Introducing sub-grid scale orographic effects in the COSMO model

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1 Introduction

Verification at the German Weather Service (DWD) has shown that the surface pressure in forecasts of the COSMO-EU model is systematically biased. COSMO-EU is an operational implementation of the COSMO limited area model (Doms and Schättler 2002, Schulz 2006) at DWD, covering almost all Europe using a mesh size of 7 km. In particular, in wintertime high pressure systems tend to develop a positive pressure bias, by 1-2 hPa after 48 h, low pressure systems a negative bias ("highs too high, lows too low") (see e. g. Damrath et al. 2007). At the same time the wind speed tends to be overestimated by up to 1 m/s throughout the entire troposphere. The wind direction near the surface shows a positive bias of some degrees.

The combination of these deficiencies leads to the hypothesis that in the model there is too little surface drag, causing an underestimation of the cross-isobar flow in the planetary boundary layer. Consequently, the solution would be to increase the surface drag in the model. This may be accomplished, for instance, by introducing an envelope orography (Wallace et al. 1983, Tibaldi 1986), but this has unfavourable effects e. g. for the simulated precipitation, or by including sub-grid scale orographic (SSO) effects, which were neglected in the COSMO model up to now. The SSO scheme by Lott and Miller (1997) has been selected for this. It is also included e. g. in the global models at ECMWF or DWD and works here well. In the following sections a short description of the scheme is given and results of numerical experiments comparing COSMO-EU with and without the SSO scheme are presented.

2 The sub-grid scale orography scheme

The SSO scheme by Lott and Miller (1997) deals explicitly with a low-level flow which is blocked when the sub-grid scale orography is sufficiently high. For this blocked flow separation occurs at the mountain flanks, resulting in a form drag. The upper part of the low-level flow is lead over the orography, while generating gravity waves.

In order to describe the low-level flow behaviour in the SSO scheme a non-dimensional height H_n of the sub-grid scale mountain is introduced:

$$H_\mathrm{n} = \frac{N\,H}{|U|} \tag{1}$$

where H is the maximum height of the mountain, U the wind speed and N the Brunt-Väisälä frequency of the incident flow. The latter is computed by

$$N = \sqrt{\frac{g}{\theta}\frac{\partial\theta}{\partial z}} \tag{2}$$

where θ is the potential temperature, g the acceleration of gravity and z the height coordinate.

A small H_n will mean that there is an unblocked regime, all the flow goes over the mountain and gravity waves are forced by the vertical motion of the fluid. A large H_n will mean that there is a blocked regime, the vertical motion of the fluid is limited and part of the low-level flow goes around the mountain. The SSO scheme requires four external parameters, which are the standard deviation, the anisotropy, the slope and the geographical orientation of the sub-grid scale orography. They are computed following Baines and Palmer (1990) from the same raw data set of orographic height which is also used for computing the mean orographic height in the model. This is currently the GLOBE data set (GLOBE Task Team 1999) which has a resolution of approximately 1 km.

The two components of the SSO scheme, i. e. the blocking and the gravity wave drag, can both be individually adjusted, or even be switched off, by a tuning parameter. Generally, these two SSO parameters need to be adjusted depending on the mesh size of the model. For this study, the same two parameter values were chosen in COSMO-EU (mesh size 7 km) as in the DWD global model GME (mesh size 40 km). This setting yields already good and satisfying results. They may be further improved by an extensive tuning effort, but this is left here for a future study.

3 Case study

In order to test the SSO scheme in COSMO-EU two continuous numerical parallel experiments, running analogously to the operational analyses and forecasts, were carried out: A reference experiment of COSMO-EU without SSO scheme (called REF), and an experiment of COSMO-EU with SSO scheme (called SSO). The period was 25 Feb. – 31 Mar. 2008.

