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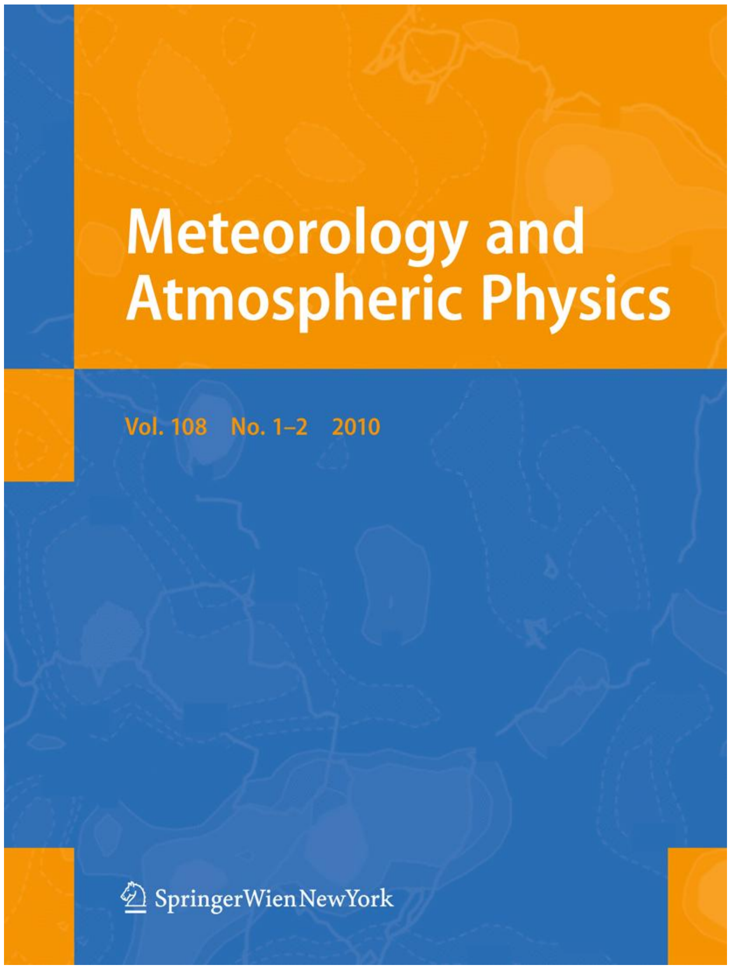

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ORIGINAL PAPER

Impact of horizontal diffusion, radiation and cloudiness parameterization schemes on fog forecasting in valleys

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Abstract Fog and low stratus forecasting experiments have been carried out with the numerical weather prediction model ALADIN on a case of long lasting fog. The model has been used with different radiation, cloud diagnosing and horizontal diffusion schemes, different representation of orography, increased vertical resolution and with or without prognostic condensates and turbulent kinetic energy (TKE). Some of the numerical set-ups are able to reproduce the fog (low stratus) field as seen in the satellite images as well as the measured 2m temperature and relative humidity diurnal cycles. The results show that cloud diagnosing schemes and overlap assumptions play a more important role than a more sophisticated radiation scheme, or introduction of prognostic cloud water, ice, rain, snow or TKE. More realistic orography representation and a more physical horizontal diffusion scheme significantly improve the modelled low stratus and 2m temperature in the areas with variable orography.

1 Introduction

Both fog and non-precipitating low stratus are surprisingly resistant to being forecast by the numerical models. Although the two phenomena are different regarding the conditions under which they form, they both require a balance in longwave heating and cooling that allows development of low stratiform clouds without the precipitation scheme removing all the moisture from them. During winter, statically stable, anticyclonic situations with low wind last for several days, and allow development of fog and low stratus (sometimes called radiative fog). These affect not only traffic and people, but also the 2m temperature and other measurable meteorological quantities.

Previous research and observation programs have increased our knowledge and understanding of the factors that affect the process of fog and low stratus formation and development. It is governed by the interaction between the surface and the lower layers of the atmosphere. Atmospheric stability, wind, temperature, humidity and radiation conditions play an important role, together with the local surface configuration, soil wetness, vegetation etc. Several fog types are distinguished, such as e.g. radiation and advection fog. Besides, a cloud that is observed as a low stratus from a valley can be observed as fog on the surrounding mountain slopes. The short range forecasting of fog and low stratus was the main topic of the COST Action 722 (Jacobs et al. 2008).

Several single column models designed for fog prediction have been described in the literature. Duynkerke (1991) analysed a case of shallow radiation fog using the Cabauw tower data and a single column model. Such an approach includes the detailed description of the local factors, but gives little attention to the advection or topographic effects. The COBEL single column model (Bergot and Guedalia 1994) depends on how good the initial conditions are. It performs well when forced with observations, but poorly when forced with an output from a numerical model (Guedalia and Bergot 1994). The sensitivity to initial conditions is so strong that the dedicated data assimilation procedure has been developed (Bergot et al. 2005). Assimilation of radiative flux observations was found to be most important (Remy and Bergot 2009).

The comparison of various single column models (Bergot et al. 2007) reveals the importance of dew deposition and gravitational settling as well as vertical

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resolution, since higher resolution enables better representation of the nocturnal inversion and the inversion at the top of the fog layer. In some cases, simulated stratus or fog is extremely sensitive to the longwave and shortwave radiation (e.g. Guan et al. 2000 or Teixeira 2000). Radiative fluxes are linked with turbulent fluxes. The radiative flux divergence cools the cloud top, while the cloud top cooling causes mixing inside the cloud. Other studies stress the importance of turbulence parameterization (e.g. Zhou and Ferrier 2008) as well as the balance between the cloud top cooling and large scale subsidence that supports transition from stratus to fog (Koračin et al. 2001).

The reasons for a missed forecast of radiation fog, usually accompanied by a strong temperature inversion, are commonly attributed to the turbulence treatment in the stably stratified boundary layer or insufficiencies of the radiation and microphysical schemes. Consequently, more sophisticated radiation schemes have been introduced to numerical weather prediction (NWP) models. Other major model improvements include prognostic schemes for turbulent kinetic energy (TKE) and cloud condensates (cloud water and ice, rain and snow). The latter includes a more detailed condensation, evaporation, melting and freezing processes than may be described in a model with water vapour as the only moist prognostic variable.

