The Turbulent Kinetic Energy (TKE) scheme in the NWP models at Météo-France

Eric Bazile[1]**, P. Marquet(*), Y. Bouteloup, and F. Bouyssel**

Météo-France/CNRM/GAME (*) DPREVI

1 Introduction

Since February 2009, the operational global model ARPEGE and the limited area model ALADIN-MF use a prognostic variable TKE (Turbulent Kinetic Energy) for the computation of the exchange coefficient for the turbulent mixing instead of the first order scheme Louis et al. (1981). It was necessary to associate a mass flux scheme (KFB) for the shallow convection Bechtold et al. (2001), to the TKE scheme Cuxart et al. (2000), to replace the pseudo shallow convection parameterization Geleyn (1987) which is based of the modification of the Richardson number in the Louis' turbulence scheme.

Nevertheless, this major change requires also further modifications or tunings, mainly in the deep convection scheme.

This new package (TKE+KFB) has improved the vertical profile in the boundary layer, especially for the stable case, the low cloud forecast, the marine strato-cumulus and the objective Heidke Skill Score (HSS) of precipitation mainly in summer.

In this contribution, after a brief explanation of the context and the motivation of this change, the turbulent scheme and the connection with the shallow convection scheme will be described. Then, some sensitivity tests such as: vertical discretisation, the horizontal advection for TKE, the stability and the time step will be discussed. Finally, some results and perspectives will be drawn.

2 Context

The GABLS1 experiment Cuxart et al. (2006) has clearly shown that the Louis' scheme used in the operational model at Météo-France (but not only) overestimates mixing in stable cases, even if, an interactive mixing length depending on the boundary layer height with a retuned stability function $F_{m/h}$ can slightly improve the low level jet Bazile et al. (2005).

However, the good behaviour of the TKE scheme in this case and the wish to use the same PBL physical parameterizations in ARPEGE NWP and in the non-hydrostatic model AROME Seity et al. (2011) for a better consistency in the PBL with the nested model have facilitated this complete renewal of the boundary layer parameterization. At the same time, it was decided to use, whenever possible, the same physical parametrization for both ARPEGE-CLIMAT and the ARPEGE-NWP models.

Sharing parameterization has many advantages such as multi scale validation (2.5km to 300km), numerical stability for time step comprised between 1mn to 30mn, variety of weather conditions but unfortunately implies more constraints and is more time consuming.

[1]*Corresponding author address*: E. Bazile Météo-France, CNRM/GAME GMAP 42 Av. Coriolis, 31057 Toulouse Cédex, France tel : (33) (0)5 61 07 84 68 - fax : (33) (0)5 61 07 84 53 email: eric.bazile@meteo.fr

3 PBL parameterization

The Eddy Diffusivity Mass-Flux (EDMF) concept Soares et al. (2004) based on a pseudo-unified or more exactly a combined "turbulent + mass-flux" scheme is used in several models, however the computations of K_Ψ and the mass flux M remains a key issue:

$$\overline{w'\Psi'} = -K_\Psi \frac{\partial \overline{\Psi}}{\partial z} + M(\overline{\Psi} - \Psi_{updraft})$$

These exchange coefficients for the momentum (K_m), for the potential temperature and the specific humidity ($K_{\theta/q}$) are written as follows $K_\Psi = C_\Psi l_m \sqrt{e}$. Then, there are used to compute implicitily the turbulent fluxes by the inversion of a tri-diagonal matrix. The shallow convective part $M(\overline{\Psi} - \Psi_{updraft})$ is computed with the scheme written by P. Bechtold for Méso-NH Bechtold et al. (2001).

The time evolution of the turbulent kinetic energy ($\overline{e}$) is computed with a prognostic equation

$$\frac{\partial \overline{e}}{\partial t} = [\text{Advect.}] + \text{Diff}_{\text{vert}} + P_{\text{dyn.}} + P_{\text{ther.}} - Diss\,, \tag{1}$$

$$\text{Diff}_{\text{vert}} = -\frac{1}{\rho}\frac{\partial}{\partial z}\left(\rho\, \overline{e'w'}\right)\,, \tag{2}$$

$$P_{\text{dyn.}} = -\left[\overline{u'w'}\frac{\partial \overline{u}}{\partial z} + \overline{v'w'}\frac{\partial \overline{v}}{\partial z}\right]\,, \tag{3}$$

$$P_{\text{ther.}} = \beta\, \overline{w'\theta'_{vl}}\,, \tag{4}$$

$$Diss = C_\varepsilon \frac{\overline{e}\sqrt{\overline{e}}}{L_\varepsilon}\,. \tag{5}$$

There are two sources of TKE: the dynamical production $P_{\text{dyn.}}$ always positive and the thermal production depends on the vertical fluxes of the potential temperature θ_{vl}, but, in stable cases, the thermal production is negative. $\text{Diff}_{\text{vert}}$ is the vertical diffusion of $\overline{e}$ and $Diss$ the dissipation which depends on the constant C_ε and on the dissipation length L_ε which is considered equal to the non-local mixing length L_m Bougeault and Lacarrère (1989) in our configuration (BL89).

