Consortium
for
Small–Scale Modelling

Technical Report No. 1

Evaluation of Empirical Parameters of the New LM Surface-Layer Parameterization Scheme: Results from Numerical Experiments Including the Soil Moisture Analysis

by

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March 2001

DOI: 10.5676/DWD_pub/nwv/cosmo-tr_1

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www.cosmo–model.org

Editors: G. Doms and U. Schättler, Deutscher Wetterdienst, P.O. Box 100465, 63004 Offenbach, Germany
Printed at Deutscher Wetterdienst, Offenbach am Main

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- to present and discuss results obtained from the model system,
- to present and discuss verification results and interpretation methods,
- for a documentation of technical changes to the model system,
- to give an overview of new components of the model system.

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Evaluation of Empirical Parameters of the New LM Surface-Layer Parameterization Scheme

Results from Numerical Experiments Including the Soil Moisture Analysis

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1 Introduction

In this note, we outline some results from numerical experiments aimed at optimizing empirical parameters of the new LM surface-layer parameterization scheme (Raschendorfer 1999). This work is envisaged in frames of the COSMO Work Package 3.1. Both "component testing", where the fidelity of the individual model components are tested independently, and "system testing", where the overall performance of the model is tested (Wyngaard and Moeng 1993), have been performed. First, the new LM surface-layer parameterization scheme has been tested independently, using a single-column atmospheric model developed at DWD and observational data from the Lindenberg Meteorological Observatory (Beyrich 2000, Beyrich et al. 2000a, 2000b). By and large the new surface-layer parameterization scheme showed a rather promising performance. A number of shortcomings have been revealed, and the ways of improving the scheme have been suggested. Results from that study will be described in Mironov et al. (2001) in some detail. We will not further discuss them here.

Although results from component testing are extremely useful in understanding whether a parameterization in question appropriately accounts for the essential physical processes at work, they cannot be conclusive. As far as operational applications are concerned, they can only be suggestive. A parameterization scheme that performs well during independent component tests may not perform equally well in the full three-dimensional model environment due to shortcomings of the other model components which have previously been tuned to compensate each other's errors. Therefore, some tuning is usually required when an improved parameterization is implemented (although it should be avoided whenever possible, see Randall and Wielicki 1997, for discussion).

2 Background

Two types of tuning parameters are distinguished, *model parameters* and *external parameters*. Model parameters are usually independent of space and time but dependent on the model formulation. That is, they are constants in the context of a particular physical parameterization used, but more generally, are functions of other physical variables that are not accounted for. Classical examples of the model parameters are the von Kármán constant and the Charnock constant. External parameters describe the application-specific parts of the model set-up, such as geometry of the model and characteristics of the model lower boundary. These may vary in space and some also in time. Examples of the external parameters are the aerodynamic roughness of the land surface (space dependent) and the leaf area index (space and time dependent).

The new LM surface-layer parameterization scheme (Raschendorfer 1999) is intimately connected with a new atmospheric turbulence mixing scheme, the latter being a version of the Mellor and Yamada (1974, 1982) level 2.5 closure using the turbulent kinetic energy as a prognostic variable. Both schemes are planned to be used for operational numerical weather prediction at DWD in spring 2001 (a detailed description of the new schemes will be published in a forthcoming issue of the COSMO technical report). The surface-layer scheme is formulated in such a way that dimensionless coefficients in the surface-layer Monin-Obukhov stability functions are expressed through the dimensionless coefficients of the Mellor-Yamada closure. As the Mellor-Yamada closure has been comprehensively tested in numerous applications (see Nurser 1996, for an overview), the estimates of its dimensionless coefficients are fairly reliable. This tends to reduce the number of LM model parameters to be tuned.

However, high complexity of the interaction of the atmosphere with the underlying surface requires the introduction of additional model parameters and external parameters into the LM surface-layer scheme. New model parameters have been introduced which directly affect the resistance of the air layer immediately adjacent to the underlying surface (laminar sub-layer, see Raschendorfer 1999, for details) to the transfer of momentum and of scalar quantities, respectively (in the LM code notation, these are RLAM_MOM and RLAM_HEAT). A new model parameter has been introduced (RAT_CAN in the LM code notation) that controls the “effective” height of the roughness (canopy) elements. It has a pronounced effect on the surface-layer resistance. This parameter would not be required if the above effective height is introduced as a space-dependent external parameter.

New external parameters have also been introduced in the surface-layer scheme to describe various types of the underlying surface in more detail (theses are the surface area indices of bare soil and of non-evaporating surface). Together with the leaf area index that is already present in the operational LM surface-layer scheme, these parameters have a major effect on evapotranspiration. More specifically, they govern the resistance to the transfer of water vapour from/to the upper soil layer and plants to/from the adjacent surface air layer. As these parameters have no influence on the resistance to the heat transfer, they can be used to change the Bowen ratio.