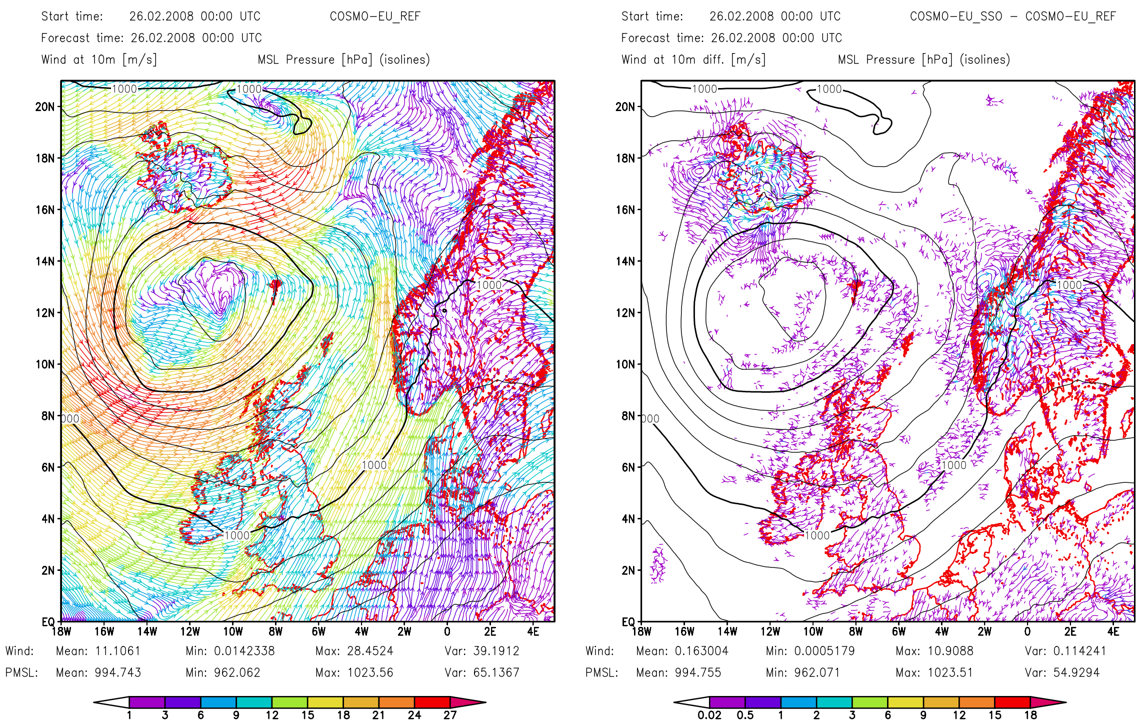

Figure 1: Left: 10-m wind (m/s) and mean sea level pressure (hPa) (isolines) simulated by the reference COSMO-EU without SSO scheme, 26 Feb. 2008, 00 UTC + 00h. Right: Difference of 10-m wind (m/s) between COSMO-EU with and without SSO scheme (SSO - REF), same date. The difference flow is usually pointing in opposite direction than the flow itself (over land), indicating that the flow is slowing down due to the SSO scheme.