The failure of the ALADIN model to forecast the sub-inversion cloudiness has been demonstrated by Kann et al. (2009), who develop an empirical enhancement scheme that compensates for the model deficiencies in the vertical temperature and humidity profiles, and activates a positive feedback with radiative fluxes that leads to an improved forecast of cloudiness, and consequently, more realistic temperature and humidity profiles.

A study of a synoptic case marked by a strong temperature inversion, low stratiform cloudiness and fog in a variety of valleys, lasting for several days during December 2004 has been chosen. The deep radiation fog and low stratus are missing from the initial conditions obtained from the global model ARPEGE and do not develop during successive operational forecasts by ALADIN model. The strength and persistence of the case has inspired this case study in order to find out why the operational model version failed. The research was performed in the framework of the different options available in the ALADIN model with the goal to find the configuration optimal for the fog forecast.

In the ALADIN model, there is a possibility to choose from different radiation, cloud diagnosing and horizontal diffusion schemes. The orography may be represented in various ways and vertical resolution can be increased. The available options have been tested on the chosen case, as well as the recently introduced schemes using prognostic TKE, cloud water and ice, rain and snow. The goal is to find the model set-up that would allow the development of low stratus and fog and, consequently, provide the best 2m temperature and humidity forecast.

The next section describes the case examined and the different schemes used followed by the results of the model simulations and conclusions at the end.

2 Data and methods

2.1 The December 2004 fog and low stratus case

During the first half of December 2004, a thick layer of low stratus and fog covered inland Croatia, Hungary and other nearby areas. Low stratus and/or fog persisted during the day and were visible on 12 UTC satellite images from 8th to 16th December (Fig. 1). In the images, cold ice clouds and snow are shown in light cyan colour, water clouds in pink, land in brown and the sea and lake surfaces in black. On 17th and 18th December, low clouds were covered by high cirrus clouds and on 19th December most of the low clouds disappeared. This situation in Zagreb persisted for 2 weeks, interrupted on two occasions for several hours, as can be seen from the measurements taken at the Zagreb-Maksimir SYNOP station (Fig. 2) of 2m temperature and humidity, pressure, cloudiness and visibility during the first 20 days of December 2004. After 4th December 2004, the diurnal cycle of temperature diminishes due to increasing cloudiness. Temperature decreases slowly, interrupted by two significant decreases during the nights from 6 to 7 and from 11th to 12th December when the sky was clear of clouds for several hours allowing more intensive cooling. The vertical structure of the atmosphere, measured on the same location (Fig. 3), shows intensification of the elevated temperature inversion on top of a saturated layer during 6th and 7th December 2004. The wind speed in the layer between the ground and the temperature inversion is low. These conditions support the formation and maintenance of low stratus and fog observed in the satellite images. The temperature inversion, characteristic for the top of the low stratus or fog layer, persists until 17th when it moves downward; the inversion weakens as the wind strengthens during 18th and 19th December 2004 (Fig. 3).

Figure 4 presents the Meteosat-8 RGB composite of channels 3.9, 10.8 and 12.0 μm for 15th December 2004, 06 UTC. Fog or low clouds are shown in light pink. Fog and low stratus are covering most of the inland parts of southeastern Europe as well as valleys on the northern side of the Alps. The area is in the weak gradient field of high pressure with the centre above northwestern Croatia and Hungary (Fig. 5). Wind speed is low, allowing for the development of radiation fog. The model results cover 2 days during that period, and consist of a 48 h forecast run starting from 00 UTC analyses on 14th December 2004.