However, the evapotranspiration is also heavily dependent on the soil moisture. Within the LM data assimilation stream (based on the observational nudging analysis technique), the soil moisture field used to be a free-running prognostic model variable that was not corrected using observations. This was the situation until March 2000, when the soil moisture analysis (SMA) scheme was introduced (Hess 2001). With the SMA, the soil moisture can no longer be considered as a purely physical quantity. Rather it is a “fitting” quantity that is determined so that the predicted 2m temperatures at 12 UTC and 15 UTC give the best fit to the observations. The impact of the SMA is a maximum during warm sunny days. In cloud conditions with low radiation impact, the effect of the SMA is much lower. In these conditions, the influence of soil moisture on the 2m temperature is small. In a sense the soil moisture analysis is a “system testing procedure” that adjusts the time and space dependent model parameters, namely the soil moistures in the two soil layers, to improve the model performance for the 2m temperature. Notice that the resulting model soil moisture is not necessarily in agreement with the actual soil moisture. More likely the SMA adjusts the soil moisture so that to compensate for errors in the day-time 2m temperature introduced by the other LM components. Clearly, an "ideal" model whose forecast is in perfect agreement with observations would not require any SMA-induced changes of the soil moisture. Thanks to the SMA, the abovementioned external parameters of the surface-layer scheme have now a minor effect on the forecast of the 2m temperature and of the 2m dew point. Any changes of the external parameters that affect evaporation would be compensated by changes in the soil moisture induced by the SMA.

The above is not true for the model parameters of the LM surface-layer scheme, first of all, for the parameters that affect the surface-layer resistance to the transfer of scalars (RAT_CAN and RLAM_HEAT). Setting these parameters incorrectly would not result in large errors in the day-time 2m temperature – the SMA would, to a great extent, make up for the deficiencies by appropriately changing the soil moisture. The shortcomings of the surface-layer scheme would, however, manifest themselves in the amplitude of the diurnal cycle of the weather elements, in the minimum temperatures at night and, most notably, in the 2m dew point. This was indeed the case in the previously performed parallel experiments, where the new LM surface-layer scheme was used but the new model parameters were not appropriately tuned (these are experiments No. 102, hereafter "exp_102", and No. 103, "exp_103"). Verification of results from those experiments, although showing a rather satisfactory overall performance of the new scheme, reveal a considerable negative bias of the 2m dew point. It therefore proved to be necessary to tune a number of parameters of the new LM surface-layer scheme with due regard for the SMA.

Although all empirical parameters of the surface-layer scheme are interrelated, as is the case for all turbulence models which are essentially non-linear, we have found that the 2m dew point is most sensitive to the model parameters that directly affect the surface-layer resistance to the transfer of scalar quantities (RAT_CAN and RLAM_HEAT). As explained above, setting these parameters correctly is hardly possible without the use of a full quasi-operational LM including the SMA. The 10m wind is most sensitive to the model parameter that directly affects the surface-layer resistance to the transfer of momentum (RLAM_MOM). As the results from "exp_102" and "exp_103" indicate, the 10m wind with the new surface-layer scheme has a slight positive bias that can be reduced by changing the value of the above parameter. Fortunately, a rough evaluation of this parameter could be made through the LM runs without the use of SMA that are much less expensive computationally.

Finally, a parameter referred to as "pattern length" (PAT_LEN in the LM code notation) helps improve predictions of the weather elements in a stably stratified boundary layer. This parameter controls the degree of enhancement of turbulence due to the sub-grid scale horizontal inhomogeneities of the surface temperature and thus affects turbulence transport. This is a feature of the new LM turbulence scheme which is not present in the operational LM. By tuning the pattern length, predictions of the minimum temperature and the nocturnal wind can be improved. Pattern length should be tuned together with the other model parameter (RLAM_MOM) that directly affects the surface-layer resistance to the transfer of momentum. A rough estimate of the pattern length could be obtained through the LM run without SMA.

Notice that pattern length is actually a location-dependent external parameter. It is related to the length scale of the inhomogeneities of the underlying surface which induce the surface temperature inhomogeneities. As this location dependence of pattern length cannot be rationally determined at present, a constant value is used in LM as if this parameter were a model parameter.

3 Experiments Performed

Since running the full LM suite in a quasi-operational mode over an extended period of time is computationally expensive, evaluating the model parameters by repeatedly performing long parallel experiments deemed unrealistic. Therefore, a series of particularly designed experiments has been performed. A few warm sunny days have been chosen, when the soil moisture changes due to SMA, and, therefore, also changes in evaporation and in the surface-layer specific humidity and dew point, are a maximum. The abovementioned empirical parameters of the surface-layer scheme are optimized by changing their values and repeating 24-hour long runs. The experiments are performed using the DWD Experimental Modelling System (Hanisch 1995).

