Study of the relationship between turbulent fluxes in deeply stable planetary boundary layer situations and cyclogenetic activity

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Abstract

The study explains the reasons of large influence of turbulent transport parameterization on cases with rapid cyclogenesis in Northern Atlantic. Theoretical relationships are examined and later verified with a use of diagnostic tools and adjoint model calculations. Results with different types of physical parameterization setup are compared. Finally, a new method is introduced, using the relations between the Richardson number and dry/conditional symmetric instability.

1 Introduction

The choice of the research topic was motivated by experiences with forecasts of rapidly developing cyclones in Northern Atlantic. Above all, it was the case of the 20 December 1998 cyclone and the devastating Christimas storms of 1999, that showed a strong dependency of successful forecasting of severe cyclonic events on parameterization of turbulent fluxes. Surprisingly, it was found, that the impact on cyclogenesis in the ARPEGE/ALADIN model is related to turbulent transport of heat in deeply stable Planetary Boundary Layer (PBL). The amount of vertical exchange of momentum and heat was at that time controlled by the so called critical Richardson number, that allows some minimum necessary diffusion in very stable stratifications. Between the years 1999 and 2002 a huge effort was done with a purpose to find optimal setting and more sophisticated expressions for this part of parameterization. However, the way, how the modification of this part of parameterization influenced the development of the cyclone, was at that time not well understood.

The original aims of this study were:

a) to understand the mechanism of cyclogenesis resulting from enhanced turbulent mixing of heat in stable PBL layers
b) to adjust the current operational scheme of vertical diffusion, coming out from the knowledge of this mechanism and with respect to cases with rapid cyclogenesis

The main attention was paid on case studies, however, it was expected to use modern tools of numerical weather prediction (NWP) as adjoint models and budget calculations as well.

2 Theoretical evaluation of turbulent transport and its influence on cyclogenesis

In the theoretical part, the link between turbulence and cyclogenesis was evaluated, using the quasigeostrophic approximation for the equation of vertical motions or for the equation of pressure tendency. The contribution of the study was the application of the model parameterization based on the K- theory on the above mentioned equations. Results were compared with the already known theoretical assumptions related to bulk representation of friction or to the Ekman spiral approximation ([4] and [5]).

The influence of turbulent transport of momentum propagates through the rotation of the friction force and corresponding tendencies of vorticity on the distribution of vertical motions (this can be derived from the vorticity equation and the so called omega equation of vertical motion). The changes in the field of vertical motions might be responsible for the support of cyclogenesis or anticyclogenesis. In the literature, this effect is recognized as a part of the so called secondary circulation (because the primary role of the friction is usually in the energy dissipation of the vortices).

After applying the expression for the friction force, as it is parameterised through the exchange coefficients, one becomes for the friction part of the omega equation :

$$\left(\nabla_p^2 + \frac{f_0^2}{\sigma}\frac{\partial^2}{\partial p^2}\right)\omega = \frac{f_0\, g}{\sigma}\frac{\partial}{\partial p}\left(\rho\frac{\partial \rho K_m}{\partial p}\frac{\partial \xi_g}{\partial p}\right) \tag{1}$$

Hence, the distribution of the maxima and minima of the vertical motions ω is dependent on the second derivations of the exchange coefficients K_m or geostrophic vorticity ξ_g in contrary to simple bulk formulas, where dependencies only on simple derivations of these parameters are expected.

The relationship between the vertical motions in p^* pressure levels and height tendencies at surface pressure p_0 level in the quasigeostrophic formulation yields:

$$\nabla_p^2\chi_0 = f_0\left[-\vec{v}_g\nabla_p\left(\xi_g + f\right)\right]_{p_0} - f_0^2\left(\frac{\omega_p^*}{p_0 - p^*}\right) \tag{2}$$

Thus, the effect of vertical transport of momentum on surface pressure depends in the model on the vertical profile of the K-coefficient as well. The exchange coefficients are controlled via the mixing length profile (currently independent on meteorological parameters) or via regulation of the Richardson number function F(Ri).

For the turbulent transport of heat, it seems, that a decrease (or increase) of static stability plays the most important role, though this is not a direct impact of vertical diffusion of heat on cyclogenesis. The static stability defined as:

$$\sigma = -\frac{RT}{p}\frac{\partial ln\theta}{\partial p} = \frac{\alpha^2}{g}\frac{\partial ln\theta}{\partial z} \tag{3}$$

appears not only in the operator of the omega equation but it is present in every forcing term on its right hand side [4] . Thus, the distribution of static stability determines the strength of the effects of temperature or vorticity advection on vertical motions and cyclogenesis.

The time tendency of the static stability can be described by using the turbulent diffusion equation, where one will obtain:

$$\frac{\partial}{\partial t}\left(\frac{\partial\overline{\theta}}{\partial z}\right) = \left[\frac{\partial^2 K_\theta}{\partial z^2}\right]\frac{\partial\overline{\theta}}{\partial z} \tag{4}$$

Thus, the variation of the K_θ coefficients has the biggest importance for static stability tendencies in those parts, where the K- profiles are not linear. The stability will decrease due to turbulent transport in the convex part of the profile, where the exchange of heat reaches its maximum. In the ARPEGE/ALADIN parameterization this appears generally just beneath of the PBL top. On the other hand, the concave part of the profile over the PBL top and in the free atmosphere leads to local increase of static stability. In the model, the amount of heat and moisture exchange was retuned in the part of the so called critical Richardson number Ri_{cr} computation inside of the F(Ri') function. This, without the parameterization of shallow convection yields:

$$Ri' = \frac{Ri}{(1 + \alpha Ri/Ri_{cr})^{\frac{1}{\alpha}}} \tag{5}$$

$$K_\theta = g l_m l_\theta \left| \frac{\partial \vec{v}}{\partial \phi} \right| F\left(Ri'\right) \tag{6}$$

The introduction of the α coefficient separated the computation of the critical Richardson number for momentum and heat. Thus, the tuning of the turbulent heat transport is not provided directly with Ri_{cr} itself but via different parameters, that decide, how much will be the limitation for heat and moisture diffusion in stable layers similar to that, used for the transport of momentum (when α is equal to one). The experiments were mostly done via overthrown value of the so called Ri_d number at the top of the model atmosphere, in the practical use assigned as the USURID control parameter [8] .

