TKE as a Measure of Turbulence

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1 Introduction

MeteoSwiss is using an integrated modelling system to simulate the dispersion of radioactive materials in emergency situations. For the prediction of the atmospheric flow, the COSMO numerical weather prediction model (Doms and Schättler, 2002) is used, which is run operationally at two horizontal resolutions at MeteoSwiss. COSMO-7 has a horizontal resolution of 6.6 km and is integrated out to 72 hours twice a day on a European domain, while COSMO-2, which is nested in COSMO-7, has a 2.2 km horizontal resolution and provides 24 hour forecasts eight times a day for a smaller domain covering Switzerland. Until December 2005 the COSMO model applied a first order closure for subgrid scale turbulence (level 2 in the Mellor and Yamada notation), which was upgraded to a one-and-a-half order (level 2.5) closure with a prognostic equation for turbulent kinetic energy (TKE) (Mellor and Yamada, 1982). Both COSMO-7 and COSMO-2 are coupled off-line with the Lagrangian Particle Dispersion Model (LPDM, Glaab et al., 1998) with hourly input meteorological data. The two models use the same grid, consequently, no grid transformation is required.

2 Turbulence coupling with the COSMO model

2.1 Coupling approaches

According to the above mentioned turbulence closure versions of the COSMO model, the coupling of the COSMO model with LPDM can be performed in three different ways. The first coupling type uses first order closure in the COSMO model, and the turbulence statistics (mainly TKE and eddy diffusivities) are post-diagnosed in LPDM with the same closure assumptions. In the second coupling type the COSMO model uses the new closure with prognostic TKE, but the turbulence statistics are still post-diagnosed in the dispersion model, while in the third type the prognostic TKE of the COSMO model is used directly by LPDM. These different coupling types resulted in highly different concentrations during the investigated case studies.

In these experiments, an imaginary radioactive emission was modelled with the COSMO-7–LPDM system on a European domain for 48 hours. The case studies covered different synoptic situations and the most pronounced differences between the coupling types were detected in the case with strong cyclonic activity (23 October 2006). In this case the modelled pollutant cloud showed similar characteristics with the first and third coupling type, while the second type resulted in a more dispersed cloud with smaller maximums (Fig. 1 upper panel).

During the investigation of the turbulence statistics in the dispersion model it turned out, that these differences are caused by highly different TKE values (Fig. 1 lower panel). With the second coupling type, much higher TKE values were detected, compared to those with the first and third type; differences could reach a factor of 10 on areas with strong cyclonic activity.

