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SINGLE-COLUMN MODEL INTERCOMPARISON FOR A STABLY STRATIFIED ATMOSPHERIC BOUNDARY LAYER

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1 INTRODUCTION

The representation of the Stable Atmospheric Boundary Layer (SBL) in the Atmospheric models is still poor (Holtslag, 2003). Changes in the turbulence schemes can lead to large differences of the near-the-surface temperature over land during winter, with significant impacts on medium-range weather forecasting or on climate integrations. The drag at the surface depends on the SBL parameterization, and its misrepresentation can be felt at the largest scales from entire continents and also at the synoptic scales where it provides the Ekman damping on the cyclones (Beljaars and Viterbo, 1998). Many large scale models use SBL schemes that provide stronger mixing than it would be expected based on local observations or earlier research, including single-column simulation studies. This is due to the fact that, in very stable situations, the models do not mix enough at the lowest levels and go to a "decoupled" mode, which can lead to run-away characteristics close to the ground (Derbyshire, 1999).

The overall objective of the GEWEX Atmospheric Boundary Layer Study (GABLS -GEWEX stands for the Global Energy and Water Cycle Experiment-) is to improve the understanding of the atmospheric boundary layer and its representation in regional and large scale climate models. A simple shear-driven SBL case, already explored through a Large-Eddy Simulation (LES) intercomparison (Beare et al., 2004), is chosen for a first evaluation of the performance of a number of research or operational schemes running within forecast or climate models. The LES intercomparison exercise offers the opportunity to intercompare the turbulence schemes to certain parameters that would rarely be at hand from the observations, such as the profiles of many turbulence quantities, in ideal conditions under control. However, the GABLS LES intercomparison shows that there remain difficulties in the layers with relatively strong stratification, such as near the ground and at the upper inversion. Keeping these limitations in mind, we consider the LES intercomparison a suitable guiding reference for this non-strongly stratified case. The differences between the LES models are relatively small and their comparison to available observations indicates that they are all approximately in agreement with Nieuwstadt's theory (1984) although the mixing intensity is slightly overestimated.

The present level of understanding of the turbulence makes PBL models still crude approximations of the reality. Besides, the operational models often tune their proposals in order to obtain good overall forecasts, even at the cost of degrading some particular issues at certain areas or layers. The intercomparison treats together all the proposals, but tries to distinguish between them depending on their final purposes.

2 DESCRIPTION OF THE CASE AND OF THE TURBULENCE SCHEMES

This case is based on the LES simulations presented by Kosovic and Curry (2000) for the stable arctic PBL. The boundary layer is driven by an imposed, uniform geostrophic wind, with a specified surface cooling rate and attains a quasi-steady state with a depth of between 150 and 250m. The complete description can be found in Beare and MacVean (2004). The LES intercomparison had the basic aim to quantify the reliability of sta-

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ble boundary layer LES. The same exact prescription has been retained for the single-column model intercomparison in order to minimise the sources of discrepancy between models and with the LES statistics. Nevertheless, weather-forecast or climate models have been included at their operational configuration.

A vertical domain of 400 meters is used, with a grid mesh of 6.25 m and a timestep of 10 seconds, to reduce the differences originating from the numerical discretisation. A constant geostrophic wind with height of 8 m s^{-1} in the u direction is prescribed, and the latitude is $73°N$ (f=1.39e-04 s^{-1}). The radiation schemes are switched off and the duration of the run is nine hours. The surface cooling rate is prescribed as well as the surface layer similarity formulae.

Nineteen different schemes have participated in the intercomparison (see Table I). The participant groups include seven National Weather Services plus the European Center for Medium-Range Weather Forecast, seven Universities and two research centers, besides their collaborators. Some of the schemes are the operational versions running in weather-forecast and climate models, whereas the other schemes are used in applications, within mesoscale models or for research purposes. Most models have run using the prescribed temporal and spatial discretisation, except ECMWF, Met Office and NCEP, which have used their operational grid and Sandia Labs, which used a very fine mesh (358 points). Most of the operational models used their own similarity functions in the surface layer instead of the recommended ones. Besides, a sensitivity run by the ECMWF (ECMWF-MO) using the proposed similarity functions is also kept.