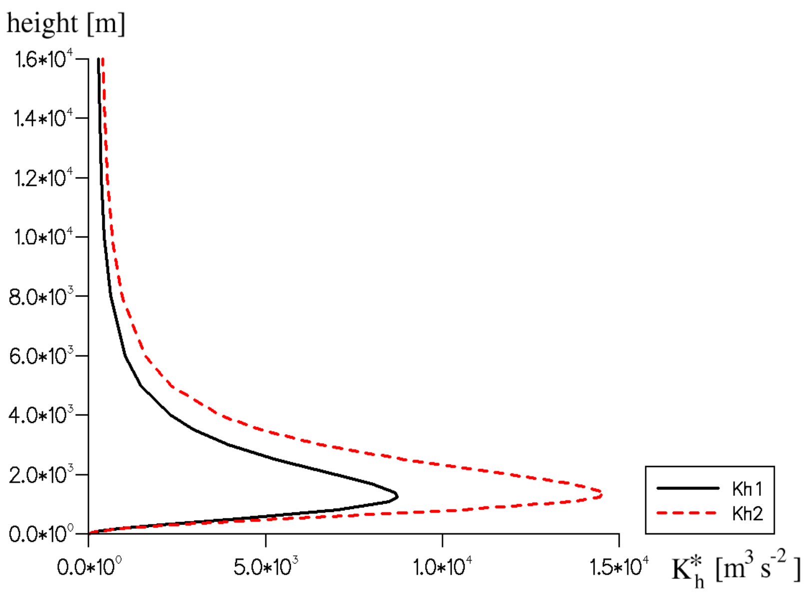

Figure 1 Comparison of the vertical profile of heat exchange coefficients for two different parameterization setups in the PBL for Richardson number=4,5.

K^*_h is actually the exchange coefficient for heat divided by wind shear. The solid line represents the results by using USURID $(1/Ri_d)$ = 0,14, that allows more stable stratification in the PBL. By USURID $(1/Ri_d)$ = 0,042 (dashed line) we decrease the limitation for Ri' and increase the vertical diffusion of heat in the PBL.

The more is the USURID parameter tuned to lower (higher) values, the maximum of the exchange coefficient in the PBL gets more (less) sharp (Figure 1), what means in the sense of the equation (4), that the static stability is decreased (increased) with time. A bit unexpected was the fact, that this effect is visible mostly around Richardson numbers between 1 and 10 (before it was assumed, that the differencies between K- coefficients increase with the stability of the stratification growing up to infinite Richardson numbers).

3 Results of diagnostics

The diagnostic studies were mostly done on the case of the 20 December 1998 cyclone, which showed the strongest dependency on the tuning of the Richardson number type of parameterization. Two principal approaches were used: The first one followed the theoretical assumptions from equations (2) to (6) with static stability as the key parameter to understand the link between turbulent fluxes of heat and cyclogenesis. The aim of the second method was to make a more objective diagnostic study, using the adjoint of the ALADIN model and to look for the sources of forecast errors in the case of decreased turbulent transport of heat.

The first approach used the former experiences on the case study of the 20 December 1998 storm [1] , knowing, that increased transport of heat has impact on the evolution of the cyclone only in the first 21 hours of the 84 hour forecasting period starting from 16.12.1998 12 UTC. Hence, the differences in static stability (or in parameter related to static stability) after approximately 18 or 24 hours of computation should mark the areas, where the forecast run is mostly sensitive to turbulent transport of heat in stable PBL (see Figure 2).

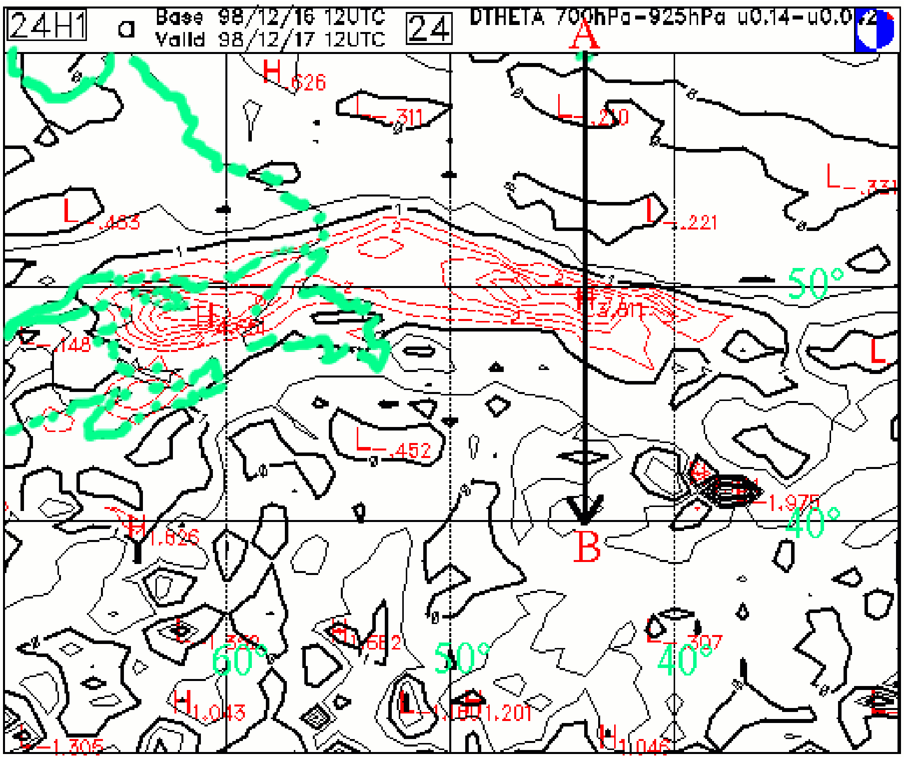

Figure 2 Static stability changes due to enhanced turbulent transport after 24 hours of model integration. The picture was obtained by computing differences of potential temperature between 925 and 700 hPa level and comparing the runs with USURID=0.14 and USURID=0.042 (see also Figure 1). Areas with significant increase (decrease) in stability while going to higher (smaller) USURID are marked by dashed and red lines. The arrow draws the direction of the cross section in Figure 3.

Further, a cross section applied on the field of potential temperature showed, that the decrease of USURID had the consequences, that were expected by theory according to local warming in lower PBL layers and cooling at the top of the PBL and above (compare Figure 1 and Figure 3). The decrease in static stability is also visible on the cross section, as the isolines of potential temperature become steeper in the case of increased turbulent transport of heat. This implies, that a parcel advected adiabatically into such environment has to to climb faster comparing to the case with bigger static stability in the PBL. This assumption was also confirmed, comparing vertical velocities in the same vertical cross section after 36 hours of computation [11] .