The turbulent fluxes are expressed in terms of the vertical gradient of the mean variables following Cuxart et al. (2000):

$$\overline{w'\Psi'} = -C_\Psi\, L_m\, \sqrt{\overline{e}} \frac{\partial \overline{\Psi}}{\partial z}$$

For momentum $K_m = C_m L_m \sqrt{\overline{e}}$, for $\overline{e}$ $K_e = C_e L_m \sqrt{\overline{e}}$ and for the potential temperature and the specific humidity $K_h = C_h L_m \sqrt{\overline{e}}\ \phi_3$. More details are available in the internal documentation Marquet (2008).

The four coefficients ($C_m = 0.126\, C_e = 0.34\, C_h = 0.142\, C_\varepsilon = 0.85$) have been modified in order to increase the mixing of the wind. The wind speed was improved in ARPEGE and in AROME during winter, but in the tropics at 850hPa, the wind speed was overestimated, especially for the Somalian Jet Bazile et al. (2008). With the TKE scheme, there is lack of mixing just above the inversion for two reasons: both the mixing length and the turbulent kinetic energy are very small. Lock and Mailhot (2006) have shown a positive impact of the enhancement of the turbulence length scales and the thermal production. An additional thermal production (only positive) coming from the shallow convection scheme (KFB) Bechtold et al. (2001) called before the TKE scheme is added in the TKE prognostic equation :

$$P_{\text{ther.}} = \beta\, \overline{w'\theta'_{vl}} + \beta\, (\overline{w'\theta'_{vl}})_{KFB}$$

The mixing length (L_m) was also modified in order to take into account the cloud depth computed in the shallow convection scheme Bouteloup et al. (2009). A similar modification was made also with the deep convection cloud with a maximum value fixed at 1000m. The TKE is increased above the inversion as shown in Fig: 1 and consequently the mixing too.

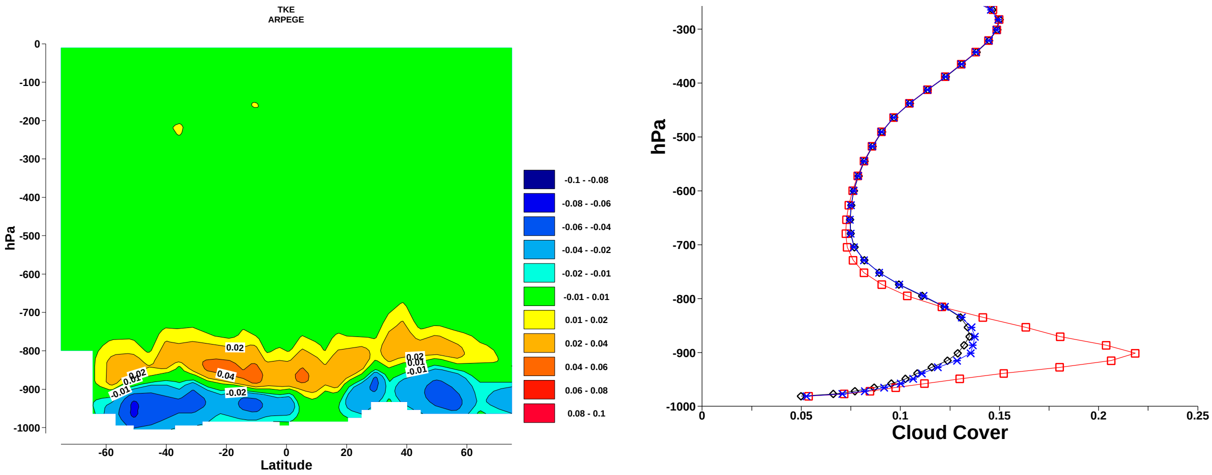

Figure 1: ARPEGE T798c2.4 $\delta t = 600s$ 25 Oct. 2011 Left: Zonal mean of the impact on the TKE field of the additional thermal production and the modified mixing length only from the shallow convection. Right: cloud cover profile: black line= OPER with TKE+KFB, Blue= OPER with TKE+KFB but without TKE advection and TKE on half-level, Red= OPER with TKE+KFB without the connection with the shallow convection scheme (L_m and the additional thermal production).