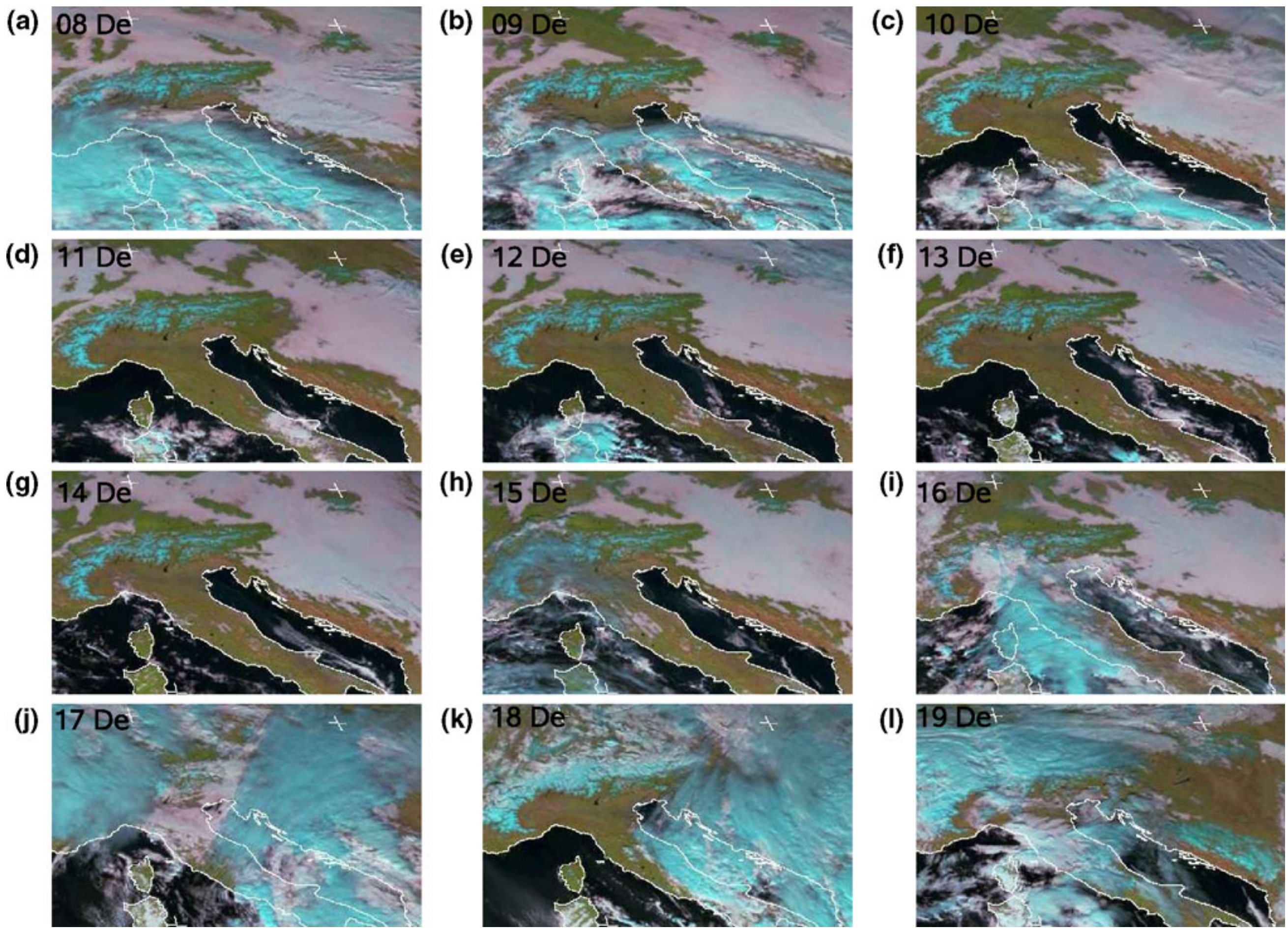

Fig. 1 Meteosat-8 satellite images for the period 8–19 December 2004, 12 UTC (the dates are written in the panels) composites of channels 1 (0.56–0.71 μm visible), 2 (0.74–0.88 μm visible) and 3 (1.50–1.78 μm near-infrared). Cold ice clouds and snow are in *light blue–green colour*, water droplet clouds in *pink*, the ground in *brown* and the sea and lake surfaces in *black* (colour figure online)

The initial conditions are the same for all model runs and diverge from reality since there was no fog in the guess for the analysis performed in the host model ARPEGE. The measured 2m temperature varied very little during those 2 days and showed no diurnal pattern in the areas with thick fog and low stratus.

2.2 Model version and general set-up of experiments

The ALADIN version operational in autumn 2004, as described in Ivatek-Šahdan and Tudor (2004), has been used as reference. That version included a very simple radiation scheme, numerical diffusion in the horizontal, no TKE and no cloud condensates. The scheme used for diagnosing stratiform cloudiness is described in the "Appendix". A two-time-level semi-Lagrangian integration scheme was used. The common fourth order numerical diffusion is computed in the spectral space. The model was run on the domain with 240 × 216 grid points and 8-km resolution in the horizontal on 37 levels in the vertical using the 327 s time-step. The initial and lateral boundary conditions (LBC) were taken from the operational ARPEGE with 3 h interval between LBC files. The data assimilation is performed in the operational ARPEGE from which the initial file is taken. In the operational ALADIN forecast in the Croatian Meteorological and Hydrological Service, only digital filter initialization (DFI) is performed in the beginning of the forecast run on the initial file. Alternative radiation, cloud diagnosing, turbulence and microphysics schemes used in this study are described below. The 2m temperature and humidity forecast was obtained by the interpolation between the lowest model level and the ground using the interpolation formula of Geleyn (1988).

2.3 Radiation schemes

The reference radiation scheme is the one of Ritter and Geleyn (1992) (referred to as RG90) based on Geleyn and Hollingsworth (1979). It has been enhanced recently with a