Notice that the SMA cost function strongly depends on the background soil moisture fields. That is, the scheme accounts for the soil moisture during the past few days and, therefore, does not immediately respond to changes in the external forcing or in model physics. Then, the use of initial fields that are not in accord with the altered model parameters almost inevitably leads to an unsatisfactory prediction of the weather elements in question, first of all, the day-time 2m temperature. This would not have been the case if the SMA had enough time to overcome its "inertia" and set the soil moisture to match the altered model parameters. Therefore, a modified SMA binary (kindly prepared by Reinhold Hess) is used in our 24-hour experiments, where the effect of the background state is practically eliminated. In this way, the SMA is used to determine the initial soil moisture fields that fit the 12 UTC and 15 UTC observations of the 2m temperature. The LM forecast run is then performed for the same day, using these initial soil moisture fields. This is different from the operational SMA implementation, where the 12 UTC and 15 UTC observations of the 2m temperature from the last day are used to correct the soil moisture fields, and the twenty-four hour tendencies from the last-day routine forecast are then added to the above fields to get the initial fields for the next-day forecast run (see Hess 2001, for details).

A large number of 24-hour runs are performed over 2 April 2000, 20 June 2000 and 23 September 2000, to evaluate the abovementioned parameters of the surface-layer scheme. Other experiments have also been performed, but their results are of intermediate character and are not mentioned. Using the estimates of empirical parameters evaluated through the above experiments, further LM test runs are performed for several dates in January 2001. The first month of the new millennium is chosen for a rather cold weather kept over a considerable part of the LM domain for much of the month. As the effect of the soil moisture changes during cold winter periods are typically small, the SMA is not used. The initial fields are taken from the operational LM. The key experiments are listed in Table 1. The SMA Mode "NBSE" (no background state effect) indicates that a modified SMA binary is used, where the effect of the background state is practically eliminated. The SMA Mode "LM" indicates that the SMA is used in the same way as in operational LM.

In order to further test the performance of the surface-layer parameterization scheme in a quasi-operational mode, a parallel experiment, exp_3306, has been set up, where the SMA is used in the same way as in operational LM. This experiment is performed for the period from 24 September to 7 October 2000. This period partially covers the time span of the exp_102 parallel experiment that was performed with the new LM surface-layer scheme but the model parameters used in exp_102 were not tuned. In order to avoid a long spin-up period due to possible inconsistency of the background soil moisture fields and a modified LM physics, the initial fields for exp_3306 are taken from exp_3321, where the soil moisture is determined to match the modified model physics. A comprehensive verification of the exp_3306 results against observational data is carried out.

Table 1: Key experiments.

Experiment Number	Time Period	SMA Use	SMA Mode
exp_3268	2 Apr 2000	Yes	NBSE
exp_3329	20 Jun 2000	Yes	NBSE
exp_3321	23 Sep 2000	Yes	NBSE
exp_3306	24 Sep – 7 Oct 2000	Yes	LM
exp_23sep2000	23 Sep 2000	No	—
exp_14jan2001	14 Jan 2001	No	—
exp_16jan2001	16 Jan 2001	No	—

4 Results

A net result from the runs performed with the use of SMA in frames of the experiments exp_3268, exp_3229 and exp_3321 is that the values of the new LM parameters, namely (in LM code notation), of RAT_CAN=1.0, RLAM_HEAT=1.0, RLAM_MOM=0.1 and PAT_LEN=500 m, are plausible and are recommended for the operational use.