The positive impact of this connection between the shallow convection and the TKE is shown in Fig: 2, the RMS error for the wind increases up to 0.8 around 850hPa at +96h (left) compared to the reference, with the additional thermal production and the modified mixing length the deterioration is only 0.2. The connection between the TKE scheme and KFB reduces also significantly the cloud cover around 800hPa while keeping the marine strato-cumulus (Fig: 1, left, black line compared to the red one)

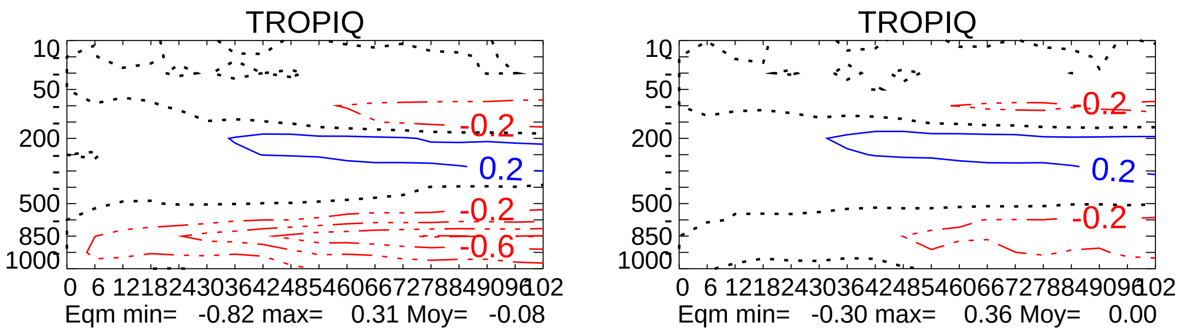

Figure 2: Difference of the RMS error for the wind against ECMWF analysis in the tropics for June 2007 between the new physics and the old operational (Louis) . Left: ARPEGE with TKE+KFB. Right: ARPEGE with TKE+KFB + thermal production + modified mixing length

3.1 Stability and vertical discretization

Until recently, during workshops on turbulence, discussions on the numerical stability and the vertical discretization of a TKE scheme were often raised. It seems natural to compute the TKE on the half-level, where the exchange coefficients K_Ψ and the vertical velocity are computed, but in the ARPEGE/IFS dynamics it is not possible to advect variables on the half-level.

Between February 2009 and April 2010, in the operational ARPEGE T538c2.4 (15km over France) with 60 vertical levels with $\delta t = 900s$ the TKE was not advected. In April 2010, a new configuration of ARPEGE was used for the operations T798c2.4 (10km over France) with 70 levels and $\delta t = 600s$. On that occasion the TKE advection was activated with the semi-lagrangian scheme, to do so, the TKE is interpolated on the full-level after the physics for the advection and then go back to the half-level for the physic. The impact is very small on the skill score and in cloud profile as shown in Fig: 1 (black line compared to the blue one). A surprisingly positive impact was observed on the wind gust diagnostic computed with the TKE ($U_{gust} = U_{10m} + \alpha\sqrt{e_{20m}}$) with a smoother wind gust pattern, especially along the coasts or areas with a jump in the roughness length field ie southwest France with the Landes forest.

For the issue of the time-oscillation or the fibrillation that existed with the Louis' scheme, an "anti-fibrillation" scheme Bénard et al. (2000) has been implemented in order to solve the problem and used in the operational ARPEGE model until February 2009.

At the beginning of the implementation of the TKE scheme in ARPEGE the question of the "fibrillation" has been addressed. A good way to evaluate those fibrillations is to compute for the temperature at the lowest model level : $Abs(T(t+\delta t) + T(t-\delta t) - 2 \cdot T(t))$. This diagnostic was computed in ARPEGE T538c2.4 with $\delta t = 900s$ for the first level above the surface for the Louis' scheme with the anti-fibrillation scheme and for the TKE scheme (Fig:3), the fibrillation is significantly reduced with the TKE scheme although no anti-fibrillation scheme was used. Two reasons can explain this positive result: the prognostic equation for the TKE has a "temporal" smoothing effect and the mixing length computation Bougeault and Lacarrère (1989) which is non local in the vertical.

The new PBL parameterizations (TKE+KFB) are less sensitive to the vertical discretization and to the time step compared to the Louis's scheme and also less noisy.

4 Results and validations

The single column model (SCM) was used on several cases: stable cases (GABLS1, GABLS2), cumulus (BOMEX, ARMCU) for the validation of the TKE scheme associated with the shallow convection scheme (KFB). Nevertheless, it was necessary to retuned the deep convection scheme, based on the moisture convergence (previously tuned with a too dry PBL), to find a "common set of parameter" for all the 1D cases and NWP evaluation.

The main improvement has been observed for the marine Srato-Cumulus and the fog forecast, thanks to a better vertical profile of the temperature (Fig: 4) and the humidity in the PBL. The dry bias in the boundary layer has been significantly reduced.

