Study of the relationships between turbulent fluxes in deeply stable planetary boundary layer situations and cyclogenetic activity (Summary)

Introduction and objectives of the study

Turbulent fluxes of momentum, sensible heat and latent heat are not only of local importance, but have an influence on global budgets of meteorological parameters (e.g. temperature, energy) and on dynamics of cyclones and anticyclones. Because dimensions of turbulent eddies are usually smaller than horizontal resolution of global and limited area numerical models, parameterizations of turbulence were used already in early generations of numerical models (Deardoff, 1972). The presented study was based mainly on analysis and forecasts of global model ARPEGE (Courtier, Geleyn, 1988) and limited area model ALADIN (Radnóti et al., 1995), which used a K-type parameterization of turbulent fluxes developed from the scheme of Louis (1979) and later modified by Louis et al. (1982). Some experiments were provided with the 1.5 order closure scheme of the ARPEGE/CLIMAT model (Marquet, 2002) and with the so called pTKE parameterization of the ALARO concept of ALADIN model (Geleyn et al., 2006).

The influence of turbulence on development of cyclones and anticyclones is often explained with relations valid for barotropic atmosphere and Ekman-Taylor spiral wind profile. The barotropic damping of cyclone due to Ekman friction and the effects of Ekman pumping/suction on generation of vertical motions can be demonstrated with use of quasigeostrophic omega or height-tendency equations and bulk aerodynamic formulas (Bluestein, 1992). Recent theoretical and numerical studies (Cooper et al., 1992; Adamson et al., 2006; Plant and Belcher, 2007) showed a considerable importance of baroclinic components of the bulk potential vorticity (PV) generated in the planetary boundary layer (PBL) by frictional forces and by transport of sensible heat. Anomalies of PV created in baroclinic zones (e.g. close to warm or cold fronts) can be advected upwards and transported polewards along the warm conveyor belt towards the centre of the cyclone. Baroclinic friction is mostly damping the development of cyclone. However, the method of PV diagnostics is rather heuristic and sometimes unambiguous in explanation of processes of cyclogenesis.

Parameterization of turbulent fluxes in the ARPEGE/ALADIN models appeared to be crucial in forecasting of some rapidly developing cyclones as were the cases of the 20

December 1998 cyclone over France and so called Christimas storms in 1999 over western Europe (Geleyn et al., 2001). The parameterization of the Louis-type stability function with limitation of the Richardson number (by so called critical Richardson number) had a key role in determining cyclogenesis. Surprisingly, this influence appeared in layers and areas of deeply stable stratifications around the top of the PBL. However, decrease of the limits for Richardson number and increase of the turbulent exchange of heat had negative impact on forecasting temperature inversions. The objectives of this PhD. thesis were therefore:

- to examine the influence of the parameterization of turbulent fluxes on generation of vorticity, vertical motions and geopotential tendencies in idealized barotropic and baroclinic atmosphere and to give a theoretical explanation for the relationship between turbulence and cyclogenesis

- to verify the theoretical concept on case studies using modern diagnostic tools as DDH statistics (Piriou, 2001), adjoint of the ALADIN model (Soci, 2003) and various diagnostic parameters. This should help to explain the mechanism of model cyclogenesis triggered by ARPEGE/ALADIN parameterization ofturbulent fluxes.

- to develop modifications of the original parameterization with respect to forecasts of rapid cylogenesis, while maintaining acceptable forecasting scores for meteorological parameters in situations with stable stratification.

- to verify the proposed modifications on case studies and with use of objective verification tools

Development of cyclone in idealized barotropic atmosphere with neutral stratification

The ARPEGE/ALADIN parameterization of turbulent fluxes was firstly tested in conditions of idealized barotropic atmosphere (Rankine vortex) with Ekman-Taylor spiral relationships for wind profile. It was shown that the first order closure representation of friction force is inconsistent with reference hodographs based on Ekman-Taylor spiral. It was further shown that consistency can be reached by modifying the representation of the momentum mixing length in the Ekman layer. In this concept the mixing length (so called barotropic mixing length later in the text) has an exponential profile in the Ekman layer which depends on the exchange coefficients in the surface boundary layer (determined mainly by vertical wind shear) and on the Coriolis force. The barotropic mixing length profile joins the original ARPEGE/ALADIN representation in the outer layer and in the free atmosphere. The detailed description of the formulas is available in the report of Simon (2005).