All the participating models, except the ODT scheme (standing for "one-dimensional turbulence") of Sandia Labs, make use of the Reynolds decomposition and use turbulence terms $F_\xi = -K_m \frac{\partial \xi}{\partial z}$ in the equations for any variable ξ (such as the wind components u, v or the potential temperature θ). The turbulence schemes are classified according to their order of closure. Five of the seven operational schemes use first order closures. In this case the fluxes are computed using

$$K_m = l_m^2 \frac{\partial U}{\partial z} f_m \quad (1)$$

$$K_h = l_m l_h \frac{\partial U}{\partial z} f_h \quad (2)$$

where K_m, l_m, K_h, l_h stand for the momentum and heat mixing coefficients and lengths, and f_m, f_h are stability functions. U means here the modulus of the wind vector. The differences between the first order schemes come mainly from the different approaches taken for the lengths and the stability functions. Two exceptions using diagnosed profiles for the mixing coefficients are NOAA-NCEP and the Met Office research model.

The lengths usually are forced to tend to κz ($\kappa = 0.4$ is the von Karman constant) in the surface layer and to some upper value λ_0 aloft, using a formula proposed by Blackadar in 1962 that gives more weight to the smallest value at the level of interest:

$$\frac{1}{l_m} = \frac{1}{\kappa z} + \frac{1}{\lambda_0} \quad (3)$$

for l_m and a similar expression for l_h if the lenghts are different. The value of λ_0 is an adjustable parameter that varies between 40 and 200 m between models. None of the participants currently distinguish between the assymptotic values for heat and for momentum. The stability functions vary between the first order models and are one main factor that can explain differences between them.

The ODT scheme (Ashurst et al, 2001), instead of using a diffusion equation for the turbulence transport, applies a random sequence of rearrangements (mappings) applied to randomly selected intervals of the 1D domain, which may be viewed as an analog of turbulent eddies. A model for the distribution of eddies is needed.

We consider here the $e-l$ models as those that use a prognostic equation only for the turbulence kinetic energy (e). Some of these schemes are, in fact, stationarised second-order schemes - except for e- , whereas the others prescribe the e equation and the lengths. In this case, we could summarise the mixing coeffients as

$$K_m = c_m \sqrt{e}\, l_m f_m \quad (4)$$

$$K_h = c_h \sqrt{e}\, l_h f_h \quad (5)$$

e is the turbulence kinetic energy, that has its own evolution equation, uses a diffusion approach for the transport of e (with constant c_e) and the Kolmogorov formula $\epsilon = -c_\epsilon \frac{e^{\frac{3}{2}}}{l_\epsilon}$ for the dissipation, which implicitly assumes isotropy and homogeneity. Since this is usually not of application in the SBL, many models vary c_ϵ or use empirical parameterizations for l_ϵ. The $e-l$ models differ in

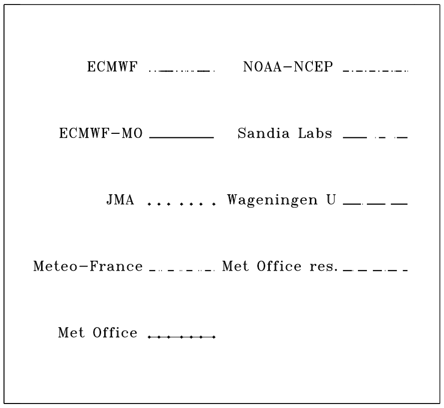

Figure 1: Labels for the 1st order models + ODT

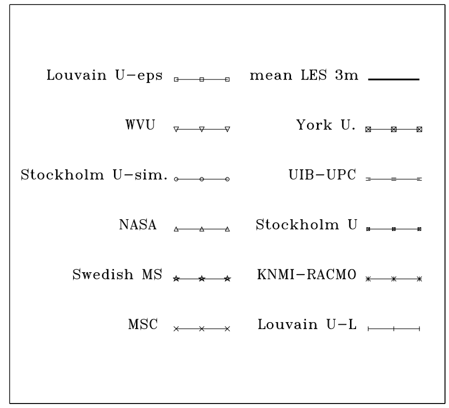

Figure 2: Labels for higher order models + LES

three aspects: the values selected for the constants $c_m, c_h, c_e, c_\epsilon$, the parameterizations taken for the lengths and the stability functions. These three factors might differ much between models.