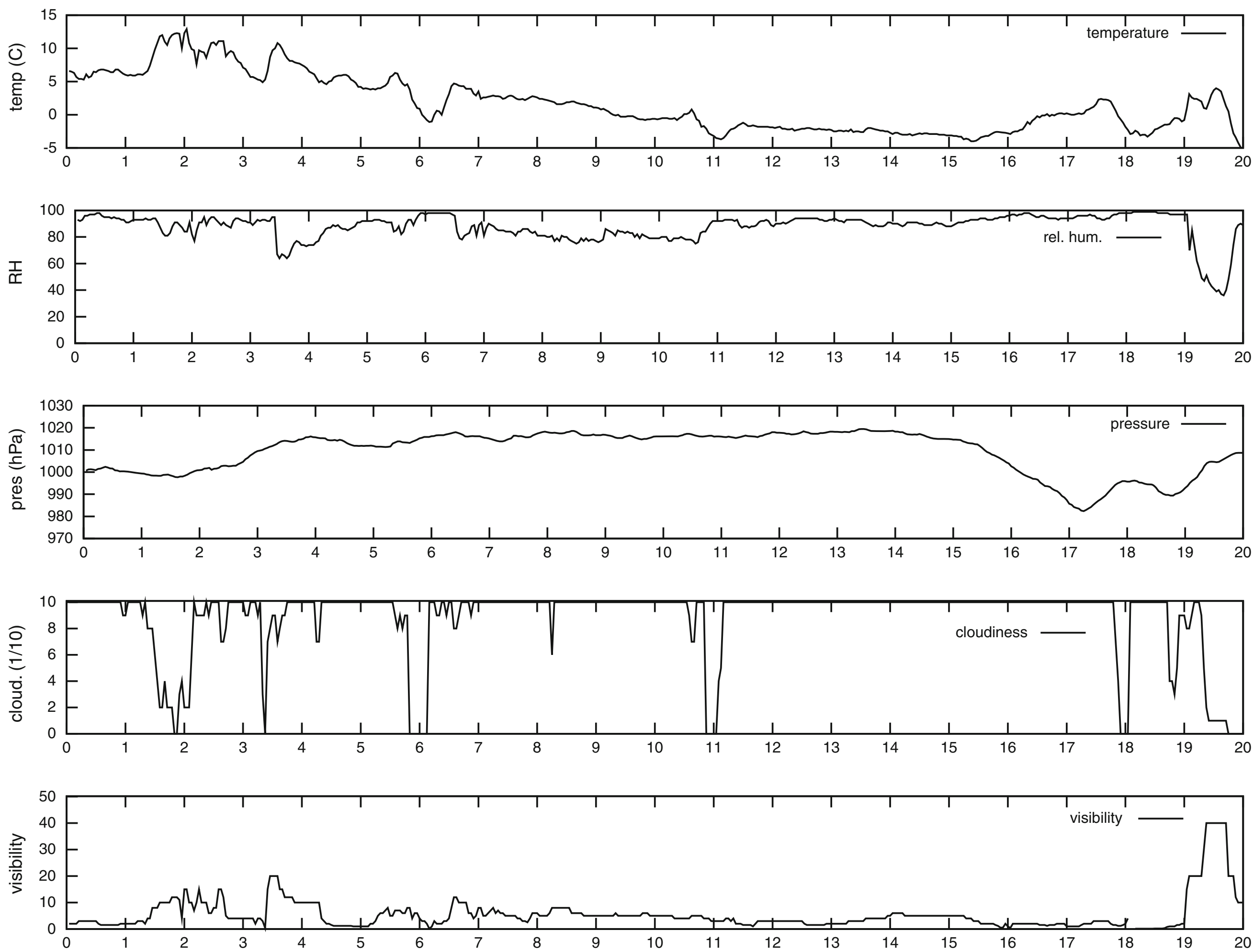

Fig. 2 The measurements taken on the Zagreb-Maksimir SYNOP station of 2m temperature and humidity, pressure, cloudiness and visibility during the first 20 days of December 2004

new statistical model for the computation of the thermal radiative fluxes (Geleyn et al. 2005b) for better estimation of saturated layer optical thickness in the thermal band, using net exchange rate (NER) formalism (Eymet et al. 2004) and Voigt effect in computation of gaseous transmissions (Geleyn et al. 2005a). This scheme is economical and allows usage at every time-step (5–10 min). Other radiation schemes available in ALADIN model are FMR (Morcrette 1989) and RRTM (Mlawer et al. 1997), which are computationally more expensive; so for an efficient forecast, the radiative transfer coefficients are computed with an interval of several hours.

2.4 Cloud schemes

The operational cloudiness diagnostic scheme (see "Appendix") was replaced by the one adapted from Xu and Randall (1996). In this scheme, the oversaturated parcel has cloudiness equal to one. Therefore, shortwave radiation is more efficiently reflected and longwave radiation is more efficiently absorbed. This helps in preserving the temperature inversion, fog and low stratus clouds.

The model deficiencies associated with wrong temperature and humidity vertical profiles are compensated by an early version of empirical scheme for the sub-inversion cloudiness (Kann et al. 2009). The scheme was used in combination with the Xu-Randall cloudiness scheme. Different cloud overlap assumptions, like random, random maximum and maximum overlap have been tested in combination with a modified vertical profile of critical minimum grid box averaged relative humidity producing a cloud.

2.5 Vertical resolution

The vertical coordinate is a hybrid pressure-type η coordinate (Simmons and Burridge 1981). Computations in the vertical are done on 37 levels using a finite difference