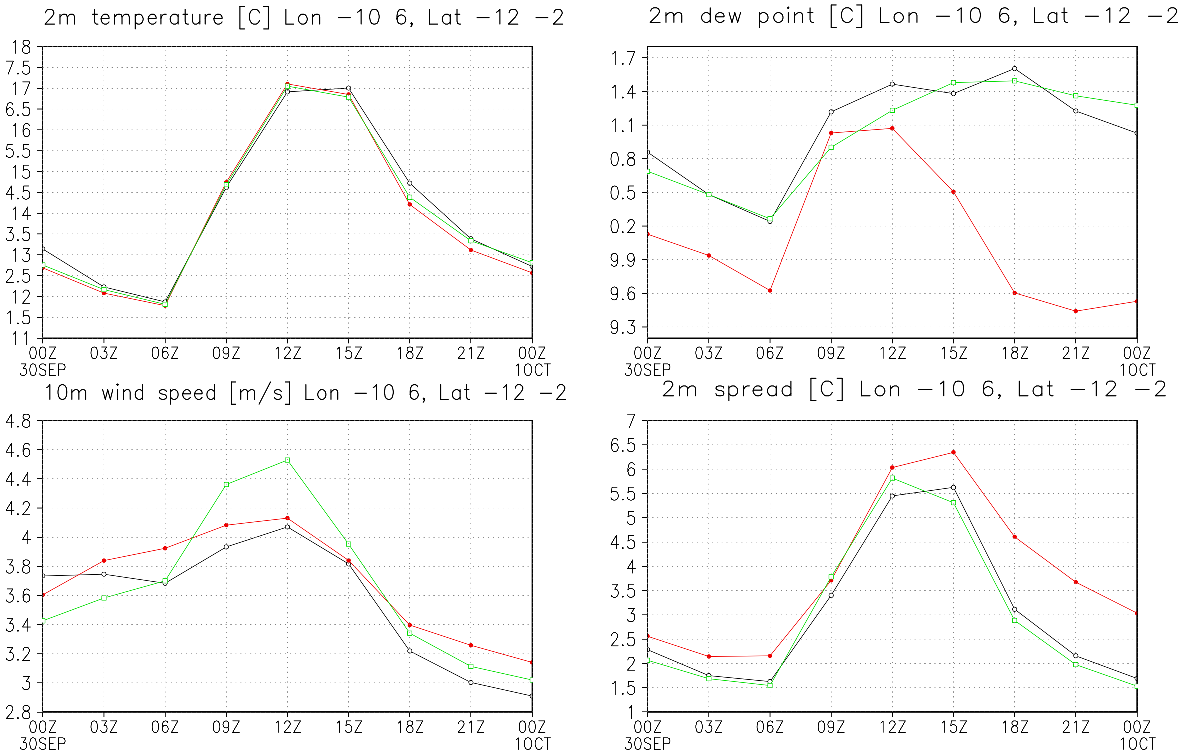

Figure 1: *The 2m temperature, 2m dew point, 10m wind speed and 2m spread from the LM analysis, black curves, from the LM operational forecast, red curves, and from a parallel experiment exp_3306, green curves. The time, UTC, and the date, 30 September 2000, are indicated at the x-axes.*

Figures 1 and 2 illustrate the performance of LM with the new physical package and the above estimates of empirical parameters versus the performance of the operational LM. The results are from a parallel experiment exp_3306. The 2m temperature, the 2m dew point, the 10m wind speed and the 2m spread (2m temperature minus 2m dew point), predicted by the operational LM, out_LM, and by the new version of LM, exp_3306, are compared with the LM analysis, ana_LM. The curves show values of the weather elements averaged over a portion of the LM domain that is most densely covered with observations. Notice that the 2m temperature and the 2m dew point in the LM analysis come from the synoptic measurements. This is not the case for 10m wind that is a purely diagnostic quantity dependent on the interpolation procedure used in the surface-layer scheme. Therefore, the plots of 10m wind only indicate the difference between the various parameterizations.