The $e-\epsilon$ models use, besides an e equation, an equation for the dissipation of e, written ϵ. Two proposals adapted for stratified flows are used here. The mixing coefficients read

$$K_m = c_m \frac{e^2}{\epsilon} f_m \tag{6}$$

$$K_h = c_h \frac{e^2}{\epsilon} f_h \tag{7}$$

Finally, the Stockolm University similarity model uses evolution equations both for e and θ^2 together with a common dissipation length scale.

3 INTERCOMPARISON RESULTS

In general, the models (labels given in Fig 1 and 2) reach a steady state after the fifth hour, as LESs do. This can be seen in figs 3 and 4 for the Boundary Layer Height (BLH), defined here as the height at which $(\overline{u'w'}^2 + \overline{v'w'}^2)^{1/2}$ falls to 5% of its surface value (u_*^2), divided by 0.95. The dispersion of the results among the single-column models is much larger than for the LES models. In general, the operational models provide SBL much higher than LESs, whereas the research models produce shallower SBLs closer to the LESs outputs.

The potential temperature (Figs 5 and 6) shows that the LES generate an inversion at the top of the SBL reproduced by most of the research models, whereas the majority of the operational schemes miss this feature due to a very large mixing efficiency, thus transporting the characteristics

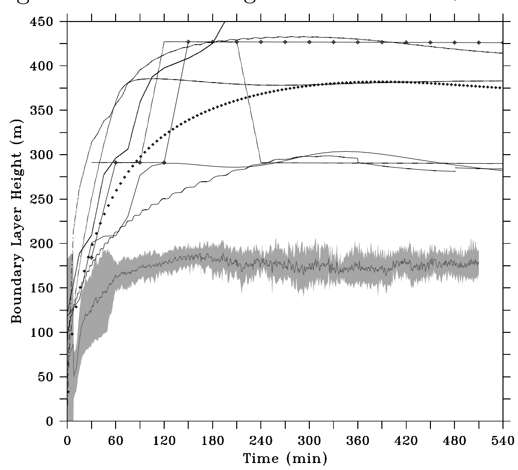

Figure 3: BLH timeseries (1st + ODT; LES:shaded)

of the air in the surface layer to the free atmosphere. These schemes also mix momentum very strongly and in most cases are not able to generate a wind maximum as the LESs do near the SBL top.

In table II the final values for the models for BLH, the surface heat flux, the friction velocity, the Obukhov length and the angle of the wind at the surface are given classified by categories. The LES values correspond to the mean value plus/minus the standard deviation. The ranges of the ensemble of the single-column models are larger than those of the LES, and the LES range occupies the lower part of the range of the ensemble. We can infer that the single-column models tend to overestimate mixing for this particular case when comparing to LES, in a larger measure for the operational than for the research models. All of the later are able to reproduce the upper inversion. If the order of the scheme is used to look at the ranges, the higher order schemes have ranges corresponding to a less intense mixing than the first order ones.

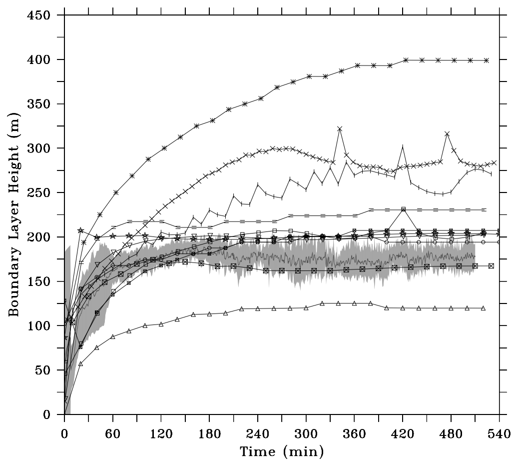

Figure 4: BLH timeseries(higher order)

Many of the characteristics just described are confirmed by the profiles of the potential temperature, the wind and their turbulence fluxes. Most operational schemes overestimate mixing, are warmer than LES in the lower part of the SBL and colder above. The research first order models manage to reproduce the upper inversion and ODT has too strong mixing below the inversion. The higher order models cluster more closely although some of them have singular behaviour. The fact that most higher order models have implicitly a critical Richardson number can explain why the SBL does not grow as much as the first order models, that use typically larger values for Ric.