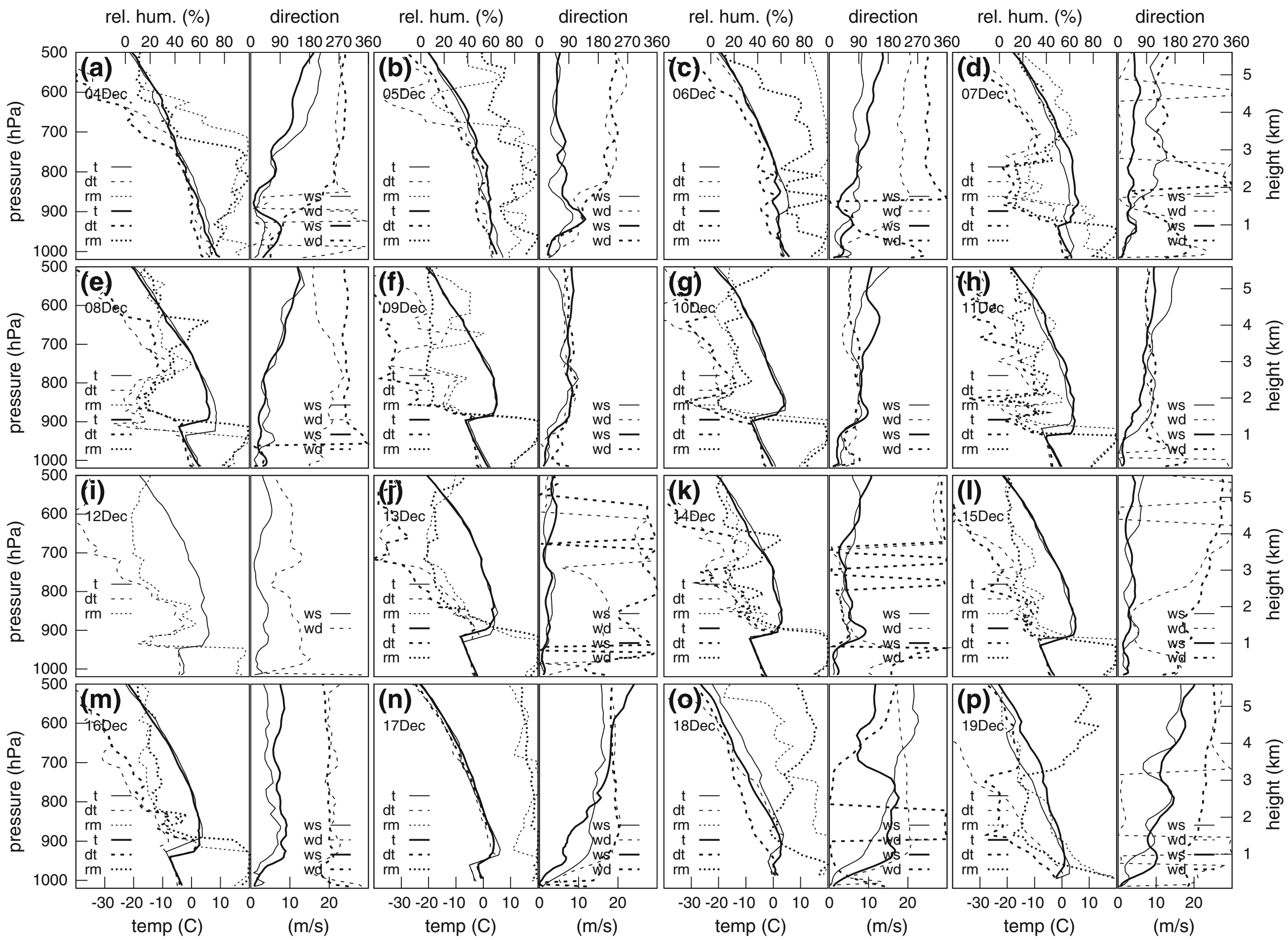

Fig. 3 The vertical structure of the atmosphere, measured on the Zagreb-Maksimir station for the period 4–19 December 2004, the dates are written in the panels. *Thin lines* show vertical profiles measured at 00 UTC and *thick lines* show vertical profiles measured at 12 UTC. The frames on the *left side of the panels* show vertical profiles of temperature (*full line*), dewpoint temperature (*dashed*) and relative humidity (*dotted*) and the frames on the *right side of the panels* show wind speed (*full line*) and direction (*dashed*)

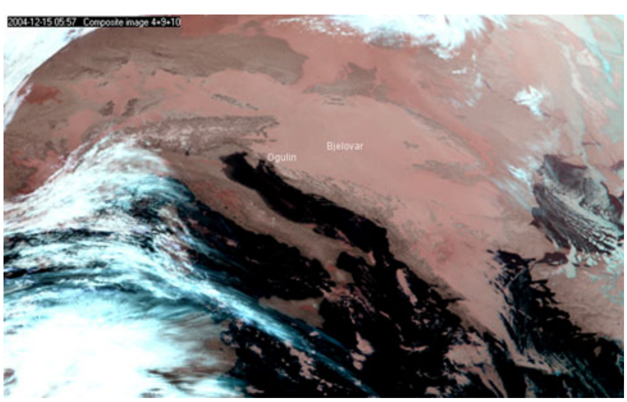

Fig. 4 Meteosat-8 RBG composite of channels 3.9, 10.8 and 12.0 μm for 15th December 2004, 06 UTC. Fog or low clouds are shown in *light pink* (colour figure online)

method. Possible benefits of higher vertical resolution were also explored in one experiment, when the model was run on 73 levels.

2.6 Horizontal diffusion

The operational ALADIN model is using a common fourth order numerical horizontal diffusion scheme acting as a numerical filter and selectively damping short waves. It is applied on the model levels that follow the orography, thus it is not purely horizontal and not physical. The significance of this problem increases with horizontal resolution. The model levels become more tilted close to the mountains and the "horizontal" mixing occurs between "the valley" and "the mountain top" producing large errors for situations with strong stratification and low wind speed. The Semi-Lagrangian horizontal diffusion (SLHD, Váňa et al. 2008) is a horizontal diffusion based on physical properties of the flow, more dependent on the state of the atmosphere. It is based on the control of the degree of interpolation needed for the semi-Lagrangian advection scheme using local physical properties of the flow. In the Semi-Lagrangian advection scheme, the origin point is

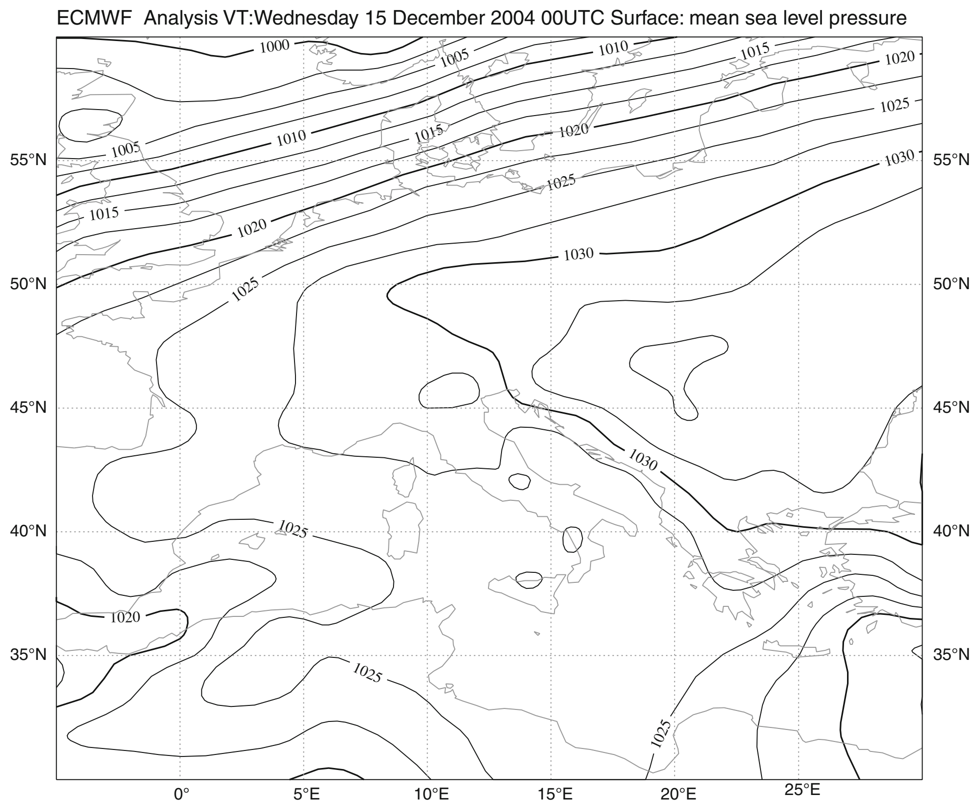

Fig. 5 ECMWF analysis of mean sea level pressure for 15 December 2004

found by interpolation, both in the horizontal and the vertical. The interpolation operator can be more or less diffusive. The interpolator characteristics depend on the deformation field computed from the local flow. In cases with weak wind, SLHD is less intensive than in cases with strong wind.