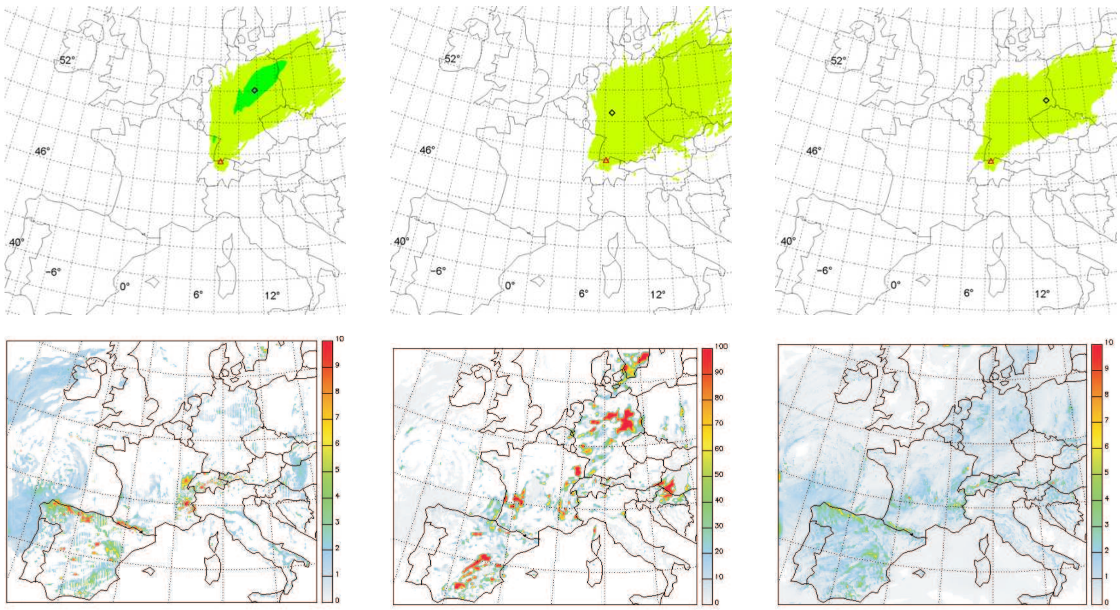

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Figure 1: Concentration calculations (upper panel) and the corresponding TKE values (lower panel) from the dispersion model for the case study of 23 October 2006. TKE values at level 41 ($\sim$460 m AGL) are shown. The three different coupling types from left to right: COSMO with diagnostic TKE, post-diagnosed by LPDM; COSMO with prognostic TKE, post-diagnosed by LPDM; COSMO with prognostic TKE, direct usage of TKE by LPDM. Note that the color-scaling of the TKE plot in the case of the second coupling type indicates higher values by a factor of 10.

These results show that the mean meteorological fields of the COSMO model are more dependent on the turbulence closure than it was previously expected. This dependency gets most pronounced if the turbulence characteristics are post-diagnosed by the dispersion model using different closure assumptions, as it has been done in the case of the second coupling type. However, if the turbulence parametrizations of the two models are consistent (first order in the first type, one-and-a-half order in the third type), more realistic TKE values are present in the dispersion model. Consequently, when coupling dispersion models to the COSMO model, always the same type of turbulence closure should be used in the two models.

2.2 TKE oscillations

Further investigation of COSMO model outputs revealed occasional unrealistic oscillations in the TKE profiles. These oscillations were discovered mainly in stably stratified situations and are considered to be a result of numerical instability in the diffusion scheme. In Fig. 2 forecasted vertical profiles from the COSMO model are shown for a grid point located over northern Switzerland. Comparing the profiles of the different variables it can be concluded that the TKE oscillations have an impact on the mean meteorological variables, as some unrealistic wiggles appear in the wind and temperature profiles as well. The magnitude of these features in the mean variables are apparently small. However, if TKE is post-diagnosed in the dispersion model from the vertical gradients of the mean varibles (second coupling type), highly unrealistic TKE values are obtained (Fig. 2, lower right panel).