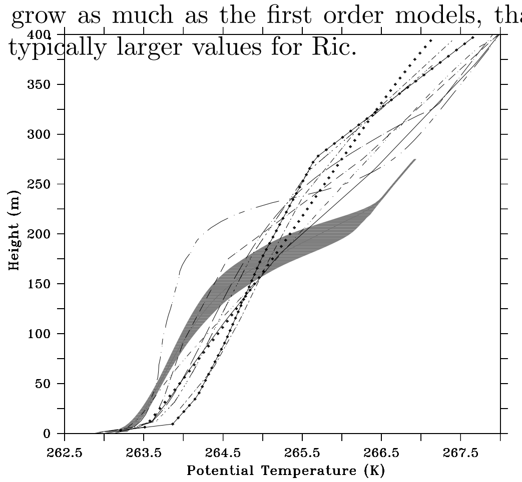

Figure 5: θ profiles (9th hour; 1st order + ODT)

Related to the wind direction at the surface (last column in table II), the differences are, at most, of 25 degrees between schemes. Such differences are significant when one focusses on the proper forecasting of the near the ground characteristics of the atmosphere.

The use or not of the prescribed similarity functions has a large impact in some schemes (such as ECMWF) whereas it is not so significant in others, at least less than the impact of the different stability functions. Concerning the spatial resolution, both the first and the higher order schemes showed little sensitivity to its degradation.

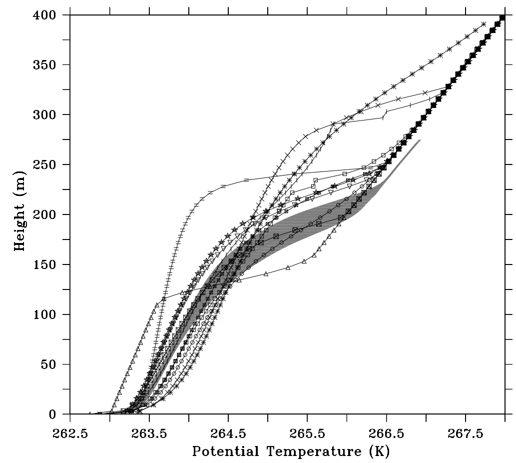

Figure 6: θ profiles (9th hour; higher order)

Mixing efficiency

One of the main subjects of the present work is the different mixing efficiency between the operational and the research models. In figure 7 the mixing coefficients for momentum are given. In general, they are overestimated compared to the LESs average, although some higher order models are very close to it. Most models have a linear behaviour with height near the ground and the maximum value is at about one-fourth to one-third of the SBL depth. This explains why the wind profiles are too well mixed in general, and those models with strong coefficients at the upper part of the SBL do not have a wind maxima at the inversion.

The heat mixing coefficients have shapes very similar to the momentum ones for most of the schemes, although the values can vary much between them. The models having large K_h at the upper part of the SBL do not generate the upper inversion. The inspection of the turbulence Prandtl numbers shows that the LESs provide an average value of about 0.8 until the inversion layer,

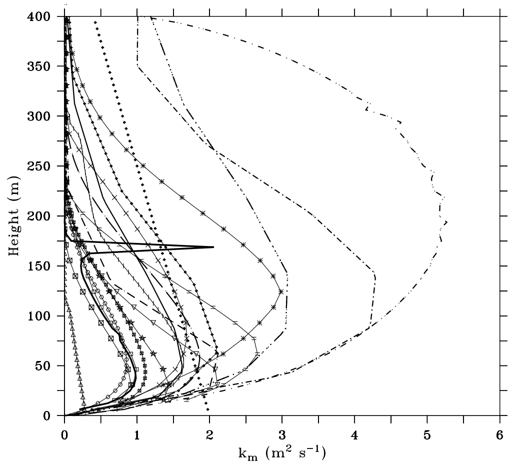

Figure 7: Momentum mixing coeff (All models, 9th hour)

they increase at the lower half of the inversion and decrease at the top. The dispersion for the values of the Prandtl number among the schemes is very large and none behaves as the LES at the inversion layer.