To get more objective view, it was decided to do adjoint sensitivity tests for the period between the impact of the tested parameterization and the start of the rapid deepening of the cyclone (from 24 to 66 hour of the used forecast run). The idea of these tests was to use forecasts with different setup of parameterization instead of analysis. Hence, we did not study the sensitivity on initial conditions but the sensitivity created by the impact of different model physics at the beginning of the selected period. More detailed description of this test can be found in [12] or in [13] . The resulting gradients of the error of 42 hour forecast with respect to temperature showed sensitivity in quite different areas, comparing to the results of simple diagnostics (see Figure 2 and Figure 4). Nevertheless, calculations of temperature and moisture budgets provided on the domains around maxima of sensitivity gradients confirmed the consequences for the tendencies of temperature and static stability, found in the previous diagnostic studies (see Figure 5). The tendency of warming due to increase of diffusion of heat (tur) is visible until 800 hPa and after it is replaced by cooling. This leads to drop of of stability around level , that approximately corresponds to the top of the PBL.

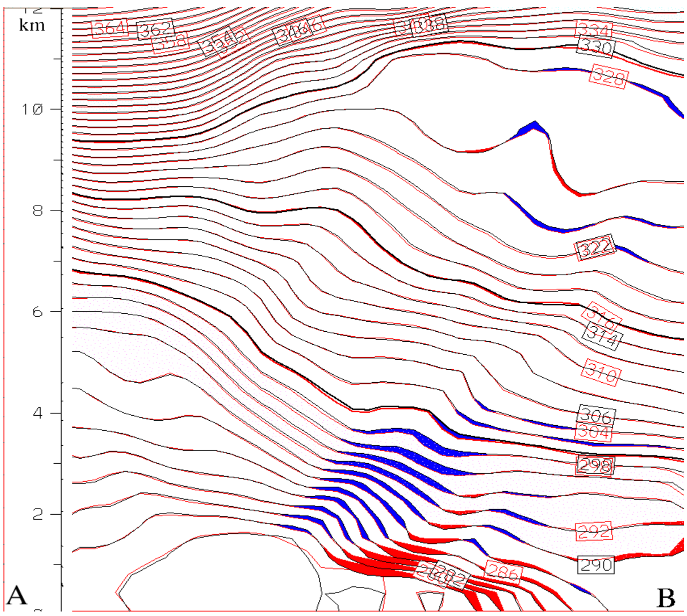

Figure 3 Vertical cross section through potential temperature field computed from the same forecast as in Figure 2. The red isolines of potential temperature belong to experiment with USURID=0,14 and the black isolines to experiment with USURID=0,042. Warming in low levels (red areas) and cooling aloft (blue areas) is obtained by decreasing USURID, thus making the slope of the potential temperature isolines steeper (decreasing static stability). Note, that the warming/cooling effects result on a slope.

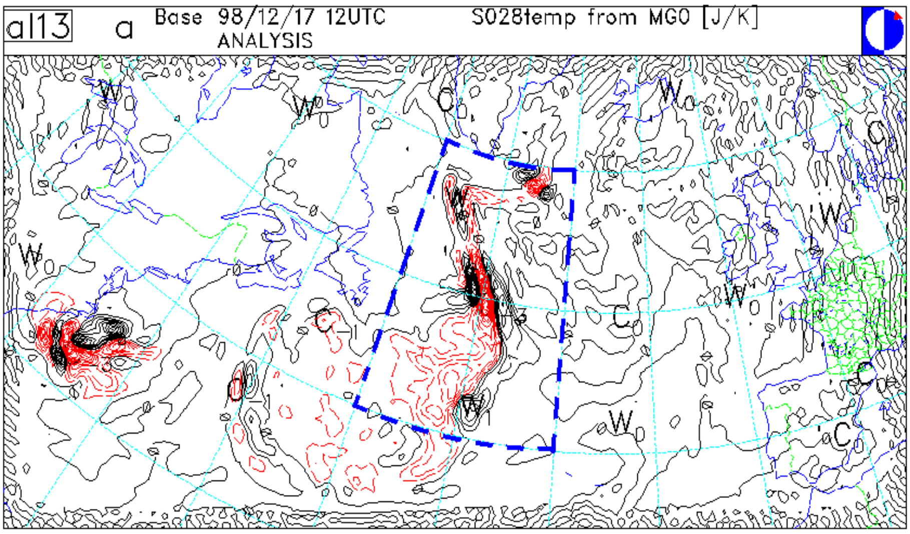

Figure 4 Gradients of the 42 hour forecast error with respect to the temperature and with the dry total energy as the cost function at model level 28. The results show the sensitivity to errors of forecast with decreased turbulent flux of heat in the PBL valid to 17 December 1998 12 UTC (experiment with USURID = 0,14). The blue dashed lines marks the domain used for budget calculation in figure 5.

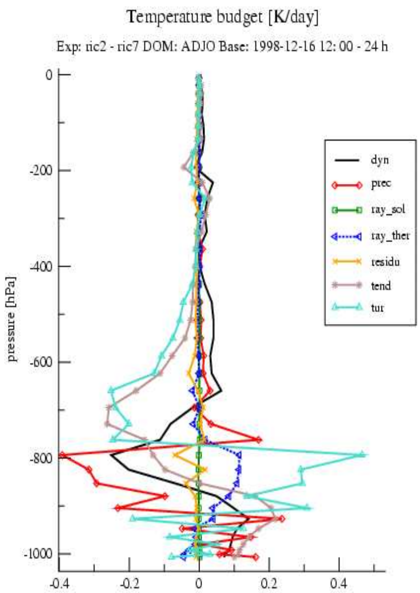

Figure 5 Comparison of the temperature budgets between the operational cy24t1 run (USURID=0,042) and the run with decreased transport of heat in the PBL (USURID=0,14). Note the contribution of the terms not including physical fluxes (black line), the contribution of the turbulent fluxes (light blue line) and the overall tendency (tend).

4 Conclusion about the link between physical parameterizations and dynamics in the case of the 20 December 1998 storm

The results of the diagnostic study explained in the previous chapter seem to agree with the theoretical concept defined by equations (2) - (6). This allows to reconstruct the evolution of the cyclone with respect to the used parameterization. Decrease of the static stability in the PBL is the most important consequence of enhanced turbulent transport of heat during the first 21 hours of computation. However, as one can see on the diagram of the 1998 storm evolution (Figure 6), the turbulent fluxes of heat do not act immediately, because the forecasting runs with different parameterization remain still very close to each other. The changes in static stability are crucial for the cyclone during its dissipating stage (between 30 and 66 hours of integration). Less stable environment supports the vertical motions and enables the cyclone to overcome this period, until it can be again reinforced (in the last 18 hours of integration). On the other hand, very deep stability over ocean (as in the experiment with USURID=0,14) entirely liquidates the cyclone and related sources of low level potential vorticity necessary for the rapid fall of pressure in the last phase of the computation (when the atmosphere arrives to the stage of baroclinic instability).