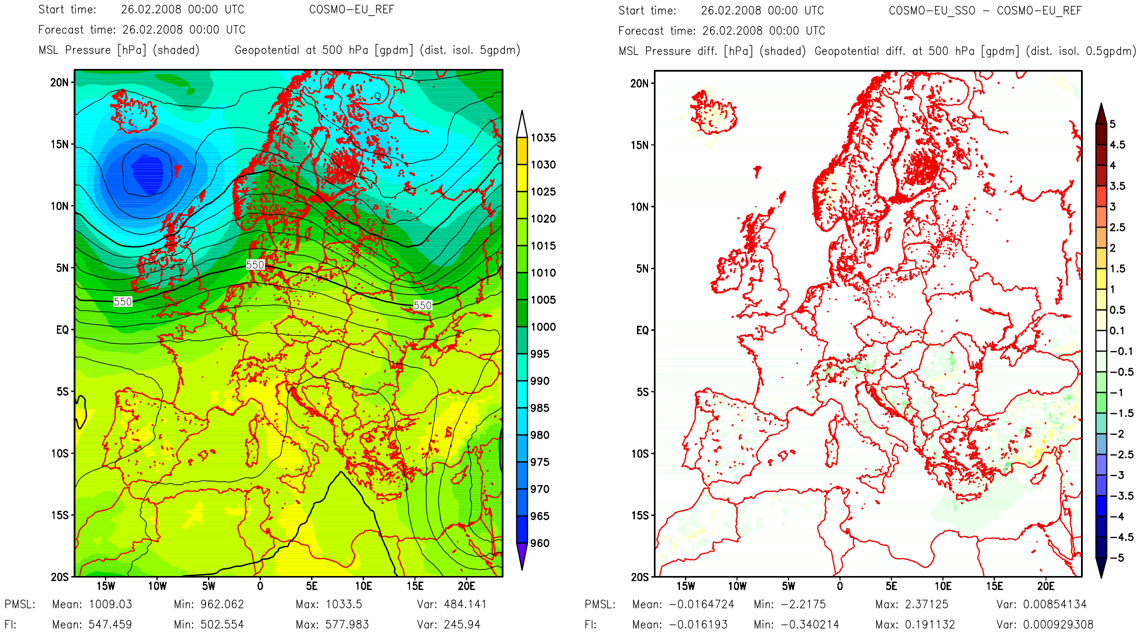

Figure 2: Left: Mean sea level pressure (hPa) and geopotential at 500 hPa (gpdm) (isolines) simulated by the reference COSMO-EU without SSO scheme, 26 Feb. 2008, 00 UTC + 00h. Right: Difference of mean sea level pressure (hPa) between COSMO-EU with and without SSO scheme (SSO - REF), same date.

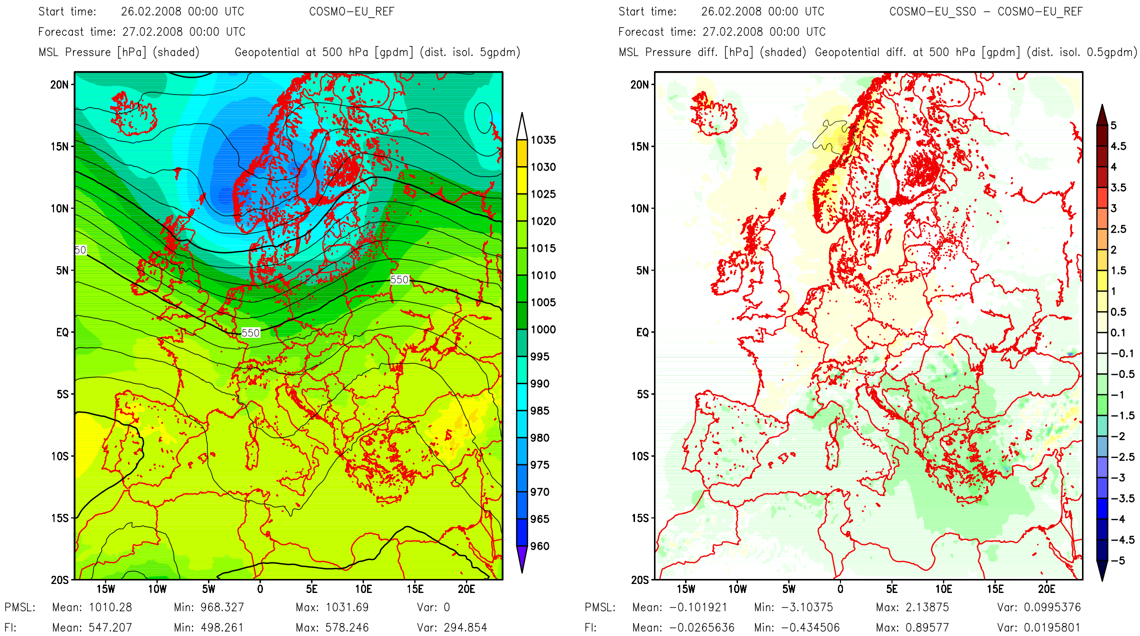

Figure 3: Same as Fig. 2, but for 26 Feb. 2008, 00 UTC + 24h.

This period was selected because several low pressure systems travelled through the model domain, providing good test cases for the SSO scheme.