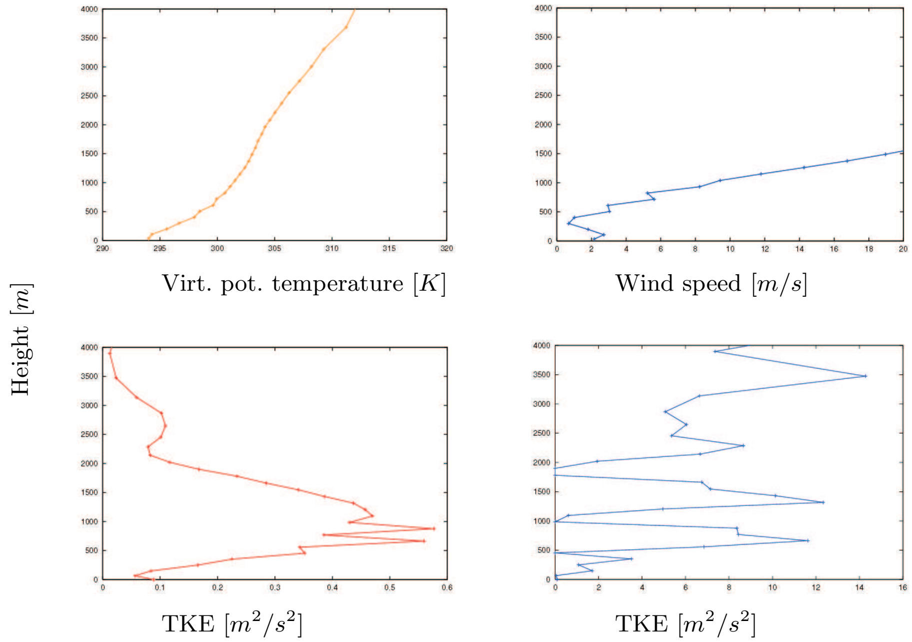

Figure 2: Forecasted vertical profiles for a grid point located over northern Switzerland on 23 October 2006 at 12 UTC. 12 hour COSMO forecast of: virtual potential temperature $[K]$ (upper left), wind speed $[m/s]$ (upper right) and TKE $[m^2/s^2]$ (lower left). In the lower right panel the post-diagnosed TKE values from LPDM are showed.

It has to be noted, that for the above described experiment the Leapfrog time integration scheme has been used. Repeating the experiment with the Runge-Kutta scheme (which is operational at MeteoSwiss since November 2007) the above mentioned TKE oscillations are of smaller amplitudes.

3 Boundary layer height determination

Results shown above imply that TKE is a rather important input variable for a Lagrangian particle dispersion model. However, TKE is not a conventional model variable and it is not verified routinely like temperature, wind or humidity. Consequently, there is a certain demand from the point of dispersion applications to achieve a better understanding of the currently used turbulence scheme and to try to validate the turbulence variables of the COSMO model in different situations. For this reason, an experiment is planned at MeteoSwiss, which aims at the intercomparison of turbulence characteristics of the COSMO model with measurements, LES data and scaling considerations. To be able to use similarity theory approaches for the determination of dispersion parameters, first the height of the planetary boundary layer (PBL) has to be determined from COSMO model outputs. In the following different methods which were applied to COSMO model outputs for PBL height determination will be discussed and results concerning their validation will be shown.

3.1 Methodology

At MeteoSwiss methods using the following characteristics were applied to COSMO model fields to diagnose the height of the PBL:

- Bulk Richardson number
- Gradient Richardson number
- TKE
- Momentum and heat fluxes
- Theoretical approaches based on surface fluxes

By calculating the bulk Richardson number (Ri_b) the diagnosed 2 m temperature was used as a reference and the no-slip condition was applied (i.e. reference wind was 0). According to the literature a critical Ri_b of 0.22 (Vogelenzang and Holtslag, 1996) was used for unstable conditions and a critical value of 0.33 (Wetzel, 1982) in stable situations. By using the gradient Richardson number a critical value of 0.38 was applied. In both cases the top of the PBL was defined as the first height where the critical value of the Richardson number was reached.

When using TKE for PBL height determination, first the maximum value of TKE was searched in a predefined lower part of the atmosphere (2000 m for unstable and 500 m for stable conditions), and the critical TKE value (TKE_c) was defined with a certain threshold (th): $TKE_c = TKE_{max} * th$. During the evaluation different threshold values were tested for stable and unstable stratification. For the momentum fluxes the same methodology was used, however, always the surface momentum flux was used as a reference to calculate the critical value. The PBL top was then determined at the height where TKE or the momentum flux first dropped below the critical value. When using the heat flux of the model the PBL height was determined as the level of the heat flux minimum.