The two physics have been compared on the Gewex Pacific Cross-section Intercomparison (GPCI), and a significant improvement was found for the transition between stratus/straco-cumulus and cumulus (Fig: 5). The total cloudiness is also improved, as shown in Fig: 6, against the ISCCP climatology.

Nevertheless, the operational model still has a warm bias over snow not caused by the turbulence parameterization but mainly due to the snow scheme and to the interface (surface layer).

For the last 4 or 5 years, following Galperin et al. (2007) and Zilitinkevich et al. (2008), turbulence seems to survive for very stable condition ($R_i >> 1$) (Fig: 7 Left). This result undermines the "notion" of the existing critical Richardson number. With the TKE scheme Cuxart et al. (2000):

$$Pr = \frac{K_m}{K_h} = \frac{C_m}{C_h \phi_3}$$

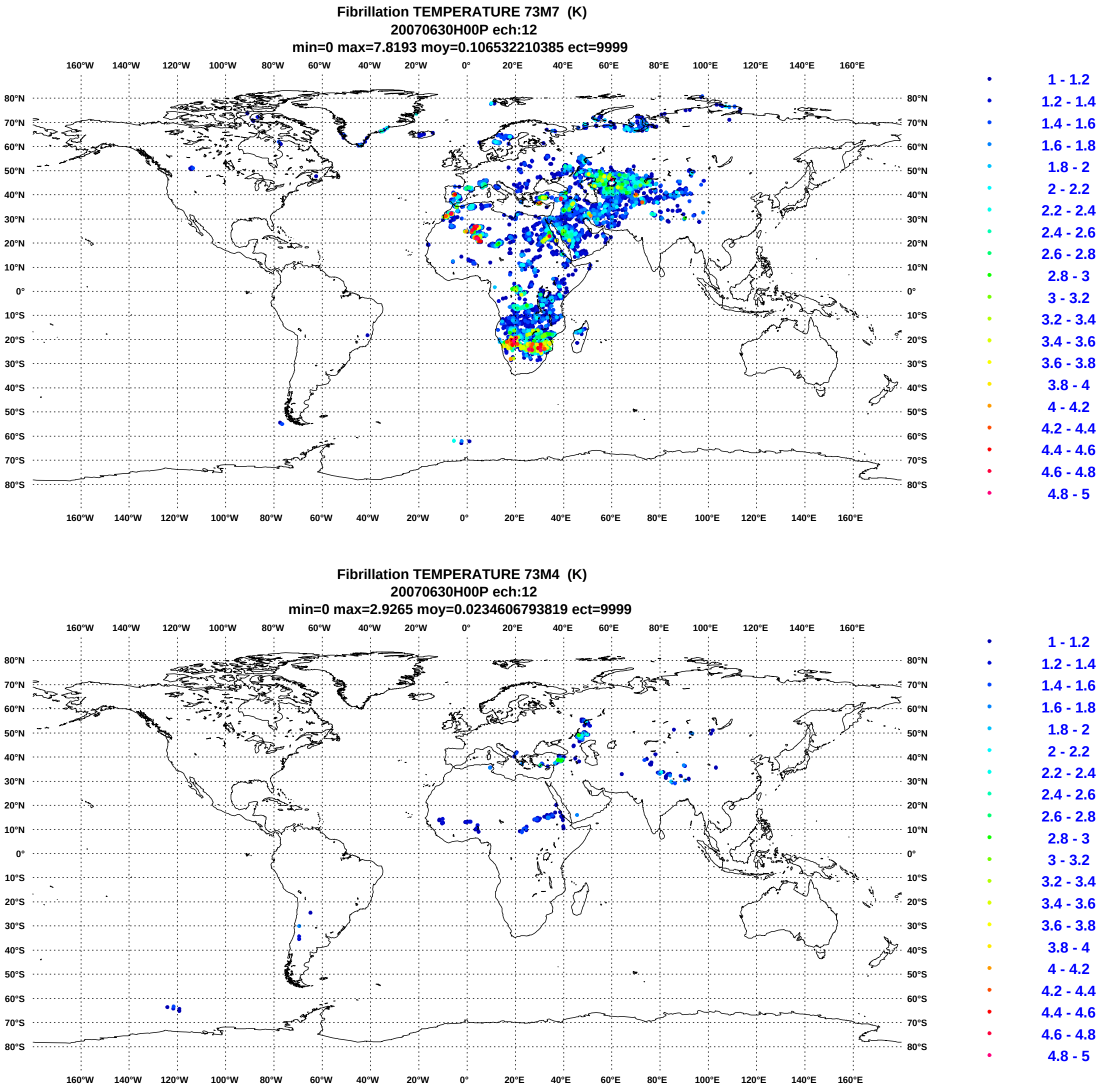

Figure 3: ARPEGE T538c2.4 $\delta t = 900s$ $Abs(T(t+\delta t) + T(t-\delta t) - 2 \cdot T(t))$ Top: ARPEGE with Louis's scheme: Max: 7.8°C, mean=0.1; Bottom ARPEGE with the TKE scheme: Max: 2.9°C, mean=0.02