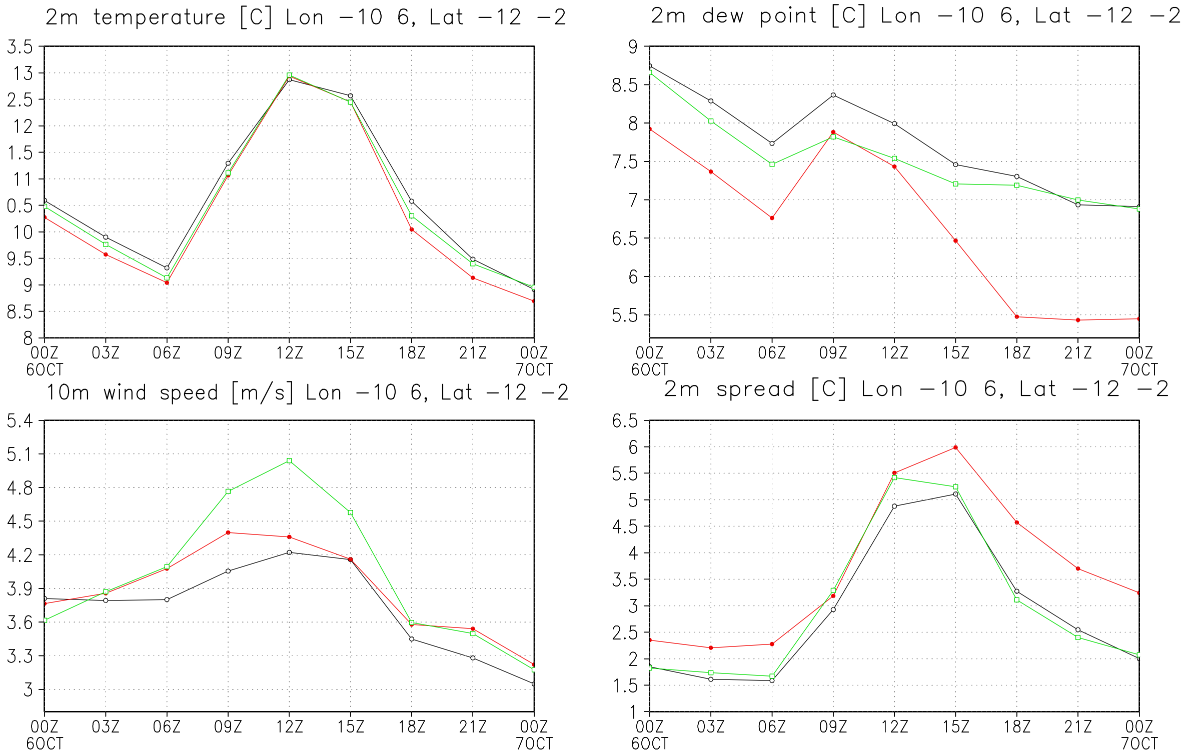

Figure 2: *The same as in Figure 1 for 6 October 2000.*

As seen from the figures, the new version of LM shows a better overall agreement with observations. A marked difference in the diurnal variation of the 2m dew point between the two versions of LM should be emphasised. In the operational LM, the diurnal course of the 2m dew point is a slightly modified re-scaled replica of the diurnal course of the 2m temperature. This is related to the diagnosis of the 2m dew point through the assumption of height-constant relative humidity in the surface layer. It leads to a strong underestimation of the dew point past 15h forecast time and, consequently, to an overestimation of the 2m spread. The latter quantity is of importance for the forecast of fogs. This overestimation is no longer the case with the new version of LM, where the diurnal course of the 2m dew point seems to be more physically realistic and compares better with observations.

Figure 3 compares the 2m temperature forecasts for 18 UTC on 16 January 2001. A test run is performed using the above values of the model parameters. The run is started at 00 UTC on 16 January 2001 with the initial fields from the operational LM. The SMA is not used. As seen from the figure, the 2m temperature is strongly underestimated by the operational LM over a considerable part of Central Europe and United Kingdom. A too rapid decrease of the temperature in the surface layer in the late afternoon hours is a long-standing problem of the LM. The deficiency is partially remedied in the new LM version. This counts in favour of the new physical package.