Theoretical approaches to determine the PBL height have also been implemented. These methods are based on the surface heat and momentum fluxes and the background stratification above the PBL. For the convective boundary layer the slab model equation of Batchvarova and Gryning (1991) was used to calculate the growth rate of the boundary layer:

$$\frac{\mathrm{d}h}{\mathrm{d}t} = (1 + 2A)\frac{Q_0}{\gamma_\theta h} + 2B\frac{u_*^3}{\gamma_\theta \beta h^2},$$

where h is the PBL height, Q_0 is the surface potential temperature flux, u_* is the friction velocity, β is the buoyancy parameter, γ_θ is the background stratification above the PBL and A and B are model constants. The integration of the above equation was started at sunrise, when the surface sensible heat flux becomes positive, and it was initiated with a PBL height of 50 m.

For the height of the stable boundary layer the diagnostic equation of Zilitinkevich et al. (2007) was applied:

$$\frac{1}{h^2} = \frac{f^2}{(C_R u_*)^2} + \frac{N|f|}{(C_{CN} u_*)^2} + \frac{|f\beta Q_0|}{(C_{NS} u_*^2)^2},$$

where f is the Coriolis parameter, N is the Brunt-Väisälä frequency and C_R, C_{CN} and C_{NS} are empirical constants.

3.1 Validation

The PBL heights determined by the above mentioned methods were validated against radiosoundings in stable and unstable situations. Ten stable and ten convective days were chosen in 2006 and 2007. On each day the PBL height methods were validated against ten radiosounding stations, consequently, the present study is based on approximately 100 cases regarding both stable and unstable situations. The following stations were chosen to cover most of the COSMO-7 domain: Essen, Idar, Lindenberg, Lyon, Milan, Munich, Payerne, Stuttgart, Trappes and Vienna.

To determine the boundary layer height objectively from the radiosoundings, the bulk Richardson number was applied for the measured virtual potential temperature and wind profiles. For convective days a critical Ri_b of 0.22 was used, which turned out to be a reliable measure and showed good agreement with the subjectively defined PBL top. For stable days a critical Ri_b of 0.33 was applied, which value worked well for well mixed stable boundary layers with an elevated inversion. However, especially in the case of radiation dominated stable boundary layers this method often failed to determine a realistic PBL height. In these cases Ri_b exceeded the critical value already at the first measurement level. If this happened, then starting from the surface the first height was searched, where the potential temperature profile was "close" to adiabatic, i.e. the potential temperature gradient was smaller than 0.72 K/100 m. The combination of these two methods showed reasonable agreement with the subjectively defined PBL top, however, to achieve a more robust method to determine PBL height objectively in stable situations is still an unresolved problem.

PBL heights determined from the radiosoundings were compared to 12 hour forecasts of the COSMO model during the above mentioned stable and convective days. In the experiments the model version 4.0.4 was used. Both horizontal resolutions of the COSMO model were tested, namely, COSMO-7 with 7 km horizontal resolution and 45 vertical levels and COSMO-2 with 2.2 km horizontal resolution and 60 vertical levels. COSMO-7 was initialized from its own assimilation cycle, while the initial conditions for COSMO-2 were interpolated from the COSMO-7 analysis due to the fact that in 2006 no assimilation cycle was running at MeteoSwiss for COSMO-2. The PBL height determination methods were applied for the COSMO model to the grid point which was closest to the radiosounding location. For the verification different scores (bias, standard deviation, RMSE) were calculated and scatter plot diagrams were analyzed.

Table 1: Verification scores for convective cases. Absolute and relative biases, standard deviation of errors and root mean square error (absolute and relative). For the different methods the critical values or thresholds are indicated in parantheses.

	Ri (0.38)	**TKE (0.1)**	**Mom. Fl. (0.1)**	**Heat Fl. (min)**	**Slab model**	**Bulk Ri (0.22)**
BIAS (m)	-775.4	-512.4	-561.4	-626.5	-2	526.7
BIAS-rel	-0.442	-0.24	-0.288	-0.359	0.09	0.441
STDEV (m)	493	556.9	518.4	684.5	560.9	802
RMSE (m)	791	613.2	626.1	782.7	401.1	675.9
RMSE-rel	0.465	0.366	0.377	0.464	0.297	0.519

Table 1 shows verification scores for the different methods applied to COSMO-7 forecasts during convective cases. The slab model performs very well with practically no bias, the bulk Richardson number method shows strong positive bias, while the other methods negative biases with the largest underestimation in the case of the gradient Richardson number. The scatter of the errors is considerably large by all the methods. Concerning the root mean square error the slab model is the best followed by the methods based on TKE and momentum fluxes.