and in the ARPEGE code:

$$\phi_3 = \beta \frac{L_m^2}{\overline{e}} \frac{\partial \overline{\theta}_{vl}}{\partial z}$$

the stability function ϕ_3 varies from 0.78 (for the stables cases) to larger or infinite values for unstable cases. In ARPEGE, a maximum value is fixed to 2.2. Then, the Prandlt number varies from 0.4 (unstable) to 1.14 only for stable cases, which is quite faraway from the observed data (Fig: 7 right blue line). Nevertheless, assuming a stationary TKE without turbulent transport, it is possible to approximate ϕ_3 as a function of Ri (equation 21 from Cuxart et al. (2000)).

With this new function (Fig: 7 right red line), the slope of the Pr, computed with GABLS1 and GABLS3 1D experiment, is very similar to the observed data and the impact on the two 1D case is neutral. Moreover, in cloudy cases the impact is very detrimental not only in the ARM-Cumulus or in the ASTEX-Lagrangian cases with a reduced cloud height development but also in the 3D experiment with a too moist PBL.

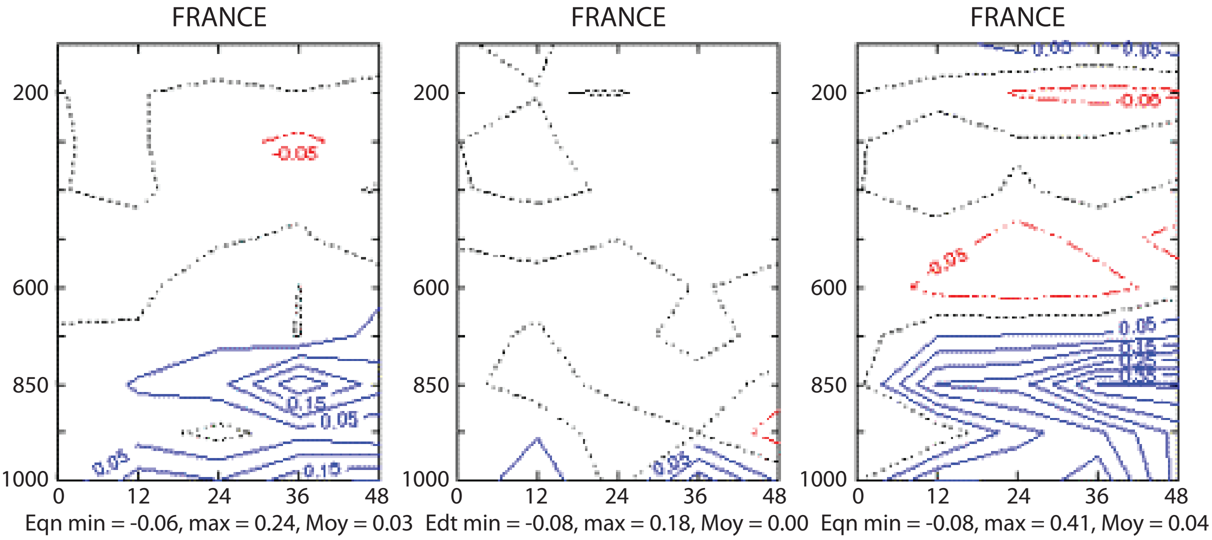

Figure 4: Impact of the TKE+KFB package on the Temperature (X=forecast length, Y=pressure) against sounding data. Blue improvement. Left: root mean square, middle: standard deviation, right: bias