One of them was on 26 Feb. 2008 which is presented here. Figure 1 shows the mean sea level pressure for the REF experiment in the Northwestern part of the model domain on 26 Feb. 2008, 00 UTC, at the beginning of the forecast, depicting a low pressure system over the Atlantic ocean, which was travelling eastward across Scandinavia during the next few days. The streamlines of the 10-m wind encircle the pressure system, with highest wind

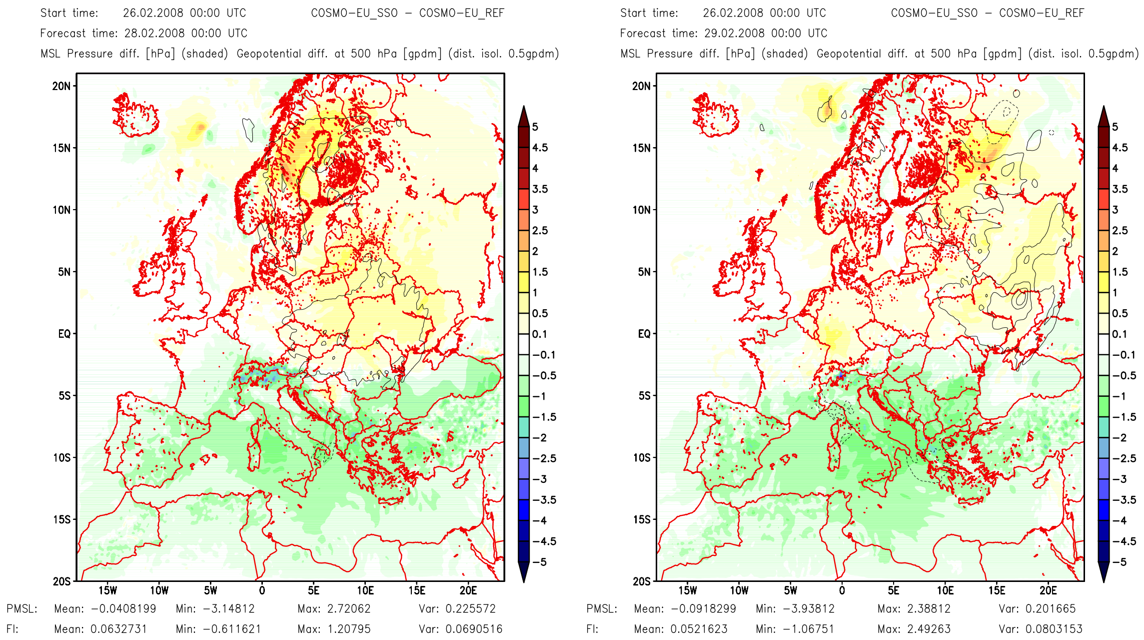

Figure 4: Difference of mean sea level pressure (hPa) between COSMO-EU with and without SSO scheme (SSO - REF). Left: 26 Feb. 2008, 00 UTC + 48h. Right: 26 Feb. 2008, 00 UTC + 72h.

speeds southwest of the core, where the pressure gradient is high, and generally lower wind speeds over land. Differences in the 10-m wind between the two experiments (SSO - REF) are mainly found over land. The difference flow is usually pointing in opposite direction than the flow itself, well seen for instance over the British Isles, indicating that the flow is slowing down due to the SSO scheme.