The stability functions used by the first order models show that they allow mixing for Ri well above 0.5, thus for stronger stratification than the higher order models do, since these schemes usually have smaller implicit critical Ri.

Turbulence lengths within the TKE-based schemes

As stated in the description of the participating models, the schemes that use a prognostic equation for the TKE, have to deal up to three conceptually different mixing lengths, the mixing length for momentum l_m, the mixing length for heat l_h and the dissipation length l_ϵ. There is a large variety of proposals among the participant schemes. In order to be able to compare the different schemes, equivalent lengths are computed as

$$l_m = K_m/\sqrt{e} \quad (8)$$
$$l_h = K_h/\sqrt{e} \quad (9)$$
$$l_\epsilon = (c_\epsilon \, e^{1.5})/diss \quad (10)$$

In this way, the joint contribution of the lengths and any other coefficient (such as a stability function or a closure constant) are given together and compared to the same quantity as provided by the LESs. The TKE for this case (not shown) is a quantity that decreases with height with values between 0.2-0.5 near the ground, the LESs average value being around 0.3. The TKE budgets show that the steady state results of a quasi-equilibrium between the shear production and the dissipation, and the buoyancy destruction and the turbulence transport contributions are an order of magnitude smaller.

The mixing lengths (fig 8) as provided by LES are of order 1, and slightly larger for heat than for momentum. The single column models do not distinguish much between the two lengths when the shape is observed, but they show a larger dispersion among them, with values between 1 and 10 m. The LES equivalent dissipation length (fig 9), regardless of the value considered for c_ϵ, is larger than the equivalent mixing length. If it is thought as the scale of the more energetic eddies, those may range from about 10 to 50 m approximatively in the SBL, with a horizontal contribution that can be significant at the inversion. On the other hand, the mixing length, much smaller, provides a scale of mixing consistent with a K-theory based on the local characteristics of the layer. In general, the turbulence schemes provide equivalent momentum and dissipation lengths of the same order of the LESs.

A tuning exercise

Nine models have made a new run, trying to fit better the LES results. This exercise is specially relevant for those models that are implemented in a larger framework and that cannot tune at will their scheme, since they are inside forecast, climate or mesoscale models.

Most models have made small changes, related either to set some limitation on the values of the length, the change of the turbulent Prandtl number or the modification of some threshold values of their scheme. The tuned results, as expected, converge much more to the LES average outputs which confirms that using the adequate Prandtl number in the scheme is a major issue to get similar results to LES.

4 CONCLUSIONS

In general, the operational models mix more than the research models with important consequences such as the missing of the development of an upper inversion and the overestimation of the surface friction velocity. The first-order approaches use very similar proposals except for the values of some adjustable parameters, such as the mixing lengths or the stability functions. The operational TKE schemes also overestimate mixing, but in a smaller degree. The research schemes, on the other hand, give results closer to the LES statistics.

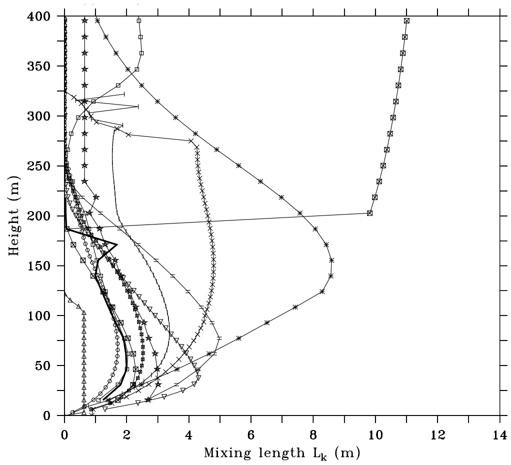

Figure 8: Eq. momentum mixing length (TKE models, 9th hour)

Many research models use also a prognostic TKE equation. Equivalent mixing lengths for heat, momentum and dissipation have been computed from LESs and for each model. The mixing lengths have values below 5 meters, while the dissipation ones are larger. In the schemes, this difference is partially taken into account through the different values of the mixing and the dissipation closure constants.