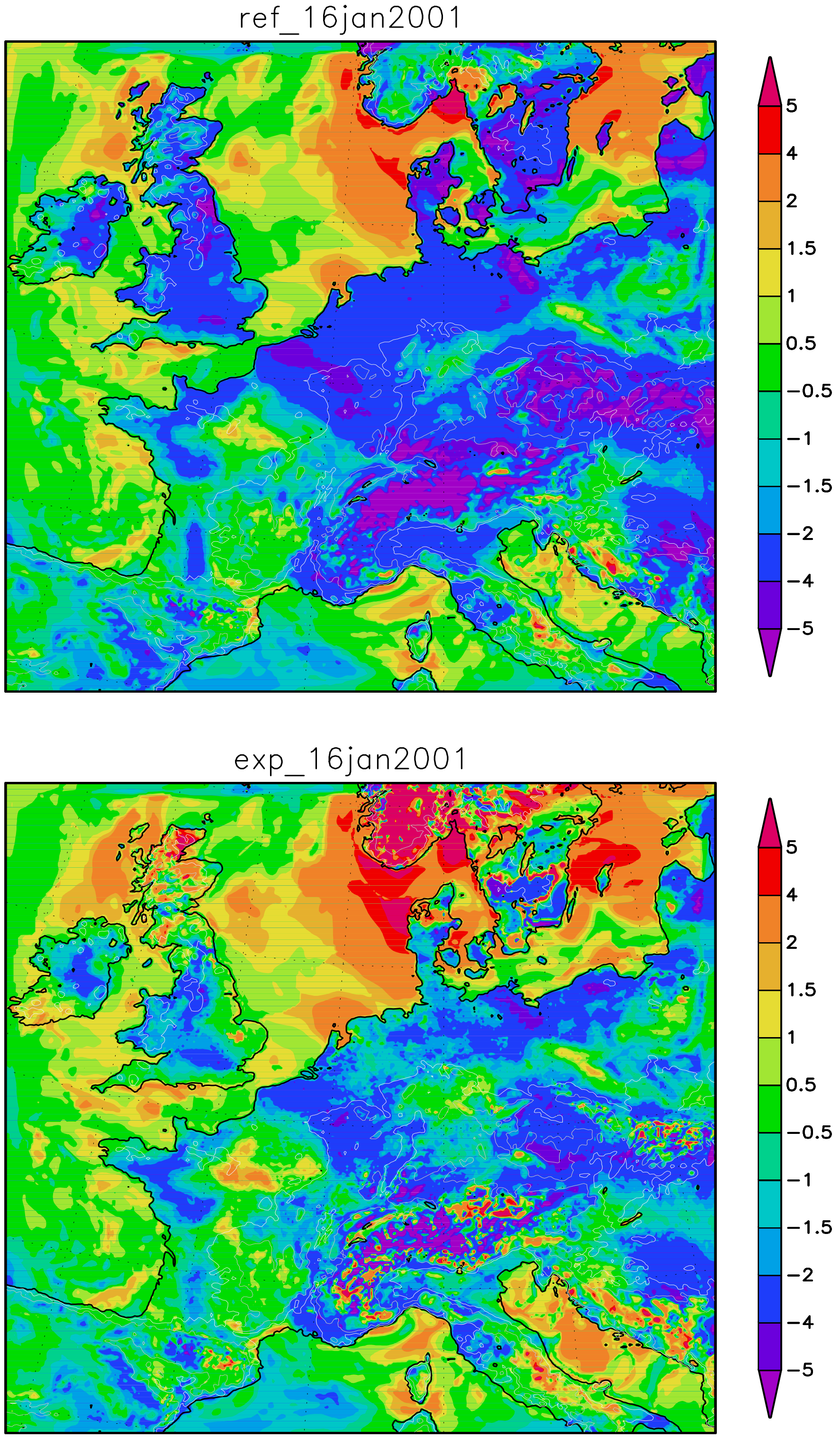

Figure 3: *Forecast error of the 2m temperature (°C), 18 UTC, 16 January 2001; the contour lines indicate the topographical heights of 200m (white) and 500m (grey); reference is the LM analysis. Upper panel: operational LM. Lower panel: test forecast with the tuned values of the model parameters as given in section 4.*

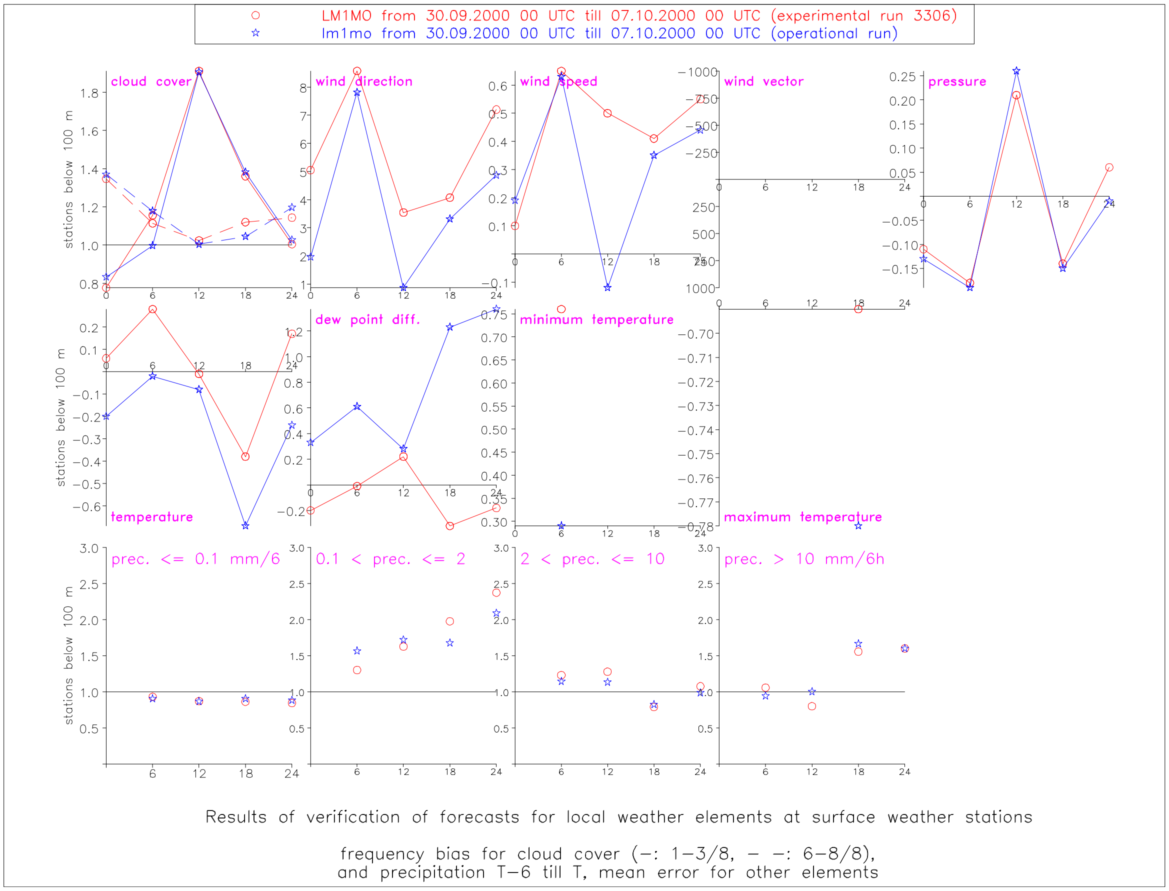

Figure 4: *Mean verification scores of all Synop Stations below 100 m for the period 30 September to 7 October 2000 (00 UTC) as a function of forecast time (00, 06, 12, 18 and 24 h). Red – experimental run exp_3306, blue – operational run.*
Mean error for all elements except for cloud cover and precipitation (frequency bias); numbers are mean values over all forecast times. Top (from left to right): cloud cover, wind direction, wind speed, wind vector and surface pressure. Middle (from left to right): temperature, dew point difference, minimum and maximum temperature. Bottom: frequency bias of 6 h precipitation amounts (prec) for the four indicated threshold intervals.