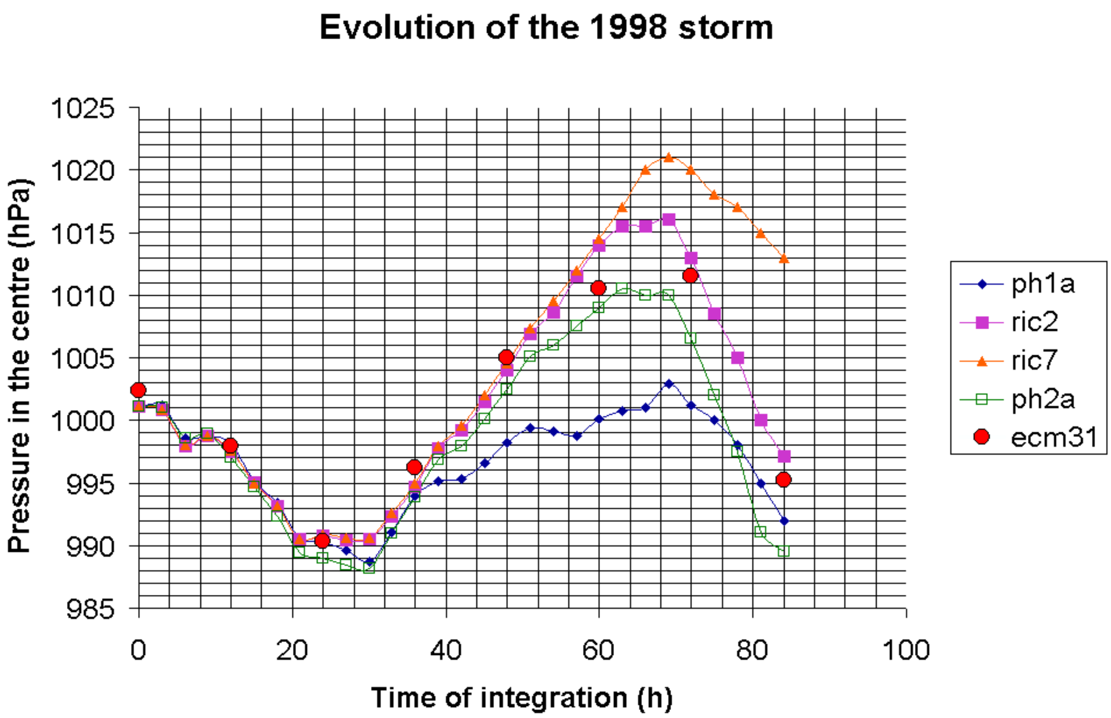

Figure 6 Time evolution of mean sea level pressure in the centre of the "20.12.1998 storm". All of the 84 hour forecasts of the ARPEGE model were based on 16.12.1998 12 UTC. The meaning of the experiments is as follows:

ph1a - run using the modifications of ARPEGE/CLIMAT version, including the Mellor-Yamada second-order closure scheme for turbulent fluxes

ric2 - run of operational ARPEGE cy24t1 with USURID=0,042

ric7 - run with operational scheme but with USURID=0,14 (decreased transport of heat in the PBL)

ph2a - run using the modifications of ARPEGE/CLIMAT but with the stratiform precipitation scheme of the operational model (after Kessler)

ecm31 - objective analysis based on the ECMWF model data

Unfortunately, comparison with the model analysis showed, that the decrease of static stability via increased turbulent transport of heat is not a step towards more realistic description of the atmosphere. The analysis show even deeper stability in the PBL, as it was reached by USURID=0,14 experiment, that leads to complete destruction of the cyclone.

Interesting informations were obtained from experiments with the physical parameterization of the ARPEGE/CLIMAT model, that includes the Mellor-Yamada second-order closure scheme for turbulent fluxes or the Smith type of precipitation scheme [15] . Succesfull forecast of the storm at the end of the model integration is here obtained at the cost of not realistic evolution, without dissipating stage and with false track of the cyclone.

Correction of this spurious effect was possible after replacing the scheme of large scale precipitation of Smith [14] by the parameterization of Kessler [9] used in the operational version of the ARPEGE/ALADIN model. Although such artificial step cannot be considered as a solution of the problem of forecasting the cyclone, it shows at least, that realistic simulation of the cyclone requires adjustments in various parts of physical parameterization, while maintaining the necessary equilibrium between the different physical fluxes.

5 Parameterization of turbulent fluxes with respect to dry and conditional symmetric instability

Experiences with the simulation of the 20 December 1998 cyclone tell us, that the current scheme of vertical diffusion cannot be simply retuned so, that one will obtain realistic results for deeply stable stratification and cyclogenesis as well. Hence, it was decided to look for different ways, how to make the parameterization of turbulent transport more situation dependent and to obtain at least a satisfying compromise.

One of the possibilities was to find an analogue to the parameterization of slantwise (shear-linked) convective processes. It was shown, that this kind of parameterization, described in the article [6] , has a strong impact on model cyclogenesis. Hence, it was supposed, that a counterpart in the scheme of turbulent transport may exist (strong slantwise motions should be accompanied by increased turbulence and exchange of physical properties on a slope).

According to the theory of dry symmetric instability [2] , the scheme was built to enhance the turbulent fluxes, if the potential vorticity will be negative. This can be easily expressed in a 2-D system, using the formula:

$$P = S^4\left(\frac{F^2N^2}{S^4} - 1\right) = S^4(Ri" - 1) < 0, \tag{7}$$

where F^2 is the absolute vorticity of a 2-D system, N^2 is the square of the Brunt-Väisälä frequency and S^2 contains vertical wind shear linked with horizontal gradient of temperature through the thermal wind equation.

It is supposed, that the conditions for turbulent transport in symmetrically unstable environment are the same as for the vertically unstable environment or at least close to the neutral one, that appears in the reference turbulent scheme by Ri = 0. Hence, the new scheme will use a modified Richardson number Ri_p, that becomes equal to zero, when the environment is neutral with respect to dry symmetric instability. Thus, extending (7) to 3-D ARPEGE/ALADIN model framework we can compute:

$$Ri_p = Ri" - 1 = \frac{\zeta}{f}Ri - 1 \tag{8}$$

and to apply it instead of the original Richardson number in the calculation of the exchange coefficients of momentum and heat (6). However, numerical instability detected during the experiments does not allow to use negative values of Ri_p, thus, all potentially unstable cases are brought by the scheme to the neutrality. Moreover, Ri_p computations are applied only for the stably stratified layers ($Ri > 0$).