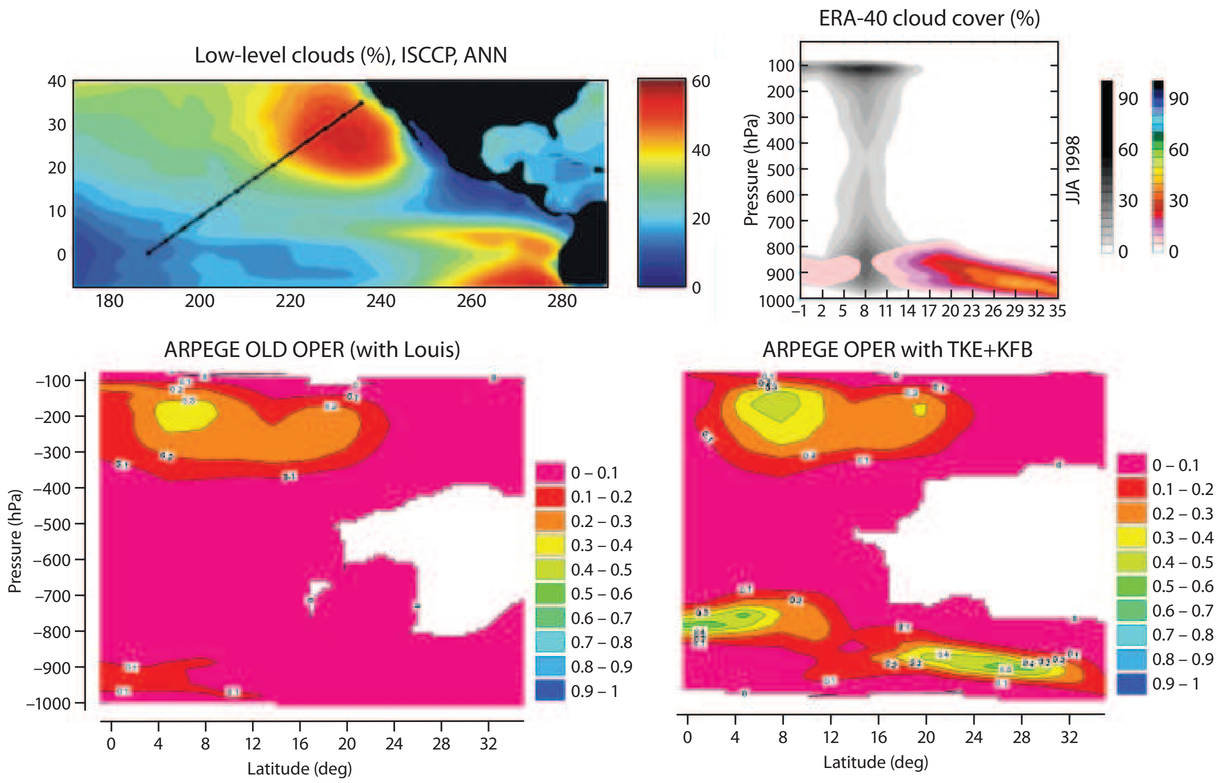

Figure 5: Top left: low-level clouds from ISCCP Courtesy Cecile Hannay (NCAR) (JJA) black line cross section. Top right: ERA 40 Cloud cover along the cross-section. Bottom left : Old ARPEGE (Version 2008). Bottom right: ARPEGE since Feb. 2009

This issue should not draw too much emphasis as first of all if the momentum mixing is under estimated with the TKE scheme for $R_i >> 1$, the mixing is very weak, secondly is the Richardson number useful to characterize the stability at the inversion above the cloud ?