2.7 Microphysics

The only "moist" prognostic variable in the reference model version is the water vapour. The resolved precipitation scheme is of the Kessler (1969) type. All supersaturation is removed through precipitation in a single time-step, leaving no suspended condensates. A simple microphysics scheme, with prognostic cloud water and ice, as well as rain and snow has been recently introduced in the model (Catry et al. 2007). The new scheme uses statistical approach for sedimentation of precipitation (Geleyn et al. 2008). The microphysics of resolved processes is kept as close as possible to the original scheme and includes simple schemes for condensation, evaporation, melting, freezing, autoconversion, collection and sedimentation.

2.8 Prognostic TKE scheme

The reference vertical turbulent exchange parameterization is a Louis et al. (1982) type scheme, using the exchange coefficients for momentum and heat computed from the vertical gradients of momentum and temperature. Vertical turbulent diffusion is also modified according to Geleyn et al. (2006) and uses the TKE as a prognostic variable. Redelsperger et al. (2001) created a smooth transition between the full TKE sub-grid scale turbulence scheme for the upper-air part and similarity laws in the surface layer. This idea has been extended to the entire atmosphere. The final turbulent exchange coefficients are computed using TKE.

2.9 Representation of orography

The orography can be represented with or without the use of an envelope. In the past few decades, the representation of sub-grid scale orography has been attempted by different means. One of the methods is the enhancement of terrain by adding an envelope (see Wallace et al. 1983), while another uses a parameterization of gravity wave drag and lift (see Bougeault 2001). In ALADIN, both methods are implemented. Envelope is obtained by adding the standard deviation of the (unresolved) sub-grid scale orography to the mean height. Removing the envelope leads to the lowering of the mountain peaks as well as the valleys. The difference is largest in the areas where the orographic variability is the highest, e.g. on the mountain slopes.

3 Results

Fog and low stratus did not develop in the operational forecast. This study is aimed to find why this happened. The reason can be attributed to the fact that the initial and forecast vertical profiles and 2m temperature and humidity are different from what was measured in reality. The model parameters used operationally (without the Kann et al. (2009) scheme) do not yield the balance of diagnosed cloudiness, radiation, turbulent and precipitation fluxes that lead to either fog or low stratus formation. Consequently, fog and low stratus do not exist in the forecast field and do not affect the radiative fluxes computation, which in turn leads to a different balanced state, without the cloud. The areas that are covered by low clouds in the Figs. 1 and 4 were cloud free in the results obtained with operational model configuration. The forecast 2m temperature and humidity show diurnal variation while measurements reveal that these parameters hardly change during 14th and 15th December 2004. This inspired a search for the model set-up that would allow correct forecast of fog and low stratus.

3.1 Impact of cloud diagnosis and radiation schemes

The tests have shown that the factor that affects the forecast the most is the formulation used to diagnose the existence and amount of clouds in a layer of the atmosphere, especially when used in combination with the Kann et al. (2009) empirical scheme for the sub-inversion cloudiness. The operational cloud scheme did not diagnose enough clouds. The new scheme diagnosed more clouds that increased the radiative flux divergence on the top of the cloud. This initiated vertical mixing in the cloud and finally led to more realistic vertical profiles of boundary layer temperature and humidity. Consequently, the diagnosed cloudiness improved further.

The 30-h forecast of cloudiness obtained with RG90 radiation scheme, random overlap, Kann et al. (2009) and Xu-Randall cloud schemes, with fourth order numerical diffusion and water vapour as the only moist prognostic variable (exp1) is shown in Fig. 6a and Table 1. The comparison of the modelled 2m temperature evolution with the measured data for runs with different cloud diagnostic formulae and overlap assumptions (experiments oper, exp1 and exp2) for one SYNOP station from the inland Croatia is shown in Fig. 7. Examples from most of the other inland stations give qualitatively similar results. The introduction of the Xu-Randall cloudiness scheme gives more clouds and improves the 2m temperature forecast. A different critical relative humidity profile has lower impact. Out of several cloud overlap assumptions, random overlap is most beneficial to the model development of fog and low stratus. Kann et al. (2009) scheme compensates for the wrong initial profiles in temperature and relative humidity while Xu-Randall formula for diagnosing cloudiness enhances the development of clouds. The resulting clouds influence the radiation transfer so that the final profiles of temperature and humidity are much closer to the measured vertical profiles.

In the operational radiation scheme with Kann et al. sub-inversion scheme, Xu-Randall cloudiness parameterization and random overlap assumption produces the thickest low cloud layer that reduces the night cooling and heating during the day. It still shows signs of diurnal variation but is closest to the measured data. Figure 6b shows the 30-h forecast obtained with RG90 radiation scheme including NER modifications (exp3). Including NER into the radiation scheme actually increases the amplitude of the diurnal variation of temperature, which gives worse 2m temperature forecast in this case (Fig. 8).

The comparison of the modelled 2m temperature evolution with measured data for runs with different radiation schemes for one station is shown in Fig. 8. Figure 6c shows the 30-h forecast obtained with FMR radiation scheme used with a 1-h interval (exp5). The FMR scheme (Morcrette 1989) allows for a larger number of spectral bands, but it is computationally expensive and is therefore called with much larger time interval (1 and 3 h were used in the experiments exp5 and exp4, respectively). The process of fog formation is slow, so one would expect that the radiation fluxes do not have to be computed in each time-step, although radiation fluxes are important for this type of a process. Unfortunately, infrequent computation/update of the radiation fluxes destroys the sensitive balance of the process that leads to fog or low stratus formation. Although the model diagnoses more clouds, it still uses the "old" radiation transfer computed in the cloud free atmosphere; so the feedback is missing. The frequency of updating the radiation fluxes may have a strong impact on the forecast quality even for a slow process such as the formation of fog and low stratus.

Figure 6d shows the 30-h forecast obtained with RRTM radiation scheme used with a 1-h interval (exp7). Even a more sophisticated scheme, as RRTM (Mlawer et al. 1997) does not improve the 2m temperature or low cloudiness forecast when used with a 1-h interval. Frequent update of radiative fluxes is essential for a good forecast of fog, while the detailed description of spectrum is less important.