For the conditional symmetric instability, the modified Richardson number after some approximations yields:

$$Ri_p = \frac{N_w^2}{N^2}\frac{\zeta}{f}Ri - 1, \tag{9}$$

where ζ is the absolute vorticity, f the Coriolis parameter, N^2 and N_w^2 are the squares of the Brunt-Väisälä frequency and its moist version, respectively.

Parameterization of the dry and conditional symmetric instability was tested on several case studies. These included the cases with rapid cyclogenesis as the cyclone of the 20 December 1998 or the famous Christimas storms from 25 and 27 December of 1999. Besides, several cases of false mesoscale cyclogenesis in ALADIN/FRANCE or ALADIN/LACE were evaluated.

The most positive effect of the parameterization of dry symmetric instability appeared in the case of the second Christimas storm in the run starting at 25 December 1999 00 UTC (Figure 7). However, the application of this scheme on the 20 December 1998 storm gave rather neutral results and in other situations the scheme was even able to trigger false mesoscale cyclones.

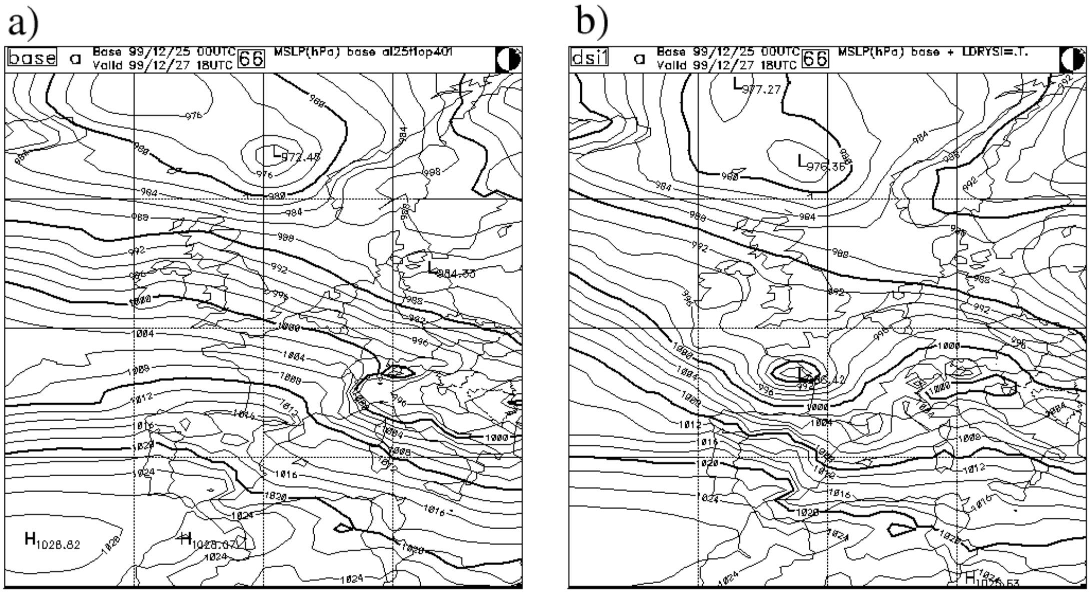

Figure 7 a) 66 hour forecast of mean sea level pressure in the reference ARPEGE run with the operational package of physical parameterization based on 25.12.1999 00 UTC (cycle 25 t1 op4). Note the pattern of shallow trough towards west from coast of France.

b) Results with activation of the parameterization of dry symmetric instability inside the scheme of vertical diffusion.

The Richardson number modified by conditional symmetric instability parameterization after (9) and applied to the scheme of turbulent transport had apparently a big influence in the case of the 20 December 1998 cyclogenesis. The storm was forecasted by both 84 and 96 hour forecast runs (Figure 8). However, the development of the cyclone does not agree with the corresponding model analysis and is getting more similar to the forecast with ARPEGE/CLIMATE type of parameterization, that does not have a dissipating stage.

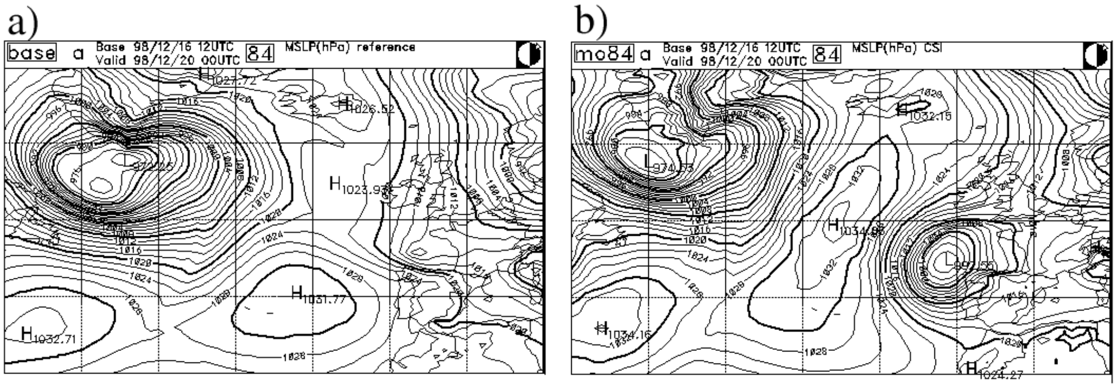

Figure 8 a) 84 hour forecast of mean sea level pressure in the reference ARPEGE run with the operational package of physical parameterization based on 16.12.1998 12 UTC (cycle 25-t1-op4).

b) Results with activation of the Richardson number directly modified with respect to conditional symmetric instability.

Experiments on further case studies showed mostly positive impact, in contrary to the scheme of dry symmetric instability. The parameterization of conditional symmetric instability keeps still better performances against the reference run in the case study of the second Christimas storm and is able to correct several forecasts of false mesoscale cyclogenesis.

To evaluate the overall impact of the modifications (8) and (9), global budget calculations for temperature, moisture and kinetic energy were provided on 96 hour runs of ARPEGE model.

For the scheme of the dry symmetric instability there is already a not negligible change, as one can see on the budget calculation of temperature (Figure 9a). But if we speak about considerable impact in the case of the dry symmetric instability, the parameterization of conditional symmetric instability has already a global impact of unwanted dimensions (Figure 9b).