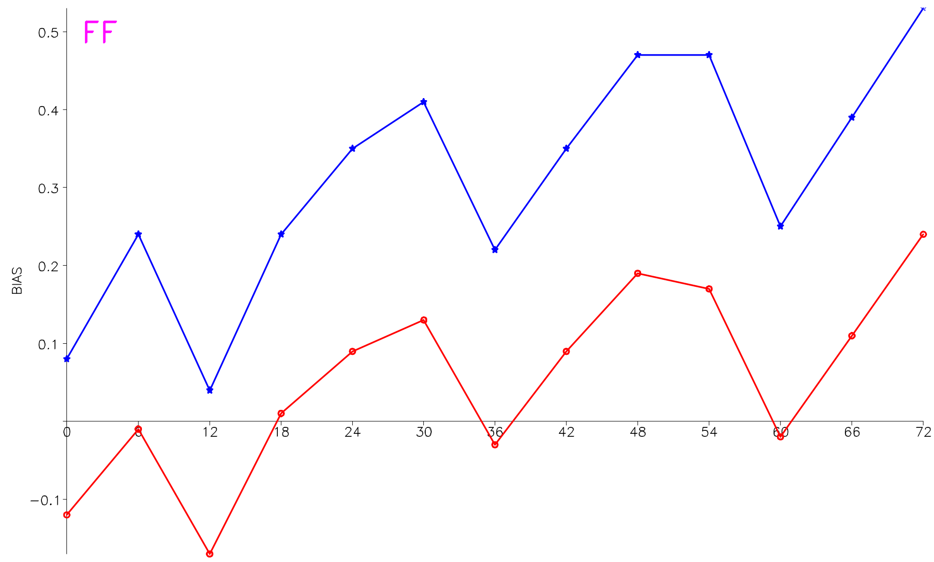

Figure 5: Bias of wind speed (m/s) versus forecast time (h) for the period 26 Feb. – 31 Mar. 2008, 00 UTC runs. Blue: Reference COSMO-EU without SSO scheme (REF), red: COSMO-EU with SSO scheme (SSO). All stations in the model domain were used.

Figure 2 shows the mean sea level pressure for the REF experiment in the full model domain, again on 26 Feb. 2008, 00 UTC. The low pressure system is clearly visible in the Northwest, in the Southern half of the domain, the mediterranean area, there stretches a region of prevailing high pressure. The geopotential at 500 hPa is overlaid as isolines showing the wave over

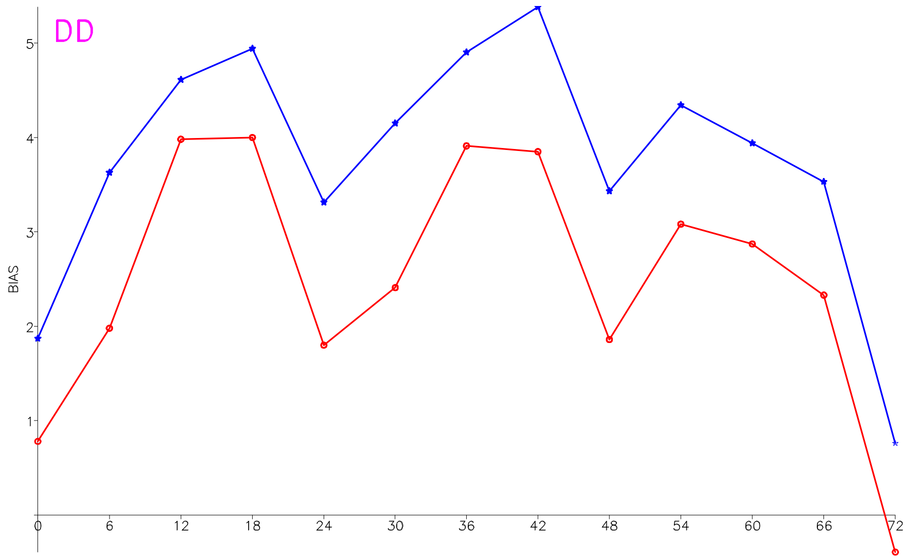

Figure 6: Same as Fig. 5, but for bias of wind direction (°). Blue: REF, red: SSO.

