Advances in Predicting Continental Low Stratus with a Regional NWP Model

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ABSTRACT

In the eastern Alpine region, subinversion cloudiness associated with elevated temperature inversions is a frequent phenomenon in autumn and winter, which often persists for several days. Although the prediction of fog and low stratus by numerical weather prediction (NWP) models has improved in recent years, these models still show deficiencies in the spatial and temporal evolution of such wintertime weather phenomena. In spite of sophisticated current assimilation schemes or simply due to unknown conditions, even the analysis shows large discrepancies compared to the true atmospheric state. Inversions are often “smeared out” and the moist layer below the inversion is too far from saturation. Model integration from such an initial state leads to strong biases in the total cloudiness and, due to erroneous radiative response, in 2-m temperature forecasts. In the present paper, an empirical enhancement scheme for subinversion cloudiness is introduced within the framework of Aire Limitée Adaptation Dynamique Développement International (ALADIN), the operational limited area model (LAM) at the Austrian Central Institute for Meteorology and Geodynamics (ZAMG). The scheme attempts to compensate for model deficiencies in the vertical temperature and humidity profiles in order to enhance or keep preexisting signals of inversions and associated low cloudiness. Thus, a positive feedback due to radiative reaction is activated, which finally leads to more realistic vertical profiles, low (and total) cloudiness, and improved 2-m temperature predictions. Case studies demonstrate the impacts of the scheme on predictions of the spatial distribution of low cloudiness and on the vertical profiles of temperature and humidity. Verification over stratus episodes within a 2-month period comparing a reference model run without the scheme with a modified model version with the subinversion cloudiness scheme confirms the ability of the scheme to improve stratus-related wintertime weather prediction.

1. Introduction

During late fall and early winter, low stratus decks frequently cover lowland areas in central Europe. The high frequency of these formations and the persistence of low stratus at that time of the year are due to stable conditions in the boundary layer as a result of reduced insolation and still warm surface waters in surrounding seas (i.e., Mediterranean, North Sea, Baltic Sea) providing large-scale sources of moisture. Whereas in the coastal areas of the North and Baltic Seas advection fog mechanisms are dominant, stratus episodes in Alpine forelands and basins have radiation fog characteristics (Bendix 2002). For numerical weather prediction the challenge in predicting low stratus is its generally shallow nature (several 100 m) and its main formation mechanism, which is a combination of radiation and turbulence effects rather than grid-scale rising motion. Once low stratus has formed, it exerts a powerful feedback on the further diurnal evolution of the boundary layer. Instead of a surface-based inversion that is destroyed or weakened by daytime heating, an elevated inversion develops, with well-mixed conditions below and little diurnal variation (Schräff 1997). Thus, large errors in the temperature forecast may occur if a model does not properly predict the onset and dissipation of low stratus.

Within the framework of the European Cooperation in Science and Technology’s (COST’s) Action 722 (entitled Short Range Forecasting Methods of Fog, Visibility and Low Clouds), the skill in fog and low stratus prediction both by operational and research models in central Europe was recently evaluated (Jacobs et al. 2008). One of the conclusions of this evaluation was that an accurate representation of the fine structure of the nocturnal boundary layer and the sharp vertical gradients at the top of the layer are necessary for a successful low stratus
forecast. If the model profiles of temperature and humidity are significantly smoother than in the real atmosphere, air at the top of the boundary layer may not get sufficiently close to saturation to produce subgrid-scale cloudiness. As a result, the feedback loop of condensation, enhanced longwave radiation flux divergence, and buoyancy-induced vertical mixing is not initiated. In addition to limited vertical resolution, shortcomings in the parameterization of turbulence are the cause of this type of problem. Furthermore, deficiencies are caused by an underforecasting of the cooling associated with the radiative flux divergence at cloud top and misdiagnosis of the buoyant production of turbulence due to problems with the vertical differencing scheme.

As part of the Austrian contribution to COST Action 722, the ability of the operational limited area model, Aire Limitée Adaptation Dynamique Développement International (ALADIN), in forecasting low stratus was evaluated. Results of the operational reference model are compared with a model version that includes an empirical enhancement scheme for subinversion cloudiness based on observed characteristics of continental low stratus (Seidl et al. 2008). Section 2 gives a short description of the ALADIN cloud scheme and the subinversion cloudiness scheme. The skill of the reference version and the enhancement scheme in predicting low stratus in the Alpine forelands is illustrated by two case studies in section 3. A comparative verification for an extended period is presented in section 4.