3.2 Impact of horizontal and vertical diffusion

In the experiments mentioned so far, fog and low stratus as well as 2m temperature forecast have improved significantly in the lowland area of inland Croatia. Unfortunately,

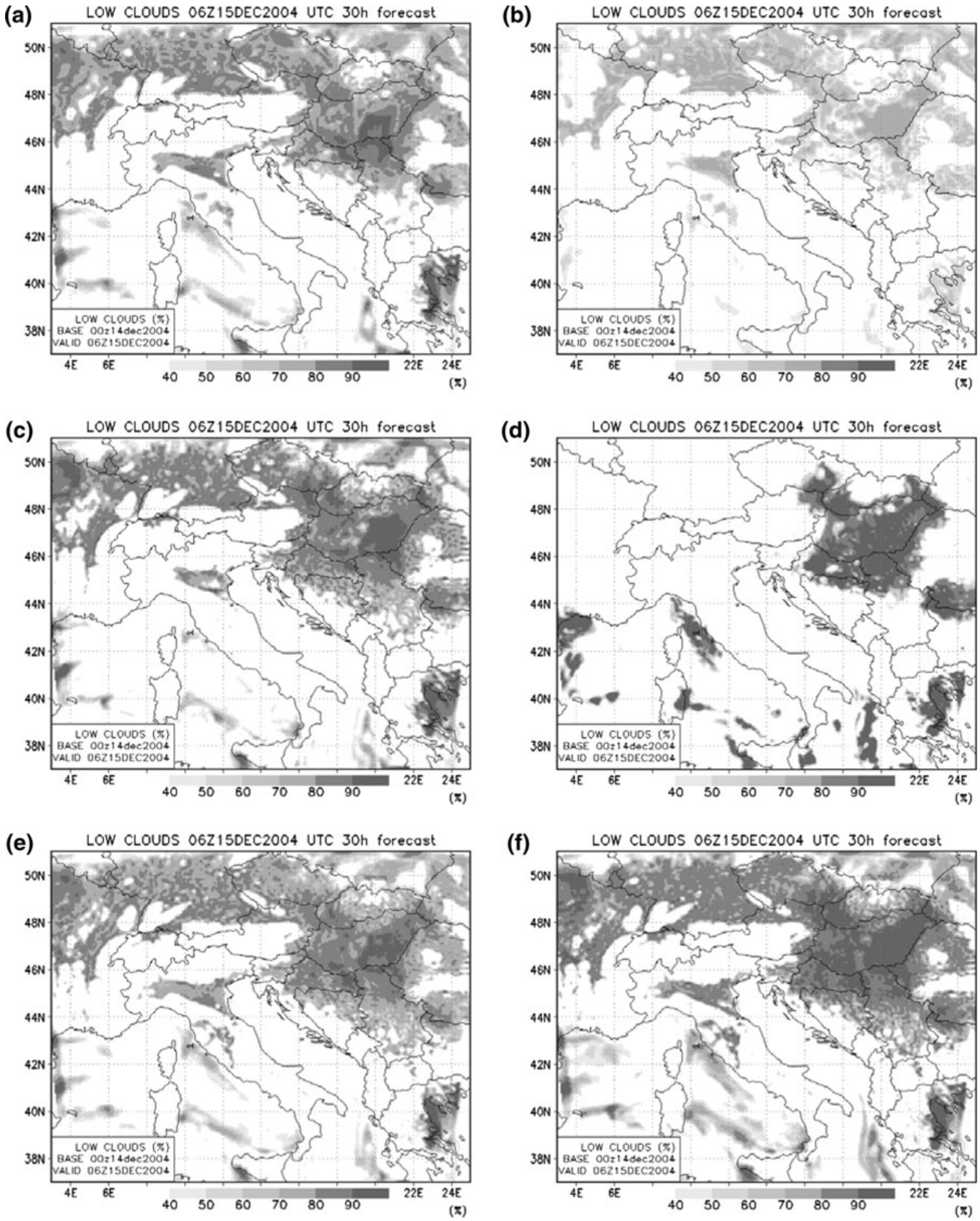

Fig. 6 Low cloudiness (0–2 km agl) 30-h forecast starting from 00 UTC analysis 14th December 2004 to 6 UTC 15th December 2004 for the experiments: exp1 (**a**), exp2 (**b**), exp5 (**c**), exp7 (**d**), exp8 (**e**) and exp10 (**f**). Additional explanations may be found in the Table 1 and text

there was little or no improvement for the SYNOP stations situated in mountainous areas.

The 30-h forecast obtained with RG90 radiation scheme, random overlap, empirical sub-inversion cloud scheme (Kann et al. 2009) and Xu-Randall cloudiness scheme, SLHD and water vapour as the only moist prognostic variable (exp8) is shown in Fig. 6e. Use of SLHD increases the amount of fog and low stratus in the valleys, especially on the border between Switzerland and Germany and in Danube valley in Austria as well as the mountainous areas of inland Croatia. The horizontal mixing is dependent on the wind deformation field, and so in the situation with low

Table 1 List of experiments

Experiment	Cloud scheme	Overlap	Horizontal diffusion	Radiation scheme	Prognostic TKE	Prognostic condensate	Cloudiness figure	Figure 2m temperature
Oper	Oper	Random	Numerical	RG90	No	No	No	7 full line
Exp1	Xu-Randall	Random	Numerical	RG90	No	No	6a	7 dashed, 8 full line, 9 full line
Exp2	Xu-Randall	Maximum	Numerical	RG90	No	No	No	7 dotted
Exp3	Xu-Randall	Random	Numerical	RG90NER	No	No	6b	8 short long dash
Exp4	Xu-Randall	Random	Numerical	FMR 3 h	No	No	No	8 dashed
Exp5	Xu-Randall	Random	Numerical	FMR 1 h	No	No	6c	8 dotted
Exp6	Xu-Randall	Random	Numerical	RRTM 3 h	No	No	No	8 dot dash
Exp7	Xu-Randall	Random	Numerical	RRTM 1 h	No	No	6d	8 dot dot dash
Exp8	Xu-Randall	Random	SLHD	RG90	No	No	6e	9 dashed
Exp9	Xu-Randall	Random	SLHD	RG90	Yes	No	No	9 dotted
Exp10	Xu-Randall	Random	SLHD	RG90	Yes	Yes	6f	9 dot dash, 10 full line
Exp11	Xu-Randall	Random	SLHD	RG90	Yes	Yes	Envelope orography	10 dashed
Exp12	Xu-Randall	Random	SLHD	RG90	Yes	Yes	73 levels	10 dotted