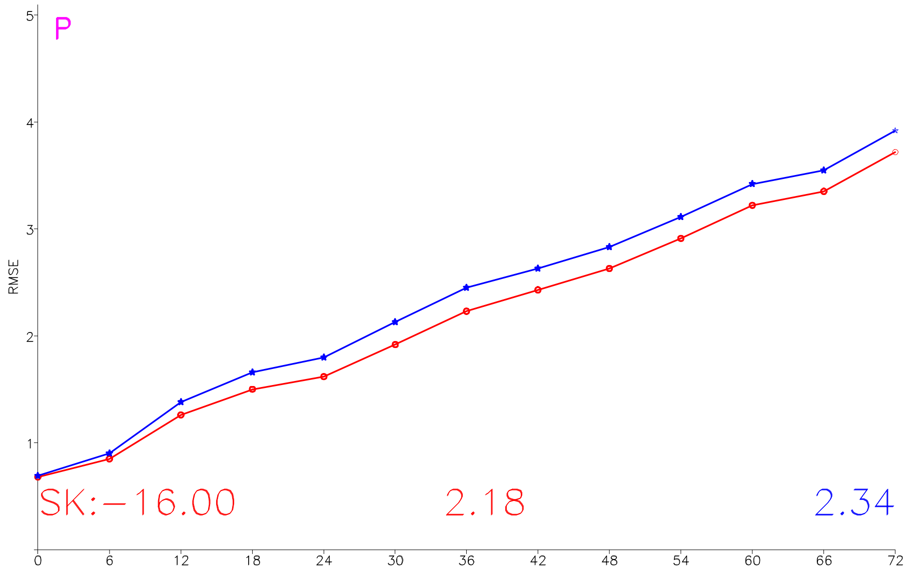

Figure 7: Same as Fig. 5, but for root mean square error of mean sea level pressure (hPa). Blue: REF, red: SSO. The reduction of its error variance in SSO amounts to 16%.

Northern Europe. In the beginning of the forecasts there are only very little differences in surface pressure between the two experiments. After 24h the low pressure system has moved further eastward (see Fig. 3). Pressure differences between the two experiments started to develop in a sort of dipole structure, the low pressure system in the North is filling up more efficiently in the SSO experiment compared to the REF experiment, the high pressure region in the South is weakening. This development continues during the further course of the forecasts while the low pressure system is moving eastward, Fig. 4 shows the pressure differences after 48h and 72h.

This case study shows that the SSO scheme, particularly by increasing the form drag, enhances the cross-isobar flow in the planetary boundary layer, which as a consequence helps filling up low pressure systems and weakening high pressure systems.

4 Numerical parallel experiments

In this section an objective verification of the REF and SSO experiment is presented. Figure 5 compares the biases of the wind speed versus the forecast time for the period 26 Feb. – 31 Mar. 2008. The REF experiment shows a positive bias of up to 0.5 m/s, while the SSO