2. The ALADIN model

a. General characteristics

The ALADIN model is a limited area version of the global Action de Recherche pour la Petite Echelle et la Grande Echelle (ARPEGE) model. At the Austrian Central Institute for Meteorology and Geodynamics (ZAMG), it is used both operationally and for NWP research. It is a spectral model that can be run in hydrostatic and nonhydrostatic modes (Bubnova et al. 1995). The version ALADIN-AUSTRIA, which is operational at ZAMG, is hydrostatic and has a horizontal resolution of 9.6 km, with 60 levels in the vertical. The mean vertical resolution of the lowest 2 km is about 200 m. The model domain is centered over the eastern Alpine region and has a size of 2770 × 2490 km². Initial and boundary conditions are obtained at 3-h intervals from the global ARPEGE model. Assimilation of observations takes place in ARPEGE only, using the four-dimensional variational data assimilation (4DVAR) technique. This information is handed over to ALADIN via dynamical adaptation of the initial state. The schemes
and parameterizations used in the version run at ZAMG for this study include a prognostic grid-scale microphysical scheme (Geleyn et al. 2008; Gerard 2007), a first-order turbulence scheme based on Louis (1979), and the Interaction Soil–Biosphere–Atmosphere (ISBA) scheme for surface processes (Giard and Bazile 2000). Shallow convection is taken into account in the turbulence parameterization by a modified Richardson number (Geleyn 1987), and in the cloudiness scheme by checking for saturation of parcels lifted from below. The model uses a mass-flux deep convection scheme (Bougeault 1985) with a trigger function based on buoyancy and humidity convergence, and a closure based on humidity convergence. Radiation is parameterized following Ritter and Geleyn (1992). The convection scheme includes a parameterization of convective downdrafts (Ducrocq and Bougeault 1995). For a detailed description of ALADIN’s physics routines, see Gerard (2005); a detailed model setup is provided by Wang et al. (2006).

b. Cloudiness parameterization

In the present ALADIN version a distinction is made between microphysical cloud condensate and radiative cloud condensate. The microphysical cloud condensate is used in the prognostic large-scale precipitation scheme, where growth and depletion of hydrometeors are treated explicitly. The prognostic large-scale precipitation scheme is part of a comprehensive package for moist parameterizations described in Gerard (2007) and Geleyn et al. (2008). The radiative cloud condensate enters the radiation scheme and is derived in a diagnostic way from atmospheric humidity. The reason why microphysical cloud condensate does not enter the radiation scheme directly is that there are still problems, particularly concerning shortwave radiation, in using the radiation scheme. In the following description, we will concentrate on the radiative cloud condensate.

The grid-scale specific cloud water content \( q_{l+1} \) (liquid + ice) in a layer (used for computation of radiative processes) is diagnosed following

\[
q_{l+1} = (q_{l+1})_{\text{max}} \left\{ 1 - \exp \left[ -\alpha \frac{(q_{l+1} - r_c q_{\text{sat}})}{(q_{l+1})_{\text{max}}} \right] \right\},
\]

with \( q_c = q + q_i + q_l \) entering from the microphysical scheme. According to (1), stratiform cloud condensate forms whenever the specific humidity \( q_l \) exceeds the value \( r_c q_{\text{sat}} \), where \( r_c \) is a critical relative humidity (pseudo-saturation) and \( q_{\text{sat}} \) denotes the saturation specific humidity. The negative-exponential expression in (1) smoothly connects two limiting cases. At small values of pseudo-supersaturation \( (q_{l+1} - r_c q_{\text{sat}}) \), the amount of condensate equals \( q_l - r_c q_{\text{sat}} \), implying no loss of condensate due to conversion to precipitation. At large pseudo-supersaturation values, the amount of condensate approaches a limiting value \( (q_{l+1})_{\text{max}} \). In the operational
model, \((q_{t+i})_{\text{max}} = 0.3 \text{ g kg}^{-1}\), and the coefficient \(\alpha\) has the value 0.4. The critical relative humidity \(r_c\) is prescribed as a vertical profile:

\[
r_c(\eta) = 1 - c_1 \eta (1 - \eta) \frac{1 + c_2(\eta - 0.5)}{1 + c_3(\eta - 0.5)},
\]

which gives \(r_c = 1\) at the bottom and top of the atmosphere and a minimum value in between. Here, \(\eta\) denotes the hybrid vertical coordinate of the model, and \(c_1 = 1.4\), \(c_2 = -0.6\), and \(c_3 = 1.1\) are tunable coefficients. The cloud fraction at a given level is computed as a function of cloud water content using the following simple relationship:

\[
n = \beta \sqrt{\frac{q_{t+i}}{q_{\text{sat}}}},
\]

where \(\beta = 0.7\) is another tunable coefficient. Total stratiform cloudiness is obtained by superposition of the cloudiness values from each level. In the model there are two options for this superposition, corresponding to the assumptions of random overlap or maximum overlap of cloudiness at adjacent levels. Operationally, the random overlap version is used.

Shallow convection is taken into account by determining pseudo-supersaturation \((q_t - r_c q_{\text{sat}})\) at any level, not only for air at that level but also for air lifted to this level from below. A dry static energy threshold (operationally at 400 J kg\(^{-1}\)) determines from how far below air can be lifted. The partitioning of \(q_{t+i}\) into ice and liquid water fractions is based on the local air temperature. An error function parameterizes the gradual transition from liquid water to predominantly ice over the temperature interval from 0 to \(-20^\circ\text{C}\) (Gerard 2005).

c. The subinversion cloudiness scheme (SK scheme)

There is still large uncertainty in NWP model forecasts of the development and breakup of low stratus or subinversion cloudiness. Reasons for these deficiencies are manifold: in many cases, even the initial state differs from the truth to a large extent. Additional uncertainty from the microphysics scheme, radiation, and turbulence contribute to limitations in forecast skill. To improve the performance of ALADIN in handling stratus situations, in the year 2002 an extension to the standard diagnostic cloudiness scheme was developed, the so-called SK scheme (Seidl and Kann 2002). It is motivated by deficiencies of the ALADIN model during typical stratus events in...
the eastern Alpine region. The main components of the scheme are derived by comparing the radiosounding measurements from Vienna, Austria [surface synoptic observation (SYNOP) station 11035], with the modeled vertical profile of temperature and humidity during stratus episodes. Basically, it is a diagnostic enhancement scheme for subinversion stratus (fog and lifted fog). In its diagnostic part (Fig. 1, left), the SK scheme scans the levels belonging to the “low cloud” category of the model, downward to the lowest model level. The saturation deficit $\rho$ is computed for each level from specific humidity values $Q$ and $Q_{\text{SAT}}$ (current and saturation specific humidity, respectively) and levels with $\rho < \rho_c$ are declared quasi-saturated ($\rho_c$ denotes the critical saturation deficit). The scheme consists of the following three criteria:

SK-1—coherent levels of quasi-saturation must define a layer of thickness $\Phi$ exceeding a critical thickness value $\Phi_c$;

SK-2—coherent inversion of critical strength in terms of temperature difference $\lambda > \lambda_c$ must also exist in order to trigger stratus diagnosis, where $\lambda_c$ denotes the critical inversion strength; and

SK-3—shift criterion, where the quasi-saturation zone may not arbitrarily penetrate into inversion layer and the penetration depth $\delta$ may not exceed the critical value $\delta_c$: $\delta < \delta_c$.

The current operational settings that were found to be adequate for continental low stratus are $\rho_c = 0.1$, $\Phi_c = 2000 \text{ m}^2 \text{ s}^{-2}$, $\lambda_c = 1.5 \text{ K}$, and $\delta_c = 2000 \text{ m}^2 \text{ s}^{-2}$ ($\Phi_c$ and $\delta_c$ are in units of geopotential).

If all three criteria are met at a grid point, the SK scheme runs its enhancement part (Fig. 1, right) in the following way: cloudiness for each level within the low cloud height range is reinitialized to zero, and each quasi-saturated level, as well as the total low cloudiness, are set to 1.0 (100%). This triggers a strong response from radiation tending to intensify or at least keep the preexisting inversion through infrared flux divergence, causing cloud-top cooling and mixing-induced warming at lower levels.