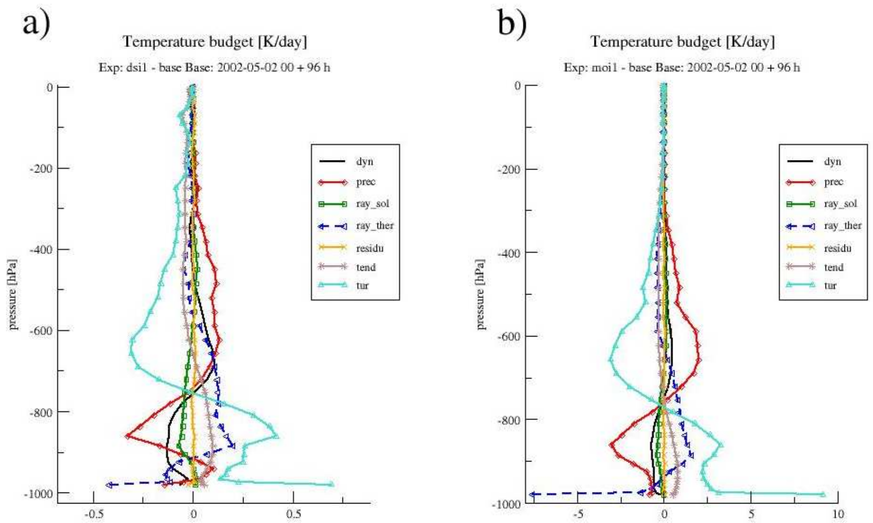

Figure 9 a) Comparison of the global temperature budgets between the run with parameterization of dry symmetric instability and the run using operational package of physical parameterization (cycle 25-t1-op4). Note the contribution of the turbulent fluxes (light blue line), the precipitation fluxes (prec) and the overall tendency (tend).

b) Comparison of the global temperature budgets between the run with parameterization of conditional symmetric instability and the run using operational package of physical parameterization.

The tendency of warming the PBL and cooling the layers of mid- and upper troposphere by vertical diffusion is much bigger than in the previous case. For water vapour budget, there is a tendency to increase the transport of moisture from lower PBL levels upwards and to compensate it partially with the precipitation fluxes.

6 Proposal for mixing length profile in cyclonic flow

The theoretical analysis of the impact of friction force on cyclogenesis described in [13] shows substantial differencies between simple parameterizations based on bulk formulas and the K- theory used in the ARPEGE/ALADIN model. The former ones are more commonly used in dynamic meteorology to explain the role of friction in macrosynoptic processes. The bulk representation of friction force acts on vertical motions and cyclogenesis via simple derivation of the exchange coefficient (that is usually supposed to decrease with height).

On the other hand, the classical K-theory gives more complicated solutions and the second derivations of the K-coefficient with height become important. This is simply the consequence of the baroclinic character of the K-theory in contrary to the barotropic manner of the bulk formulas (that are wind shear independent). However, there should be at least some common characteristics valid for both types of parameterizations (e.g. Ekman pumping or suction, that is usually observed in cyclones and anticyclones of synoptic scales).

New relationships could be found through experiments in a simple barotropic atmosphere and comparing the effects of Ekman pumping produced by current parameterization with exact solutions from Ekman spiral.

Nevertheless, we can already expect, that a correct solution might distinguish between the shape of the mixing length profile for a cyclonic or anticyclonic environment (see [13]). Current parameterization of the ARPEGE/ALADIN model uses a situation independent PBL profile of mixing length, that nearly corresponds to the profiles of K_h^* exchange coeffitients depicted in Figure 1. At the beginning of this study it was supposed, that a concave profile for the mixing length in the PBL might be more effective for the transport of the momentum in the areas of cyclones. The formula for the new mixing length profile representation yields :

$$l_{m/\theta} = \frac{\kappa(z + z_{0/\theta})}{1 + \frac{\kappa(z+z_{0/\theta})^n}{\lambda_{c/\theta}}} \left(a + \frac{2}{e^{b(z-H)} + e^{-c(z-H)}} \right) \tag{10}$$

It is necessary to remark, that the first part of the formula is close to the one, proposed by Blackadar [3] , while the second part is a shaping function with tunable coefficients a, b, c. Finally, the mixing length is normalised (divided) by parameter d, that represents the maximum of the shaping function. The above mentioned adjustment of the mixing length profile was used only in cyclonic flow. For the anticyclonic flow the old representation of the mixing length profile ([10] and [13]) was considered to be sufficient (see Fig.10).

Experiments on situations with false cyclogenesis and the 20 December 1998 rapid cyclogenesis showed a significant impact. However, by forecasting cyclogenesis, the adjustments in the mixing length profile related to turbulent transport of heat seem to be more important, than similar corrections in the momentum part of the computation. The results show, that such change of the shape of the mixing length curve, as presented in Figure 10, can give acceptable forecasts of rapid cyclogenesis. Before, more intense cyclogenesis was achieved through considerable increase of the exchange coefficients at the top of the PBL, with all negative consequencies for temperature inversions (mostly in anticyclonic flow).

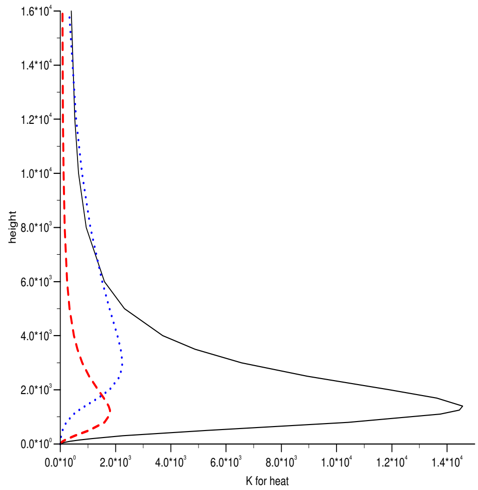

Figure 10 Comparison of various vertical profiles of heat exchange coefficients with the one using the new representation of mixing length in cyclonic environment, all valid for Richardson number=4,5. The height is in meters, K is the coefficient of heat exchange, similar to the K_h^* in figure 1 (unit is $m^3 s^{-2}$).

The solid line depicts the basic profile for older operational setup used in the experiments with critical Richardson number (see chapter 2). The dashed line shows the reference operational configuration (used at the beginning of the year 2003), that was not succesfull in forecasting the 20 December 1998 cyclone. The dotted line represents the possible cyclonic profile of heat exchange coefficient using the definition of mixing length after formula (10). The coefficients used are: a=0.25, b=0.1, c=2.0, d=1.89, n=1.1, H=1260 m, λ_θ=120.