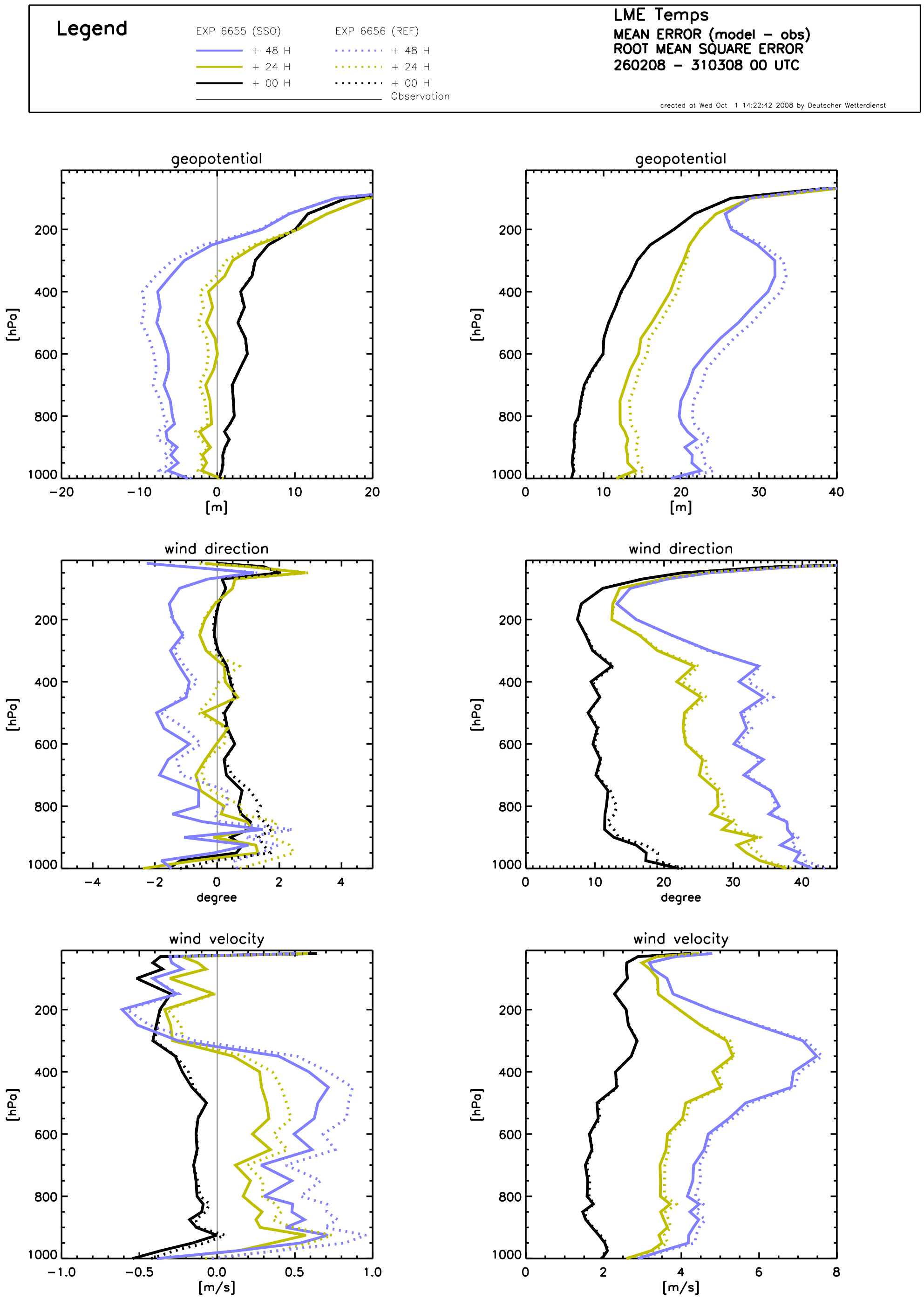

Figure 8: Upper air verification for geopotential (top), wind direction (middle) and wind speed (bottom) for the period 26 Feb. – 31 Mar. 2008, 00 UTC runs. Dotted lines: Reference COSMO-EU without SSO scheme (REF), solid lines: COSMO-EU with SSO scheme (SSO). Left column: Bias, right column: Root mean square error. Black lines: + 00h, yellow lines: + 24h, blue lines: + 48h. All radio sondes in the model domain were used.

experiment is basically bias free. The positive bias of the wind direction is reduced by about 1° in the SSO experiment (Fig. 6). The root mean square error of the vector wind is reduced as well, and also the negative bias of the mean sea level pressure (not shown). In particular, the root mean square error of the mean sea level pressure is significantly reduced, namely, the reduction of its error variance amounts to 16% (see Fig. 7). This means that the pressure patterns are much better captured by COSMO-EU with the SSO scheme.

Figure 8 presents an upper air verification of the two experiments with respect to geopotential, wind direction and speed. This shows a similar and consistent improvement of the model performance by the SSO scheme as well. COSMO-EU without the SSO scheme tends to develop a negative bias in the geopotential and a positive bias in the wind speed, both throughout the entire troposphere. Both biases are reduced by the SSO scheme. Furthermore, a positive bias in the wind direction in the lower troposphere is also getting smaller. Finally, the root mean square errors of all three quantities are slightly reduced as well.

5 Conclusions

The sub-grid scale orography scheme by Lott and Miller (1997) was implemented in the COSMO model. The scheme takes care of two different processes: a blocking of the low-level flow in case the sub-grid scale orography is sufficiently high, and a treatment of gravity waves excited in the flow over the mountains which will propagate through the atmosphere and eventually dissipate. Both processes tend to slow down the mean flow on different levels in the model. In particular the increased form drag results in an enhanced cross-isobar flow in the planetary boundary layer. As a consequence this weakens the development of high pressure systems and helps filling up low pressure systems.

This behaviour of the SSO scheme was successfully tested in COSMO-EU in a selected case study. The objective verification of a continuous numerical experiment with the SSO scheme in COSMO-EU for the period 26 Feb. – 31 Mar. 2008 shows good improvements. In particular, the positive bias of the surface wind speed is basically removed, and the positive bias of the surface wind direction is reduced. The root mean square error of the mean sea level pressure is significantly reduced, namely, the reduction of its error variance amounts to 16%. This means that the pressure patterns are much better captured by the model. Not shown was that the negative bias of the mean sea level pressure is reduced as well, and also the root mean square error of the vector wind. In addition to the surface weather elements the upper air verification shows a similar and consistent improvement as well.

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