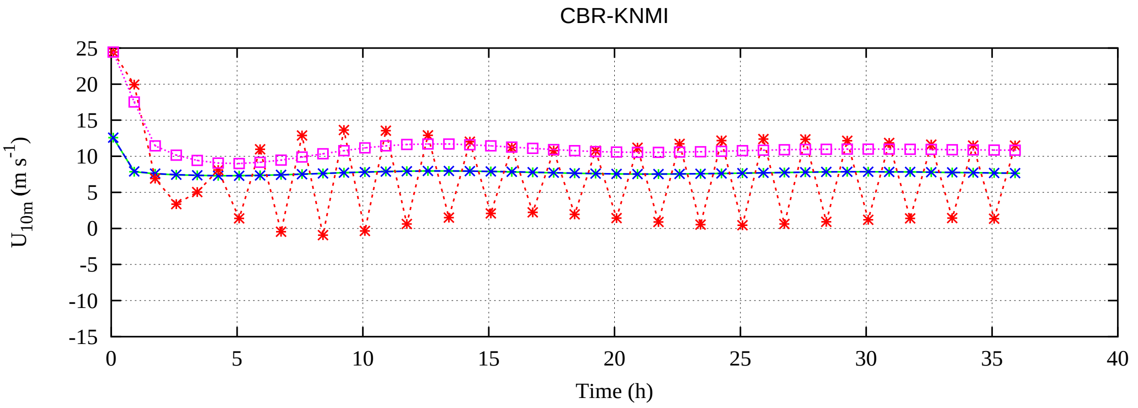
3 Single Column Model Results

Four idealized simulations were performed, representing simple and wide spread situations in a dry boundary layer:

- Leipzig case: thermally neutrally and shear driven with strong winds
- Ayotte case: convective boundary layer with some shear
- Ayotte without wind: pure convective case
- SABLES: Intermittent turbulence in a thermally stable boundary layer

Only results from Leipzig simulation will be shown, but tests of instability have been carried on also in the other idealized cases. Following Nielsen and Sass (Newsletter 35), 1D-HIRLAM Leipzig case is run for 36 hours to have a quasy steady state, with a timestep of $\Delta t = 300$s. Mean winds are initially equal to geostrophic values (17.5 m s^{-1}).


CBR-INM


CBR-KNMI

U component of wind is shown in these plots. Reference line (continuous, with pluses) means standard simulation, with a roughness length of $z_0 = 0.4$ m (gives a $u_* \approx 1.1\mathrm{m\,s}^{-1}$ when simulation becomes steady). We tested first if impliciting expressions had neutral impact with low friction velocities. Long dashed lines with crosses are the results, almost equal to reference values. Then we increased u_* up to 3 m s^{-1} looking for instability in wind components (medium dashed lines, with stars). Noisy and "jumpy" values from timestep to timestep are then obtained, (although only shown every 10 timesteps, the same picture is seen with every value), as it was stated in previous section. If implicitation modifications are used, results become regular and without noise (short dashed lines, with squares) in both formulations, without any remarkable difference in the implicited results. KNMI expression for implictation has also been tested in CBR_INM simulations, and results show no appreciable differences. CBR_KNMI and CBR_INM absolute results are then different in this tests due to the different way mixing length is computed. Although this high values of friction velocity are somewhat unrealistic, and very rarely are measured in nature, the results of both formulations show equivalent results: oscillating wind values change from oscillating values to a regular evolution with time. This study have been also tested in the other idealized simulations mentioned before and show similar results (not shown).