Figure 3 shows the dependence of model errors on the observed PBL height. With every method – except the bulk Richardson number method – the same features can be observed, namely, the shallower (∼700 m) boundary layers are overestimated, while the higher (∼2500 m), well-developed boundary layers are underestimated by the COSMO model. To understand this problem, model forecasts for the station of Lindenberg were investigated in more details. For this station extensive measurement data was available, including soil moisture measurements. The underestimation of well-developed PBLs could be caused by a too moist soil compared to measurements in the COSMO analysis. This high soil moisture leads to overestimated latent and underestimated sensible surface heat fluxes, and consequently a too moist and under-developed boundary layer (Fig. 4). For convective days PBL height results from the COSMO-2 model do not show significant differences from the results of COSMO-7. This could be caused by the fact, that the investigated convective cases showed great sensitivity towards the soil moisture, which was similar in the two models due to the common analysis used.

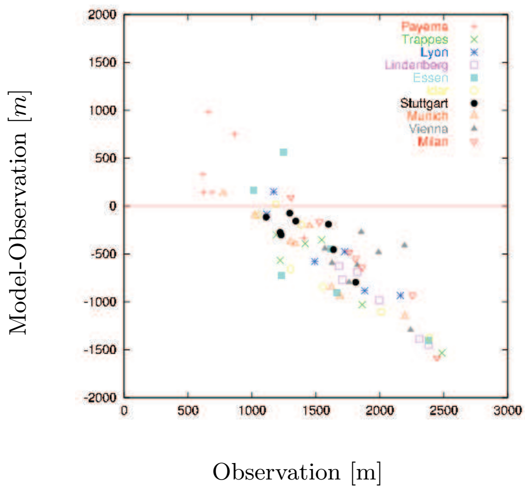

Figure 3: Scatter plot diagram of the determined PBL heights from 12 hour COSMO-7 forecasts. On the y-axis the model errors are depicted. Results of the TKE-method (with a 10% threshold) are shown for convective days.

For stable days the same methods were investigated as for convective cases, however, with somewhat higher thresholds. Both with the TKE and momentum flux method a threshold of 20% proved to be the most appropriate, in contrast to the 10% threshold used during unstable days. The use of higher thresholds was necessary due to a known problem of the COSMO model in stable situations. As a minimum turbulent diffusion coefficient of $K_{min} = 1\ m^2/s$ is applied in the COSMO model, it causes the very stable boundary layer to be more active than in reality, and consequently higher thresholds are needed to find a suitable PBL top in the model.

While during convective days usually all the methods were succesful in finding a PBL top, it

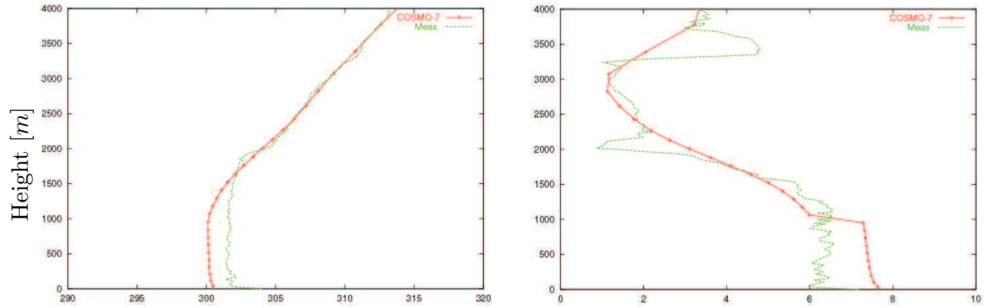

Figure 4: Forecasted vertical profiles of the COSMO-7 model (red line) compared to the radiosounding (green line) at Lindenberg on 18 July 2006 at 12 UTC. Left panel: virtual potential temperature [K]; right panel: specific humidity [g/kg].