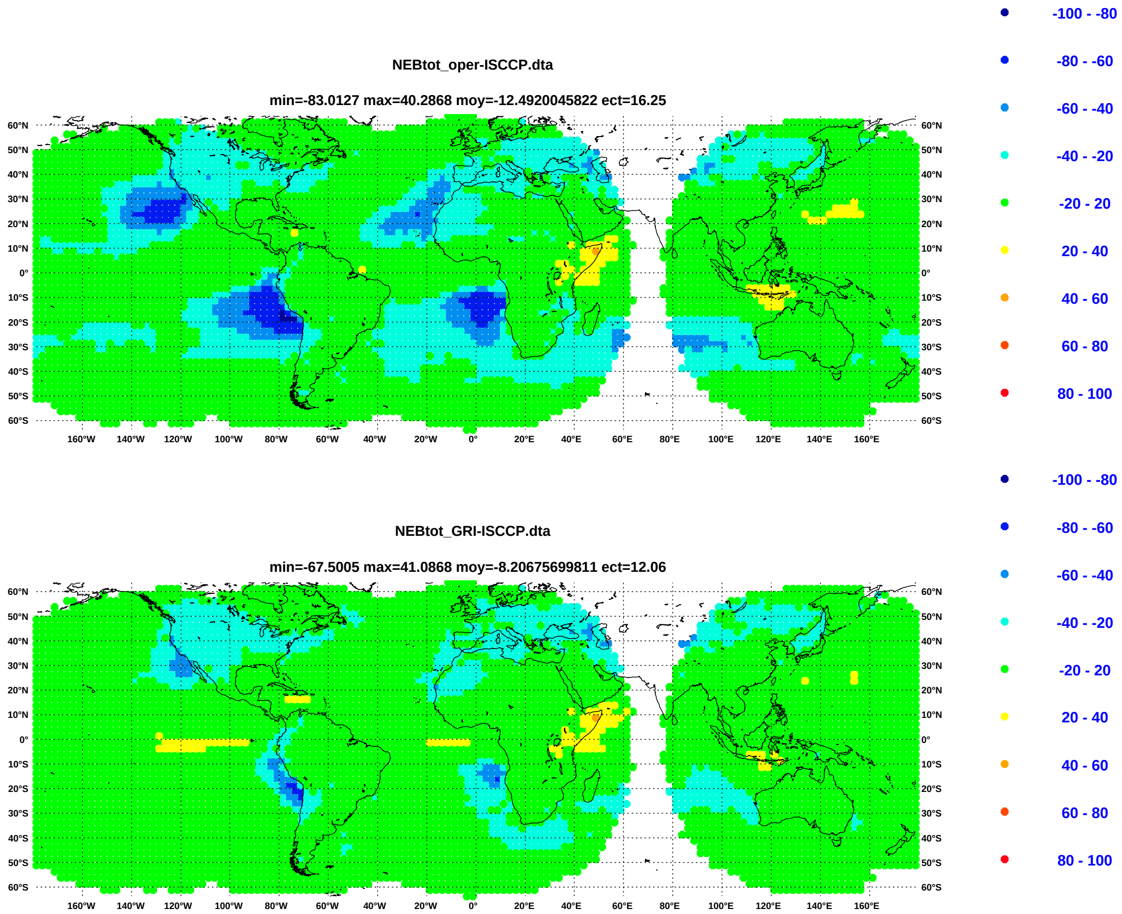

Figure 6: Average of monthly mean (DJF+JJA) of the ARPEGE (T224 c2.4 L60) cloudiness minus ISCCP climatology. Top: old operational model. Bottom: with TKE+KFB

5 Concluding remarks

The renewal of the boundary layer parameterization in a global model is an exciting challenge. It requires determination, patience and optimism to accept, at once, several modifications in the settings in the model. This development was initiated by the Climate group 15 years ago, then from 2005, it was a goal for the NWP and it is really the result of a fruitful collaboration between the NWP, Climate and Meso-Scale teams.

The new sub-grid vertical mixing (TKE + KFB), used in ARPEGE/ALADIN since Feb 2009 improves:

- the temperature and the relative humidity in the boundary layer
- the low-level clouds (fog) forecast, the marine strato-cumulus and the transition between strato-cumulus to deep convection along the GPCI transect
- the quantitative precipitation forecast thanks to some modifications or tuning in the deep convection scheme

The new PBL parameterization (TKE+KFB) is also less sensitive to the time step and to the number of vertical level compared to the Louis' scheme.

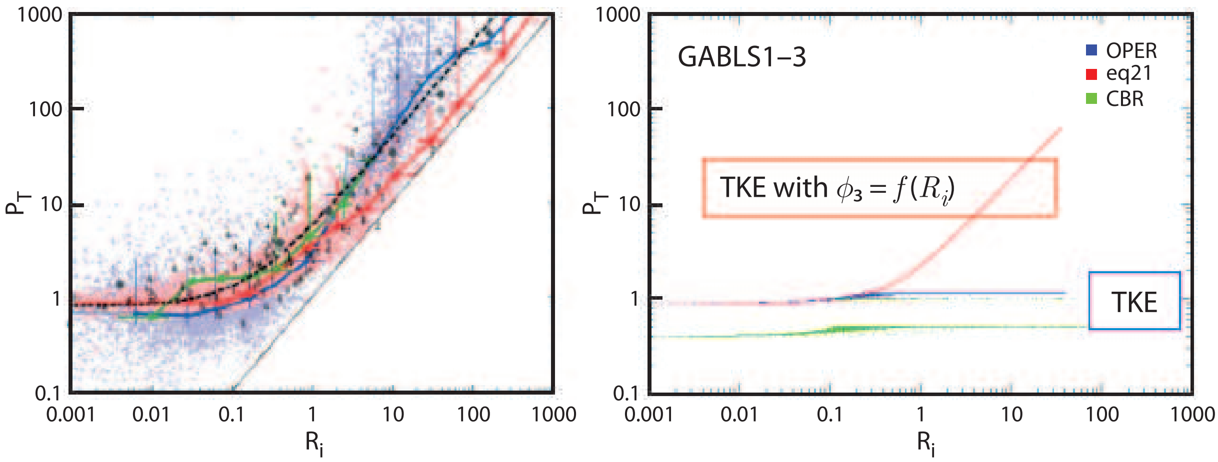

Figure 7: Left: Prandtl number versus Ri from Zilitinkevich et al. (2008). Right: Prandtl number versus Ri from two 1D case (GABLS1 and GABLS3). Blue line: OPER. Red line: with $\phi_3 = f(Ri)$ eq.21 from Cuxart et al. (2000)

In the coming years, we will investigate the interaction between the snow scheme and the turbulence (possibility to use observed data from Antarctica, Dome C), the issue of the critical Richardson number and the ϕ_3 formulation with the TKE scheme and, for the medium term the Total Turbulent Energy Mauritsen et al. (2007)

References

Bazile, E., Beffrey, G., Joly, M., and Marzouki, H. (2005). Interactive mixing length and modifications of the exchange coefficient for the stable case. In *ALADIN Newsletter*, number 27, pages 152–156. Météo-France.