The following series of figures illustrates the behavior of the SK scheme. The results were obtained from a 10-h integration with a single-column (1D) version of ALADIN-AUSTRIA placed at the location of Vienna for the 0000 UTC 2 December 2000 initialization time. Results of the reference run and the modified run with the SK scheme are compared.

Figure 2 shows vertical profiles of the cloudiness level by level for both runs within the lowest 4 km of the ALADIN model. The reference run contains only a very weak signal of subinversion cloudiness, reaching a maximum cloudiness of less than 10%, whereas the run with the SK scheme contains many levels with 100% cloudiness (fog layer). Accordingly, the response from radiation routines is very different in the two runs due to a strongly differing cloudiness diagnosis. Figures 3a and 3b show the importance of the SK scheme for the radiation flux...
Without SK-Scheme

![Image of low cloudiness forecast without SK-Scheme](image-url)

**FIG. 6.** Low cloudiness forecast of the reference ALADIN-AUSTRIA model run, initialized at 0000 UTC 22 Dec 2007, +24 h lead time. Black-to-white shading indicates the fractional low cloudiness (%).

Divergence in foggy situations, like on 2 December 2000 in the eastern parts of Austria (for the net solar flux, the difference between incoming and outgoing radiation is shown; for the net longwave flux, outgoing minus incoming radiation). At the top of the stratus layer, around 900 m above sea level, there is significant vertical flux divergence in the SK run, visible as a jump from very low net longwave flux to values close to 100 W m\(^{-2}\) and more toward higher levels. Values of the net solar flux are significantly smaller in the SK run than in the reference run. The radiative loss of heat at cloud top is accompanied by just a small radiative gain within the fog layer.

With SK-Scheme

![Image of low cloudiness forecast with SK-Scheme](image-url)

**FIG. 7.** Low cloudiness forecast of the ALADIN-AUSTRIA model run with the SK scheme, initialized at 0000 UTC 22 Dec 2007, +24 h lead time. Black-to-white shading indicates the fractional low cloudiness (%).
This situation is quite different in the fog-free reference run where at 1000 UTC there is a total radiative gain of heat from the surface up to about 6000 m above sea level (net solar flux exceeding the thermal flux), with a maximum at the lowest model levels. Once the SK scheme initiates cloudiness, the radiative response just described will start to act, which in turn tends to keep or intensify preexisting inversion layers at further time steps. This event forms a prototype for stratus cases, which frequently occur during autumn and winter in central Europe and the eastern Alpine region, respectively. Thus, the conditions shown above are representative of the majority of events.

3. Observed and predicted stratus patterns

a. Case study I: Winter stratus forecasts issued at 0000 UTC 22 December 2007

On 23 December 2007, a pronounced low-level anticyclone covered central and eastern Europe as indicated by the operational surface pressure analysis at 0000 UTC (Fig. 4). Its center was located over Hungary, bringing southeasterly winds to the Vienna basin. This type of pattern is typical for the development and persistence of a lifting inversion around Vienna. Several SYNOP stations observed fog or low stratus (e.g., Vienna; Budapest, Hungary; and Prague, Czech Republic). During daytime, high-resolution visible satellite imagery from the Meteosat Second Generation (MSG) satellite provides information about the spatial distribution of the fog and low stratus coverage that affected most of the northern and eastern parts of Austria as well as the neighboring countries to the east (Fig. 5). The spatial and temporal variabilities of the cloudiness were rather low; thus, the image from 0900 UTC 23 December 2007 can be regarded as being representative for the whole stratus episode, which lasted from 19 to 24 December 2007.

Comparison of the spatial distribution of the low stratus layer from the satellite image with the forecasted low cloudiness (Fig. 6), initialized at 0000 UTC 22 December 2007, +24 h lead time, shows that significant improvements are obtained by the SK scheme. In the reference run, fractional low cloudiness far below 50% is diagnosed, but widespread cloud fractions between 95 and 100% are reached in the eastern and northern parts of Austria as well as in Hungary, Slovakia, and Bavaria (Fig. 7). Figure 8 depicts the predicted vertical profiles of the temperature and dewpoint for the experiment without the SK scheme (Fig. 8a) and with the SK scheme (Fig. 8b) at a grid point that is situated about 50 km east of Vienna. The profile is compared with the radiosounding at Hohe Warte in Vienna (SYNOP station 11035) at 0000 UTC 23 December 2007 (Fig. 8c). Without stratus coverage, the elevated inversion tends to lose its strength and migrates to become a surface inversion during the night due to nighttime cooling. Thus, the 2-m temperature also decreases unrealistically without using the SK scheme. With the SK scheme, the model keeps and intensifies the elevated inversion in a realistic way through infrared flux divergence.