Table 2: Number of cases during stable days, when the different methods were able to diagnose a PBL height (maximum number was 93).

Ri (0.38)	**TKE (0.2)**	**Mom. Fl. (0.2)**	**Heat Fl. (0.2)**	**Zil.**	**Bulk Ri (0.33)**
32	65	82	75	93	54

was not the case for stable situations. A method was considered unsuccessful in this respect, if either the diagnosed PBL top was at the first model level (i.e. 30 m by COSMO-7 and 10 m by COSMO-2), or no PBL top was found below 5000 m. The first case was mainly associated with the Richardson number methods, while the second case with methods based on TKE or the turbulent fluxes. The number of successful diagnoses (Table 2) was the highest with the momentum flux method and lowest with the gradient Richardson number method. The diagnostic method based on the Zilitinkevich equation could give a PBL height in every case as the only condition to solve this equation is that the surface heat flux should be negative.

To be able to perform a fair intercomparison between the different methods, verification scores were calculated only for those cases when all the methods were successful in finding a PBL top. These verification scores for COSMO-7 forecasts during stable days are shown in Table 3. The biases of the different approaches do not show such a clear tendency as the definitiv underestimation observed during convective situations. For stable days the Zilitinkevich method shows the smallest biases with a slight underestimation. Also an underestimation could be observed when using momentum fluxes or the gradient Richardson number. However, in the case of TKE, heat flux and the bulk Richardson number method, a clear overestimation is shown, which corresponds to the above mentioned assumption of the too active stable boundary layer in the model. Concerning the root mean square error, the method based on the Zilitinkevich equation performs best followed by the bulk Richardson number method and the momentum flux approach

Finally, it has to be noted, that using radiosoundings to determine the height of the stable boundary layer is rather difficult and consequently the verification results should be handled with certain caution. The subjective evaluation of the radiosounding profiles showed that the above mentioned automatic methods could provide too high values during stable conditions.

Table 3: Verification scores for stable cases.

	Ri (0.38)	TKE (0.2)	Mom. Fl. (0.2)	Heat Fl. (0.2)	Zil.	Bulk Ri (0.33)
BIAS (m)	-230.1	814.9	-146.7	240.8	-114.6	-12.9
BIAS-rel	-0.425	3.1	-0.148	1.193	-0.095	0.14
STDEV (m)	191.3	603.4	189.1	391.9	181	176
RMSE (m)	246.2	839	191.4	344.2	164.7	133.1
RMSE-rel	0.572	3.14	0.448	1.328	0.404	0.424

4 Summary and Outlook

Different turbulence coupling approaches between the COSMO model and the Lagrangian Particle Dispersion Model have been investigated. It has been shown that the TKE in the dispersion model is highly sensitive to the chosen coupling type. Occasional unrealistic oscillations in the COSMO model – which are considered to be a result of numerical instability – could also have an impact on the post-diagnosis of the turbulence fields.

To be able to compare the turbulence characteristics of the COSMO model with scaling considerations, different methods for diagnosing the boundary layer height from COSMO outputs have been tested and validated against radiosounding data. Next to the theoretical approaches, the momentum fluxes of the COSMO model proved to be a good indicator of the PBL height.

As a next step, PBL heights from the COSMO model are planned to be verified against LIDAR measurements, which are considered to be more reliable than radiosoundings in stable conditions. An extensive testing of the COSMO models turbulence scheme is also planned in the framework of the COSMO Priority Project UTCS. The turbulence characteristics of the COSMO model are going to be compared with measurements and LES data, to achieve a better understanding of the model's performance.

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