Dynamics of cyclonic and anticyclonic flow in baroclinic atmosphere with statically stable stratification

The method of quasigeostrophic diagnostics was used to study the impact of momentum, sensible heat and latent heat fluxes on the dynamics of idealized baroclinic atmosphere with statically stable stratification. The pressure and temperature fields were constructed as sinusoidal waves, the atmosphere was hydrostatic and almost saturated. These conditions enabled analytical computation of most of the terms in quasigeostrophic omega and geopotential height-tendency equation. Barotropic influence on vertical motions (e.g. Ekman pumping) and geopotential tendency were analyzed using zero order closure (bulk formulas), while baroclinic effects were studied with first order closure parameterization of the ARPEGE/ALADIN model. It could be concluded that the magnitude of the friction terms is comparable with that of the dynamical terms (large scale vorticity and temperature advection).

The barotropic terms indicate rise of geopotential height (primary effect) and generation of ascending motions in cyclonic trough (Ekman pumping, effect of secondary circulation), height fall and descending motions in anticyclonic ridges (Ekman suction). The distribution of vertical velocity (and also height-tendency fields) for baroclinic friction forcing term is significantly different from the barotropic contribution. Rise of height and upward motions can be for example expected at front side of the trough, while fall of the geopotential and downward motions are likely at rear side of the cyclone. The vertical motions generated by baroclinic friction are of opposite sign above the PBL, but their magnitude decreases significantly.

Vertical motions generated by turbulent transport of sensible heat are about one order of magnitude smaller than those induced by friction. Upward motions can be found close to the axis of troughs and ridges, downward motions are situated between them. The results are qualitatively similar for the baroclinic term in lower PBL, at higher levels (over 925 hPa) the sense of the generated vertical motions reverses sign. On the other hand, the impact of sensible heat transport on geopotential height-tendency is bigger than for momentum transport. It causes fall of height at lower and rise of height at upper levels of the PBL. Maxima of the tendencies are situated close to the trough (ridge) axis. Another important consequence of the sensible heat transport is the decrease of static stability, which is most intense at the top of the PBL. On the other hand, analysis of the quasigeostrophic omega equation shows that generation of upward (downward) vertical velocity at frontal (rear) side of the cyclone due to stability changes at the right hand side of the equation is partially compensated by stability changes at the left hand side of the equation. The drop of static stability has influence on the potential vorticity distribution and causes decrease of the PV amount in the PBL. The influence of the latent heat transport seems to decrease the effect of the sensible heat transport. Although, quantitative analysis would require more detailed description of cloud and precipitation physics.

Influence of the physical parameterization on modelling the cyclonic development in baroclinic atmosphere

The way of parameterization of the mixing length and stability function in first order closure method has significant influence on vertical velocity and geopotential tendency distribution of idealized baroclinic atmosphere. It can be shown that qualitative consistency with bulk method can be reached in some conditions (e.g. by decrease of vorticity with height at front side of the cyclone). The sense of generated vertical motions depends on the second order derivations of the mixing length of momentum. Concave profiles of the mixing length give the opposite signs for vertical motions and geopotential tendencies than the convex profiles used by the ARPEGE/ALADIN parameterization. The decrease of the limit of Richardson number in the stability function (by parameter USURID) determines the rate of static stability drop at the top of the PBL. This can modify (increase) the slope of isentropes and enhance frontogenesis.

Experiences with tests in idealized quasigeostrophic atmosphere enable to construct conceptual models that might be different for barotropic effects (e.g. Ekman friction) and baroclinic components (forced mainly by geostrophic wind shear). Differences between the two approaches are also caused by nonlinear behaviour of the first order closure method used to parameterize the baroclinic influence of momentum and sensible heat transport. It is concluded that indirect effects of turbulence (such as modification of frontal circulation) can also have large impact on cyclogenesis.