This case is typical for winter stratus situations in this area. Studying a variety of stratus episodes during the last years in an operational environment showed that the SK scheme performs similarly in many cases, providing useful guidance for the forecasters.
Case study II: Summer stratus

On 8 July 2004, an unusual stratus event took place in the eastern and northern parts of Austria. In the course of an approaching cold front, a southeasterly flow pattern combined with low-level moisture led to the formation of an elevated inversion and associated subinversion cloudiness. The stratus cover persisted for 4–6 h, until insolation led to the dissipation of the lifted fog layer. Figure 9 shows the operational surface pressure analysis of ZAMG, issued at 0600 UTC 8 July 2004. The visible satellite image from 0600 UTC is shown in Fig. 10. The cloudy areas in the southwestern parts are related to the southerly flow (upslope cloudiness) and are not a subject of this study. Figures 11 and 12 compare ALADIN-AUSTRIA low cloudiness forecasts without and with the SK scheme for +07 h lead time. Without the scheme, the model is only able to forecast a higher percentage of low cloudiness in the northernmost part of Austria bordering the Czech Republic. The use of the subinversion enhancement scheme significantly improves the spatial distribution of the stratus layer as compared with the satellite imagery. The stratus layer penetrates more strongly toward southeast Austria and also slightly into the Danube valley. The improvements of the cloud distribution are mainly caused by better representation of the vertical temperature and humidity profiles, thus leading to a positive feedback and to improved cloudiness prediction. Figure 13 illustrates this enhancement by comparing the vertical temperature and dewpoint profiles for the same lead time (+07 h) for the experiment without the SK scheme (Fig. 13a) and with the SK scheme (Fig. 13b). It can be seen that the scheme allows for a more realistic elevated inversion and associated subinversion cloudiness, again due to the cloudiness–radiation feedback mechanism.

This rather unusual event shows that the enhancement scheme is able to also improve non-winter-type stratus forecasts, although deficiencies in the spatial and temporal distributions still exist. The length of the episode and the dissipation of the high fog layer were forecasted realistically.
Both examples demonstrate the benefits of the scheme, which allows for a better spatial distribution of the predicted low cloudiness (stratus) and—due to feedbacks of cloudiness and radiation processes—for an improved representation of the vertical temperature and humidity profiles. Application of the scheme on a larger sample of case studies has confirmed that the scheme does not tend to overforecast the low cloudiness and that the dissipation

**Without SK-Scheme**

![Figure 10](image1.png)

**FIG. 10.** High-resolution MSG visible satellite image at 0600 UTC 8 Jul 2004. The white-gray areas in the northern and eastern parts of Austria indicate low stratus, whereas in the south-western parts (Carinthia and Tyrol) of Austria, the areas with low clouds are mainly upslope clouds associated with the southwesterly flow and the approaching cold front.

![Figure 11](image2.png)

**FIG. 11.** Low cloudiness forecast of the reference ALADIN-AUSTRIA model run, initialized at 0000 UTC 8 Jul 2004, +07 h lead time. Black-to-white shading indicates the fractional low cloudiness (%).
of the stratus layer, for example in the course of a frontal passage, is not hampered.

4. Improvements to wintertime weather forecasts in Austria through use of the SK scheme

To assess the impacts of the SK scheme in a more systematic, quantitative way, experiments were performed for the period 1 November–31 December 2007. The chosen 2 months represent the main period of fog and low stratus episodes in the eastern Alpine area. Apart from the introduction of the SK scheme, both model configurations were identical. Integrations were performed until +72 h and only 0000 UTC initializations were considered. Verifications of the 2-m temperature, 10-m wind speed, 2-m relative humidity, and total cloudiness were performed against measurements from six Austrian SYNOP stations (situated in the north, east, and southeast of Austria).