In the study, two models use an additional prognostic equation for the dissipation, in both cases adapted for stably stratified flows, and one model uses an equation for the potential temperature variance. Furthermore, the model of Sandia Labs uses a totally different approach. The results of these models are also within the scatter of the other participants.

The vertical resolution does not appear as an important issue and most schemes are able to produce major changes through minor adjustments in their formulation. The tuning exercise shows that the decrease of the turbulence Prandtl leads to much shallower SBL for most of the operational models. Some first order schemes also reduce or eliminate Ri_c to avoid excessive mixing in this SBL case. The TKE models show also that a limitation on the upper values of the mixing length is convenient.

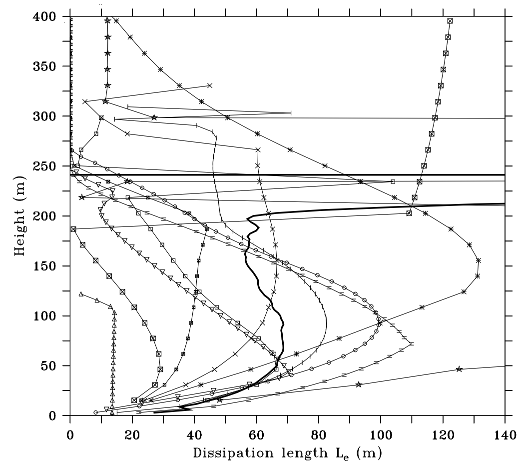

Figure 9: Eq. dissipation length (TKE models, 9th hour)

However, for this conceptually simple case some items are still open, such as the behaviour at the upper part of the inversion. To study the problem of decoupling, that couldn't be addressed with the prescription of the case, and to check how schemes perform in a more strongly stratified SBL, another intercomparison exercise could be of interest, using data from the available experimental data sets, since LESs will probably not be ready for that stage.

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Table 1: Model name, use and scientists

Model	Use	Type	Scientists
ECMWF	oper	1st order	Beljaars
NOAA-NCEP	oper	1st order	Freedman & Ek
MeteoFrance	oper	1st order	Bazile
JMA	oper	1st order	Kitagawa
Met Office	oper	1st order	Beare
Met Office res	research	1st order	Beare
Wageningen U	research	1st order	Steeneveld & Holtslag
Sandia Labs	research	ODT	Wunsch & Kerstein
MSC	oper	$e-l$	Mailhot
KNMI-RACMO	oper	$e-l$	Lenderink
UIB-UPC	research-meso	$e-l$	Conangla & Cuxart
NASA	research-meso	$e-l$	Xu & Cheng
WVU	research	$e-l$	Lewellen
York U.	research	$e-l$	Weng & Taylor
Louvain U-L	research	$e-l$	Schayes & Hamdi
Louvain U-eps	research	$e-\epsilon$	Schayes & Hamdi
Swedish MS	research	$e-\epsilon$	Perov
Stockholm U	research	$e-l$	Svensson
Stock.U-sim	research	$e-\theta^2$	Mauritsen & Svensson

Table 2: Summary by categories

Model	BLH (m)	$\overline{w'\theta'}_s$ (K m s^{-1})	u_* (m s^{-1})	L (m)	Surface angle ($\circ$)
LES	[160,195]	-[0.010,0.013]	[0.26-0.30]	[120-170]	[32-38]
1d models	[120,483]	-[0.005,0.027]	[0.25-0.36]	[98-204]	[21-46]
oper.	[285,483]	-[0.013,0.027]	[0.29-0.36]	[98-204]	[21-36]
research	[120,290]	-[0.005,0.018]	[0.25-0.34]	[98-154]	[30-46]
1st	[284,483]	-[0.013,0.027]	[0.30-0.36]	[102-204]	[21-40]
higher	[120,399]	-[0.005,0.018]	[0.25-0.33]	[98-152]	[24-46]