Diagnostic studies of cyclogenesis at mid-latitudes

The relationships between turbulent fluxes and cyclogenesis in ARPEGE/ALADIN models was exploited on case studies of rapid cyclogenesis (assigned as type A) and some cases of false mesocyclogenesis (type B). An example of the first type was the case of a rapidly developing cyclone which hit the territory of France on 20 December 1998. The evolution of the cyclone was rather complicated, having three stages (first grow, dissipation and fast reinforcement) and unusual long track (Simon, 2002). It was shown that forecast of this event depended on decrease of the static stability at the top of the PBL caused by decrease of the Richardson number limit and by enhanced turbulent fluxes. The areas of sensitivity can be found in baroclinic zone easterly from Newfoundland peninsula. The effect of static stability decrease is indirect and acts on cyclogenesis with big time delay (almost 42 hours) and large distance from the source (at eastern part of the Atlantic). This can be explained by enhancement of frontal vertical motions (caused also by higher slopes of the isentropes) which slow down the damping of the cyclone in its dissipation stage. This helps to maintain a shallow surface low and associated baroclinic zone, which is important for rapid reinforcement of the cyclone due to baroclinic instability (Simon, 2003). The adjoint model sensitivity tests and DDH statistics generally agree with this concept and with relationships between the decrease of static stability and increase of the velocity of upward vertical motions.

The barotropic and baroclinic components of PV tendencies in the PBL describe rather direct effects of turbulence on cyclone dynamics (confirming the importance of the baroclinic contribution). It is concluded that the temperature gradient in p-system is a good indicator of baroclinicity and of the possibility of enhanced turbulence, what is confirmed by vertical cross-sections and diagnostics of local TKE maxima within baroclinic zones.

Parameterization of turbulent fluxes in atmosphere with high baroclinicity or symmetric instability

The motion of the parcels at frontal boundaries is typically slantwise, following the surfaces of constant wet-bulb potential temperature (moist case) or the isentropic surfaces (dry case). Hence, the turbulent exchange of physical properties probably does not result exclusively in the vertical direction. Large horizontal wind shears across frontal boundaries suggest possibility of horizontal turbulent exchange of momentum which can be provided along the frontal surface. An analytical parameterization of turbulent flux of momentum along isentropes has been developed for ARPEGE/ALADIN physical parameterization (Simon, 2007). The scope of the scheme is to modify the original vertical turbulent flux in way, which would represent the contribution of slantwise turbulent flux to the horizontal acceleration. It was shown that the meaning of turbulent exchange along isentropes will amplify with increase of the horizontal wind shear (above all at small scales and in modelwith high horizontal resolution).

Another, rather empirical scheme of Richardson number limitation was developed to support turbulent transport of momentum and heat in baroclinic areas and allow more stable stratification in non-frontal areas. The area with high baroclinicity is determined by function of critical horizontal temperature gradient β_T, which reaches its minimum at mid-tropospheric levels. The Richardson number in static stability function is limited by function Ri_L. Hence, the Richardson number in baroclinic areas is modified as follows:

$$Ri' = \min\left(Ri_L, Ri\right) \qquad \text{if} \qquad \left|\nabla_p T\right| \geq \beta_T \tag{1}$$

The shape of the β_T and Ri_L functions was defined with model experiments, on case studies. The turbulent transport in non-baroclinic areas is computed with original ARPEGE/ALADIN parameterization with rather stable setup (better for forecasts of temperature inversions).

The parameterization of turbulent fluxes in areas with dry and moist symmetric instability was based on the relationship between three-dimensional potential vorticity and the Richardson number (Simon, 2003). However, experiments on the 20 December 1998 case study showed non-realistic behavior of simulated cyclone, probably due to exaggerated area of the scheme application.

Tests of the turbulence parameterizations in 1- and 3- dimensional numerical models

The parameterizations of the barotropic mixing length and baroclinic limitation of Richardson number were tested in 1-D version of ALADIN model with the ALARO kind of physical parameterization (pTKE scheme) on CASES99 measurements (GABLS2 project, Svensson and Holtslag, 2006). Friction force hodographs were constructed for various parameterization schemes (TKE, pTKE) for almost barotropic atmosphere. It could be shown that the profile of the model friction force is brought by vertical diffusion towards the reference Ekman spiral hodograph, despite of theoretical inconsistency analyzed for idealized barotropic atmosphere. On the other hand, the barotropic mixing length parameterization shows positive influences on forecasts of some meteorological parameters (e.g. temperature and wind profiles) and more realistic fields of sensible heat fluxes. Stronger limitation of Richardson number, however, seems not very suitable for barotropic atmosphere.