Although low stratus is a rare event (even in November and December, nonstratus cases dominate the verification scores), the impacts of the scheme on the prediction of total cloudiness are visible. However, only stratus events (i.e., days where stratus was observed) within these 2 months were taken into account in order to point out the impacts of the scheme on the mean scores. Thus, the derived verification sample consisted of 19 days with observed stratus coverage. With respect to the mean bias, mean absolute error (MAE), and root-mean-square error (RMSE), improvements in the total cloudiness are obtained for all forecast projections (Fig. 14a). Averaged over the full verification period, the mean relative improvements reach values up to 18%. Especially during daytime, the model is able to reduce the negative bias of the total cloudiness substantially. Note that although the total cloudiness is verified, the relative improvements are mainly due to differences in the low cloudiness, as the SK scheme is treating the lowest troposphere only. The degree of improvement is strongly dependent on the sample size and location. Thus, even better results would have been obtained for specific, selected locations.

Due to feedback by the radiation flux divergence, improvements in total cloudiness forecasts implicitly are supposed to be directly associated with improvements in 2-m temperature forecasts. Figure 14b indicates that the mean bias, MAE, and RMSE are reduced accordingly, especially during the night, where the cold bias is significantly reduced by more than 1 K due to reduced radiative surface cooling. The maximum temperature generally shows smaller errors than during the night, regardless of use of the subinversion cloudiness scheme. One reason for the small contribution of the SK scheme to improvements in the maximum temperatures could be the general cold bias that is superimposed. Without the SK scheme, the model tends to heat the surface layer due to underestimated cloud cover. Thus, the cold bias is compensated by erroneously forecasted cloudiness during the
daytime. Nonlinear feedbacks also have a positive impact on the 10-m wind speed, leading to a small reduction in bias, MAE, and RMSE (Fig. 14c). Additionally, the incorporation of the subinversion cloudiness scheme leads to improvements in 2-m relative humidity and mean sea level pressure for all forecast projections, although not as pronounced as those for 2-m temperature and total cloudiness.

5. Summary and conclusions

Today’s numerical weather prediction models still have difficulties in predicting precisely the spatial and temporal distributions of (high) fog and low stratus. There are several reasons for these difficulties. The NWP analysis may not be able to capture subtle but essential details of the atmospheric state, such as the sharpness of an inversion, and/or the model physics are not capable of simulating the processes that contribute to the formation, persistence, and dissipation of low stratus. An empirical subinversion cloudiness scheme was introduced into the operational LAM at ZAMG, ALADIN-AUSTRIA, which enhances preexisting signals of elevated inversions and low stratus. Through the positive feedback of radiation flux divergence and cloud formation, the model is able to intensify or keep the temperature inversion more realistically, which leads to an error reduction in the cloudiness and 2-m temperature. Two case studies of a typical winter-type stratus situation and of an unusual summer stratus event show the beneficial impacts of the SK scheme on the spatial distribution of low cloudiness and on the vertical temperature and
humidity profiles. Extended verification for stratus episodes within a 2-month period demonstrate that the cloudy boundary layer generally develops in a more realistic way, which also leads to slight improvements in the other parameters, like mean sea level pressure.

The scheme has been calibrated on typical continental fog and low stratus episodes and probably has to be adapted for application in other areas (e.g., coastal regions). Improvements to the scheme could be obtained by taking into account liquid water content, which could serve as an additional criterion that indicates a signal for low stratus. Furthermore, the impacts of increasing the horizontal and vertical resolution on the performance of the scheme need to be evaluated. One may also ask to what extent an empirical addition such as the scheme presented here is still needed within the framework of very high-resolution forecasting models. First experiments with the Application of Research to Operations at Mesoscale (AROME) prototype at a resolution of 2.5 km indicate improved low cloudiness compared with ALADIN-AUSTRIA, but still show deficiencies in the temporal and spatial distributions. It appears that the inclusion of an enhancement scheme of the type presented here is still beneficial, in spite of the high resolution and sophisticated microphysics in the NWP model.

REFERENCES


Fig. 14. BIAS, MAE, and RMSE of the (a) total cloudiness, (b) 2-m temperature, and (c) 10-m wind speed. Dashed lines show the ALADIN reference run without the SK scheme, and solid lines show the ALADIN run with the SK scheme.