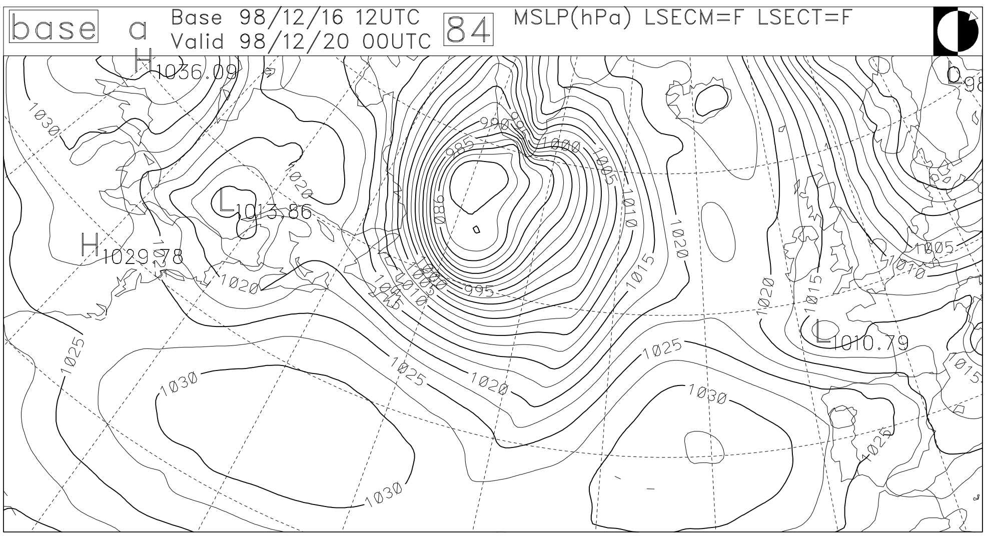

Figure 11 Reference 84 hour forecast of mean sea level pressure on ALADIN model (with 33 km spatial resolution) based on 16.12.1998 12 UTC.

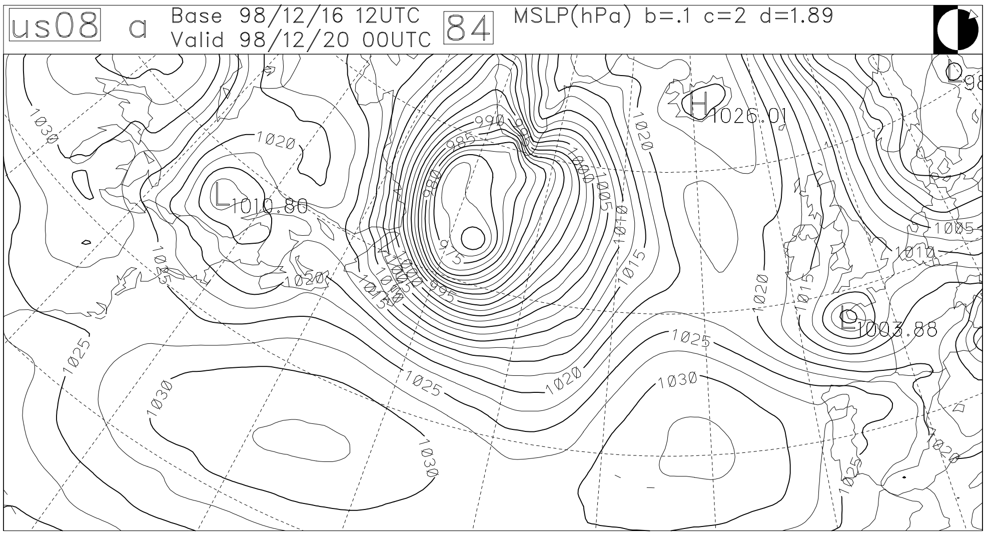

Figure 12 84 hour forecast of mean sea level pressure on ALADIN with different representation of mixing length profile in cyclonic flow, computed after formula (10). Compare with figure 11.

7 Optimalization of the Richardson number for situations with dry and conditional symmetric instability

First experiments done with modified Richardson number Ri_p (defined by equation 8) in situations with dry and conditional symmetric instability needed a lower boundary, where Ri_p should be not smaller than zero. However, forcing of the turbulent scheme from deeply stable to neutral conditions in regions with symmetric instability appeared to be too extreme. Several studies showed, that symmetric instability gives an acceleration to the parcel rather at the beginning of vertical slantwise motions. Later, strong ascending motions on a slope are possible even in environment with small symmetric and convective stability [7] . This knowledge influenced further study on parameterization with modified Richardson number Ri_p increasing its lower limit (before we assumed $Ri_p \geq 0$). Experiments showed, that the lower limit of $Ri_p = 0.25$ gives the best results in cases with rapid cyclogenesis (see also Figure 13) and small improvements in the forecasts of false cyclogenesis in ALADIN model. For ARPEGE model, retuning of the Ri_p number exaggerates the depth of the forecasted cyclones, however, the position is much improved (compare Figures 8 and 14). The noise in the forecast of mean sea level pressure is suppressed and forecasts of anticyclones in Northern Atlantic seem to be more realistic as well.

Further study pointed towards more realistic description of the relationship between symmetrically unstable flow and the Richardson number. Actually, the majority of the experiments were done without using the geostrophical adjustment of vorticity and Richardson number in formula (9). However, the original concept of symmetric and conditional symmetric instability described in [2] was based upon geostrophical approximations (thermal wind relationships, etc.). Tests were done on both cases with false cyclogenesis and rapid cyclogenesis, where the Ri_p number was computed with geostrophic vorticity and geostrophic wind shear. Nevertheless, only minor changes were observed against the results of the former experiments, where the parameters of symmetric instability were not in geostrophic form.

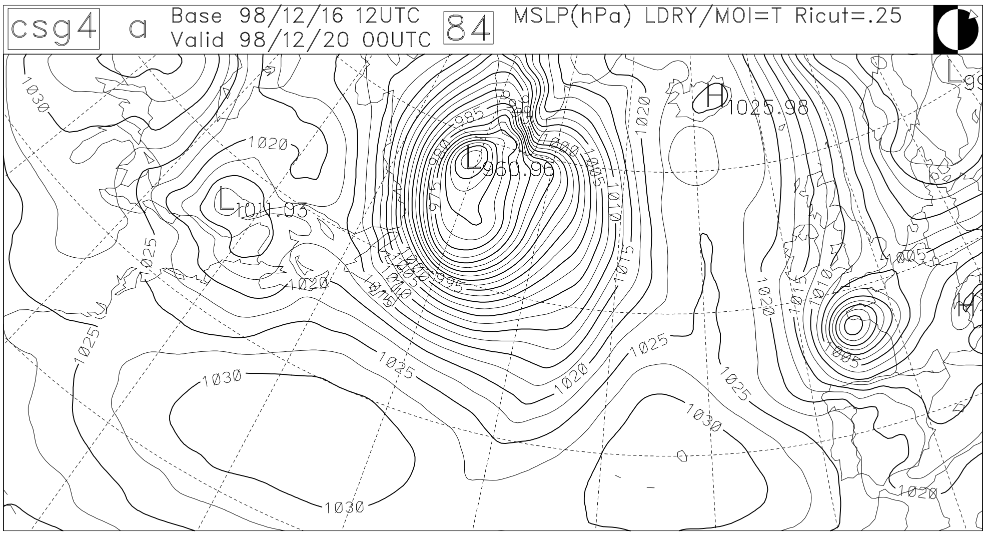

Figure 13 84 hour forecast of mean sea level pressure in the ALADIN run based on 16.12.1998 12 UTC. The turbulent fluxes are parameterised with respect to conditional symmetric instability, assuming the modified Richardson number $Ri_p \geq 0.25$.