Figures 4 – 6 show results of verification of exp_3306 performed with the standard verification package of the DWD Department of Research and Development. For the weather stations whose height above the sea level does not exceed 100 m, the new version of LM reveals considerable lower mean error (Figure 4) of the 2m dew point and of the 2m temperature.

For these stations, the root-mean square error (Figure 5) is practically the same for the 2m temperature but is marginally smaller for the 2m dew point. The mean error is slightly higher for the 10m wind speed, however. The new LM version also shows a slight improvement in predicting the cloud cover, as seen in the upper left panel in Figure 5.

For all stations analysed (Figure 6) the major advantage of the new LM version is manifested in the mean error of the 2m dew point, particularly past 12h forecast time, and of the 2m temperature, particularly during the night time.

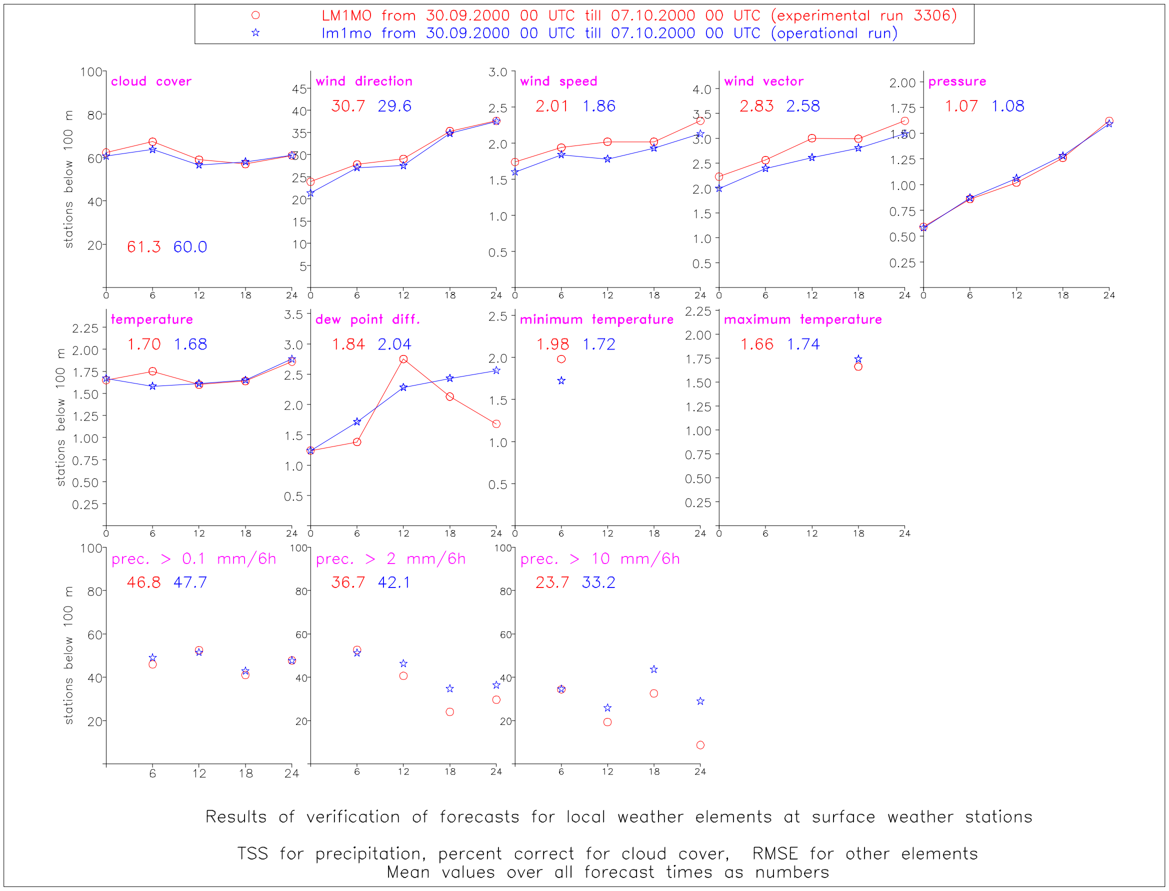

Figure 5: *As in Figure 4, but root-mean-square error for all elements exept for cloud cover (percent correct, upper panel left) and precipipitation (TSS, lower panel).*

5 Conclusions

A preliminary verification of results from the experiments described above lends considerable support to our estimates of parameters of the new LM surface-layer scheme. A negative bias of the 2m dew point is now largely reduced. The 10m wind is now reduced by about 0.4 $\mathrm{m{\cdot}s^{-1}}$ during the day and by about 0.1 $\mathrm{m{\cdot}s^{-1}}$ during the night as compared with exp_102. This reduction was suggested by verification (performed by Ulrich Damrath) of results from exp_102 against observations. As compared to the operational LM, the new parameterization scheme yields a number of improvements. Among them are a more realistic diurnal course of the 2m dew point as compared to the operational LM, and higher 2m temperatures during the evening and the night hours which are known to be underpredicted by the LM.