The tests continued with three dimensional global model ARPEGE and limited area model ALADIN on 16 cases with rapid cyclogenesis and 5 cases of false mesoscale cyclogenesis. The barotropic mixing length parameterization showed mostly neutral or slightly worse results compared to reference ARPEGE/ALADIN forecasts (not successful in forecasting rapid cyclogenesis). Similar results were achieved with parameterization of turbulent fluxes along the isentropes (suppressing rapid cyclogenesis, small positive effect on damping false mesoscale cyclogenesis). The most successful was the introduction of baroclinic limitation of the Richardson number provided with critical temperature gradient β_T and parameter Ri_L after (1). Thus, turbulent fluxes were enhanced in baroclinic zones, while a reference parameterization setup remained in non-baroclinic areas allowing more stable stratifications (e.g. in situations with temperature inversions). The scheme was better in forecasting rapid cyclogenesis in comparison with the reference parameterization in 50 percent of all cases. It means not only systematic decrease of pressure in the centre of the cyclones, baroclinic limitation of Richardson number improves also forecasts with too deep cyclones predicted by reference scheme. However, worse results occurred in some cases with false mesoscale cyclogenesis. It could be also shown that selective parameterization for baroclinic areas does not have negative impact on forecasts of cloudiness or precipitation (when the forecasts of mean sea level pressure is neutral compared to the reference and to the analysis).

Global statistics and objective verification

Medium-range global statistics (budgets) for temperature, moisture and kinetic energy were computed with the DDH tool from forecasts of the ARPEGE model. The outputs were computed as budget differences of forecasts using tested parameterizations (experiments) and reference ARPEGE forecasts. It was shown that barotropic formulation of the mixing length increases the static stability around the PBL levels and the impact of the scheme is not very big in global means. However, parameterization of turbulent fluxes along isentropes has negative features that are mainly caused by difficulties in specifying some residual terms which depend on second order horizontal derivations of the windspeed. The scheme of baroclinic limitation of Richardson number causes moderate decrease of the static stability above the PBL (around 750 hPa level) but the global temperature tendencies are smaller than by overall tuning of turbulent fluxes with USURID parameter (probably due to better selectiveness of the scheme).

Objective verification has been provided on model ALADIN with statistical tool VERAL (Janoušek, 1999). Barotropic formulation of mixing length and the scheme of baroclinic limitation of Richardson number were tested during two periods with prevailing cyclonic (15.12.2005-1.1.2006) and anticyclonic (7.1.2006-18.1.2006) weather situations over central Europe. The scores for most of the parameters are rather neutral with respect to the original parameterization with stable setup of turbulent fluxes. Nevertheless, further reduction of static stability (e.g. in the case of stronger baroclinic limitation of Richardson number) would have negative influence on temperature forecasts, above all in the free atmosphere.

Conclusion

The results of analytical and diagnostic studies enable to conclude that the main mechanism which influenced the forecasts of rapid cyclogenesis in the ARPEGE/ALADIN model was based on the reduction of static stability in zones with moderate or strong baroclinicity. Parameterization of turbulent fluxes with baroclinic limitation of Richardson number can improve the forecasts of cyclones without considerable negative impacts on forecasts of another meteorological parameters. This modification of the original ARPEGE/ALADIN scheme should be treated rather as reasonable compromise, while realistic forecasting of cyclones requires also revision of other parts of physical parameterizations (e.g. precipitation). Some positive influence on modelling of turbulent fluxes can be expected also from the proposed barotropic formulation of the mixing length or another selective parameterization scheme based on diagnostics of the atmospheric baroclinicity.

Future research of the relationships between turbulent fluxes and cyclogenesis will need a non-linear diagnostic approach to assess the PV generation in the PBL and application of the PV inversion (for objective evaluation of vertical velocities or geopotential tendencies). Specific observations of meteorological parameters in baroclinic environments are necessary as well, above all aerial observations at upper PBL levels and in the free atmosphere. Another possibility is to provide explicit Large Eddie Simulations (LES) along frontal boundary. Such demanding and numerically expensive experiment will be probably available in some of the future generations of numerical models with very high spatial resolution.

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