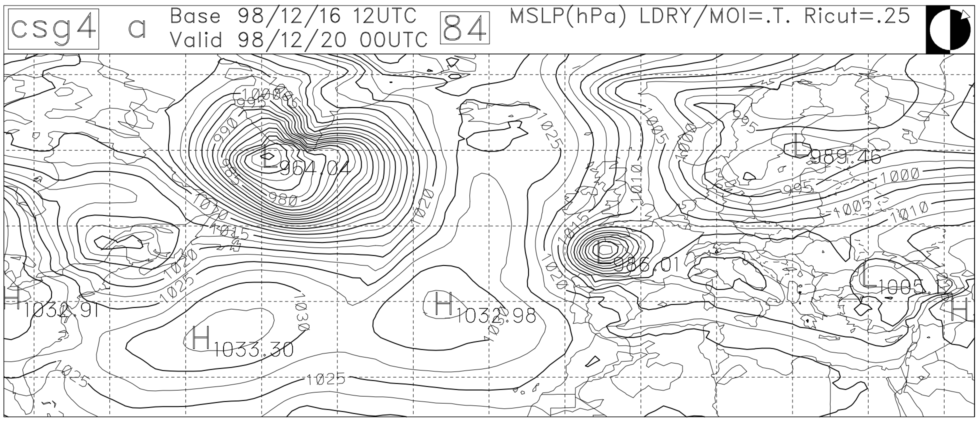

Figure 14 84 hour forecast of mean sea level pressure on ARPEGE, based on 16.12.1998 12 UTC. The turbulent fluxes are parameterised with respect to conditional symmetric instability, assuming the modified Richardson number $Ri_p \geq 0.25$. Compare with figure 8b.

8 Conclusion and proposals for future study

Original idea of this study was to explain, why enhanced turbulent transport of heat improves the forecasts of rapidly developing cyclones. Further, it was supposed to build the parameterization upon this knowledge. However, theoretical and experimental achievements presented in this paper convince, that the turbulent diffusion of heat should be considered rather as an accelerator than cause of deepening the cyclones. In the case of the December 1998 storm, increased turbulent transport of heat helped the cyclone to pass towards areas with good conditions for rapid cyclogenesis. Experiments with the ARPEGE/CLIMAT model (with different scheme of physical parameterization) confirmed the importance of several other parts of the model physics as cloudiness or stratiform precipitation. Hence, it is not possible to get realistic results only by modifying the parameterization of turbulent heat exchange. The comparison with analysis even shows, that with this approach the model cannot have optimal performances both for simulation of deep cyclogenesis and for simulation of inversion. Thus, the concentration on the vertical transport of heat declined, though it is and it has to be still taken into account, when setting up the experiments.

The idea of introduction of the dry and conditional symmetric instability effects inside the parameterization of turbulent fluxes was inspired by experiments on slantwise convection. It was expected, that the modifications will have impact on the cases with false mesoscale cyclogenesis, while rather neutral results were supposed for the large scale cyclones. However, forecasts of the sever storms of winter 1998 and 1999 showed much larger importance of parameterization of symmetric instability processes.

The drawback of the newly proposed scheme is, that it does not keep the equilibrium in the atmosphere, because of global (and large) decrease of static stability at the top of the PBL. It came out, that the diagnostics inside the scheme of turbulent diffusion probably overestimates the occurrence of both dry and conditional symmetric instability. Moreover, the stability criterion presented by the modified Richardson number Ri_p does not really describe the stability conditions in slanted ascent, that are probably more complicated. Some recent experiments described in chapter 7 of this report show, that introduction of slightly stable turbulent scheme for symmetrically unstable situations gives better results than the former neutral one. Hence, more investigations in the future will be required to understand the turbulent processes by the presence of dry or conditional symmetric instability.

According to the equation (1), an alternate solution can be found, leading to simple adjustment of the rate of vertical turbulent exchange of momentum with respect to character of the flow. This is possible through making the expression for the mixing length situation dependent. Different approach for cyclonic and anticyclonic flow could be the key to find a good solution for both situations with rapid cyclogenesis and temperature inversion. However, the study described in chapter 6 should be considered as preliminary. More detailed research is needed to find a more realistic and acceptable formulation of the vertical profile of mixing length.

Finally, it can be concluded, that the study of the turbulent fluxes and cyclogenesis propagated from the area of NWP operational problems more towards area of research. In the future, probably different schemes of physical parameterization will replace the one used in the experiments described in this paper (e.g. in the non-hydrostatic AROME model). Nevertheless, the problem of correct description of turbulent fluxes with respect to mesoscale and large scale atmospheric processes will be not solved simply by increasing the resolution of the model. Thus, further investigation related to this research topic can be expected during the future development in ARPEGE/ALADIN/AROME models.

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Appendix

Notation

a,b,c,d	shaping parameters of model mixing length
f,f_0	Coriolis parameter
g	gravity acceleration
K_ψ	turbulent exchange coefficient of parameter ψ
l_ψ	mixing length for parameter ψ
n	assymptotic parameter for mixing length
N^2,N_w^2	square of Brunt-Väisälä frequency for dry/moist air
p	pressure
P	potential vorticity
R	specific gas constant
Ri	Richardson number
Ri'	limited Richardson number for parameterization of stable layers
Ri_p,Ri''	Richardson number modified by dry/conditional symmetric instability
T	temperature

α	parameter of momentum/heat limitation of Richardson number
ζ	absolute vorticity
θ	potential temperature
ξ_g	geostrophic vorticity
κ	Von Kármán constant
$\lambda_{c/\theta}$	assymptotic mixing length for momentum/heat
ρ	density
σ	static stability
ϕ	geopotential
χ_0	surface height tendency
ω	vertical velocity (p- system)

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