Bazile, E., Bouteloup, Y., Bouyssel, F., and Marquet, P. (2008). From the GABLS's result to the ARPEGE NWP system: an easy ride ? In *18th Symposium on Boundary Layer and Turbulence Stockholm-Sweden*, page 4 Pages. AMS,http://www.met.wau.nl/projects/Gabls/index.html.

Bechtold, P., Bazile, E., Guichard, F., Mascart, P., and Richard, E. (2001). A mass flux convection scheme for regional and global models. *Quart. J. Roy. Meteor. Soc.*, 127:869–886.

Bénard, P., Marki, A., Neytchev, P., and Prtenjak, M. (2000). Stabilisation of non-linear vertical diffusion schemes in the context of NWP models. *Mon. Wea. Rev.*, 128:1937–1948.

Bougeault, P. and Lacarrère, P. (1989). Parameterization of orography-induced turbulence in a mesobeta scale model. *Mon. Wea. Rev.*, 117:1872–1890.

Bouteloup, Y., Bazile, E., Bouyssel, F., and Marquet, P. (2009). Evolution of the physical parameterizations of ARPEGE and ALADIN-MF models. In *ALADIN Newsletter*, number 35, pages 48–58. Météo-France.

Cuxart, J., Bougeault, P., and Redelsperger, J.-L. (2000). A turbulence scheme allowing for mesoscale and large-eddy simulations. *Quart. J. Roy. Meteor. Soc.*, 126:1–30.

Cuxart, J., Holtslag, A., Beare, R., Bazile, E., , Beljaars, A., Cheng, A., Conangla, L., Ek, M., Freedman, F., Hamdi, R., Kerstein, A., Kitagawa, H., Lenderink, G., Lewellen, D., Mailhot, J., Mauritsen, T., Perov, V., Schayes, G., Steeneveld, G.-J., Svensson, G., Taylor, P., Weng, W., Wunsch, S., and Xu, K.-M. (2006). Single-column model intercomparison for a stably stratified atmospheric boundary layer. *Bound.-Layer Meteor.*, 218:273–303.

Galperin, B., Sukoriansky, S., and Anderson, P. (2007). On the critical richardson number in stably stratified turbulence. *Atmo. Sci. Letters*, 8:65–69.

Geleyn, J.-F. (1987). Use of a modified richardson number for parameterizing the effect of shallow convection. In *Collection of Paper Presented at the WMO/IUGG NWP Symposium, Tokyo,4-8 August 1986*, pages 141–149.

Lock, A. and Mailhot, J. (2006). Combining non-local scalings with a tke closure for mixing in boundary-layer clouds. *Bound.-Layer Meteor.*, 121:313–338.

Louis, J., Tiedtke, M., and Geleyn, J.-F. (1981). A short history of the operational PBL-parameterization of ECMWF. In *Workshop on Planetary Boundary Layer Parameterization*, pages 59–79. ECMWF. Available from ECMWF, Shinfield Park, Reading, RG29AX Berkshire, UK.

Marquet, P. (2008). Documentation of the TKE-CBR turbulent scheme in the CLIMATE version 5.0 of ARPEGE. In *Internal Documentation*. CNRM.

Mauritsen, T., Svensson, G., Zilitinkevich, S., Esau, I., Enger, L., and Grisogono, B. (2007). A total turbulent energy closure model for neutrally and stably stratified atmospheric boundary layers. *J. Atmos. Sci.*, 64:4113–4126.

Seity, Y., Brousseau, P., Malardel, S., Hello, G., Benard, P., Bouttier, F., Lac, C., and Masson, V. (2011). The AROME-France convective-scale operational model. *Mon. Wea. Rev.*, 139:976–991.

Soares, P., Mirandand, P., Siebesma, P., and Teixera, J. (2004). An eddy-diffusivity/mass-flux parameterization for dry and shallow cumulus convection. *Quart. J. Roy. Meteor. Soc.*, 130:3055–3079.

Zilitinkevich, S., Elperin, T., Kleeorin, N., Rogachevskii, I., Esau, I., Mauritsen, T., and Miles, M. (2008). Turbulence energetics in stably stratified geophysical flows: Strong and weak mixing regimes. *Quart. J. Roy. Meteor. Soc.*, 134:793–799.