As a word of caution we note that in the experiments described above more emphasis has been placed on the performance of the surface-layer scheme over the land surface. The situation over the water surface motivates further investigation which may entail further modification of the surface-layer scheme.

Finally, the pattern length that is now kept constant independent of location should eventually be turned into a location-dependent two-dimensional field somewhat similar to what is now the aerodynamic roughness length of the land surface.

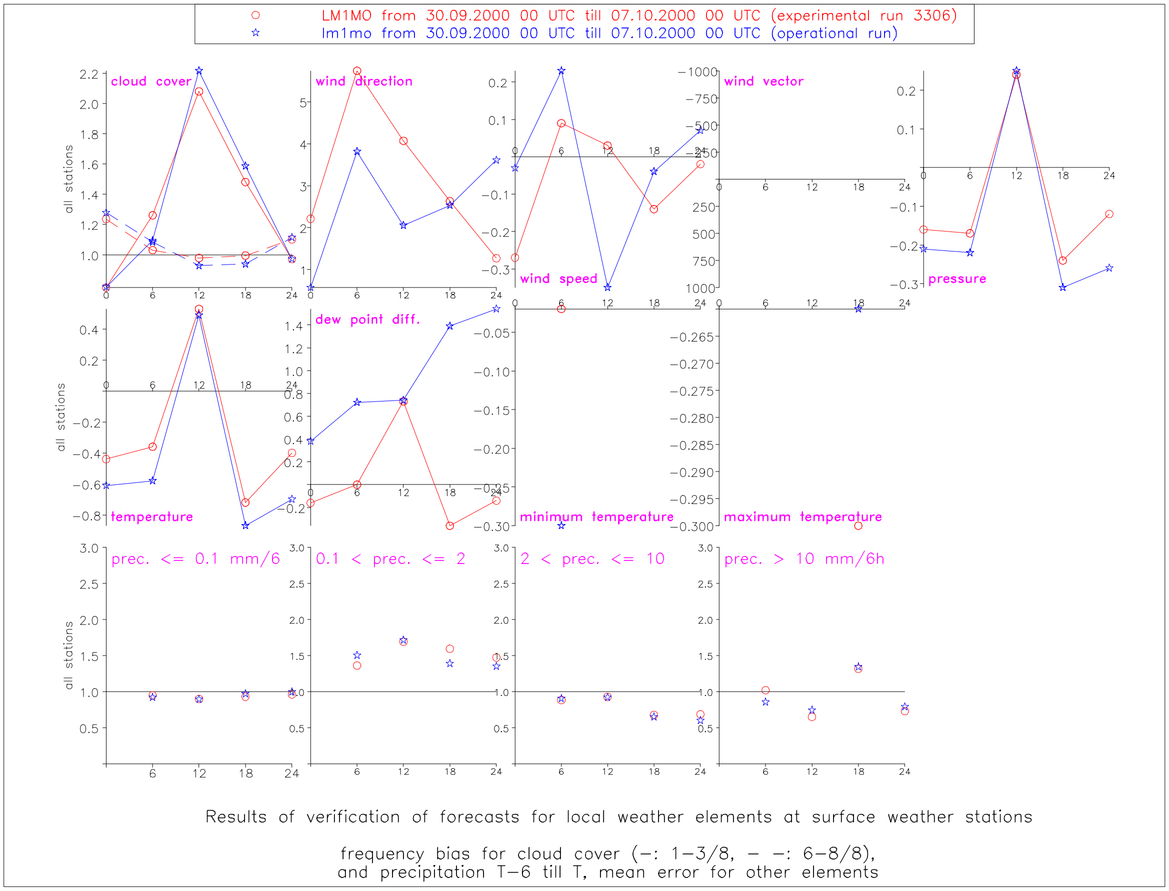

Figure 6: *As in Figure 4, but for all stations in the integration domain.*

Acknowledgements

We thank Erdmann Heise, Reinhold Hess, Günther Doms, Ulrich Damrath, Michael Buchhold and other colleagues at DWD for discussions and helpful suggestions. We are particularly grateful to Thomas Hanisch for innumerable suggestions concerning the use of the DWD Experimental Modelling System. Without his suggestions this work would have hardly ever been completed.

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