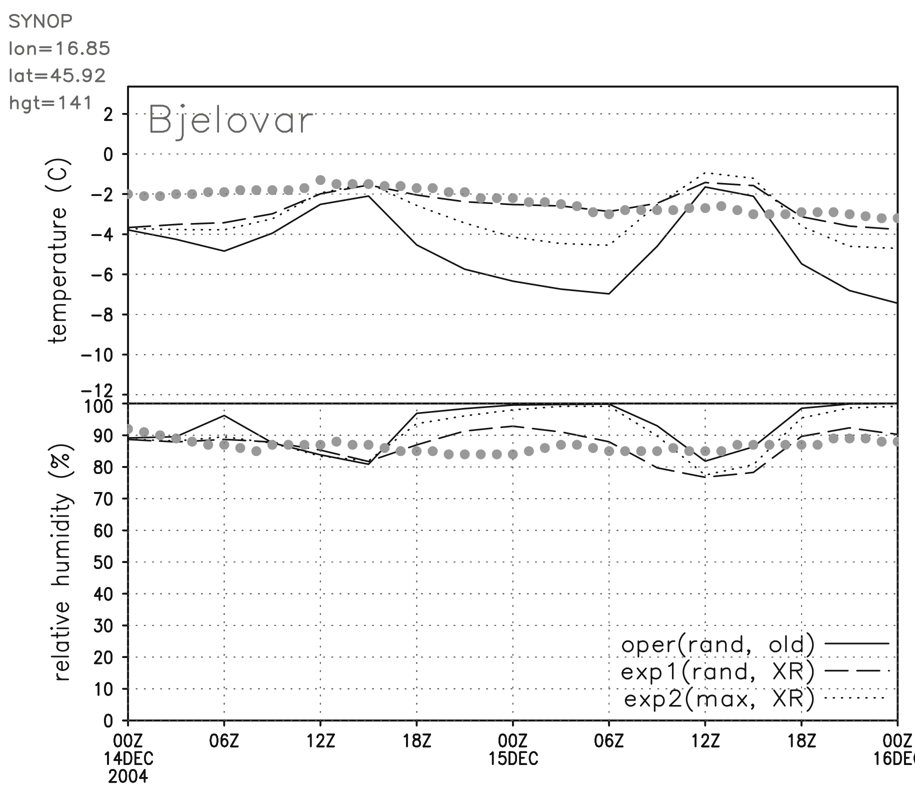

Fig. 7 Comparison of the modelled 2m temperature and relative humidity evolution with measured data (*large grey dots*) for Bjelovar SYNOP station, the following experiments: oper (*full line*), exp1 (*dashed*) and exp2 (*dotted*). Additional explanations may be found in the Table 1 and text

wind speeds, the moisture stays in the valley allowing for the development of low stratus. The comparison of the modelled 2m temperature and relative humidity evolution measured data for runs with Xu-Randall cloudiness scheme, random overlap and different horizontal diffusion schemes for SYNOP station Ogulin, situated in a narrow valley in Croatia is shown in Fig. 9. The same figure shows that introducing prognostic TKE has a small positive influence.

3.3 Impact of prognostic condensates

Cloud water and ice, rain and snow are introduced as prognostic variables. When specific humidity is the only moist prognostic variable, the excess humidity is removed from the over-saturated air as precipitation. Introduction of the prognostic condensates keeps this humidity in the atmosphere and participates in the formation and evolution

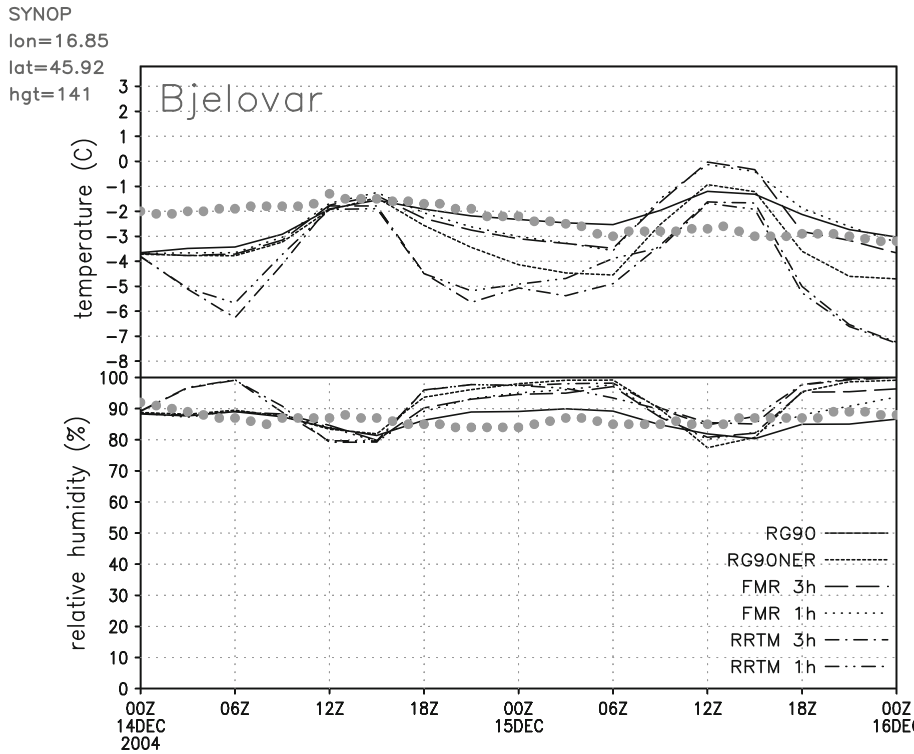

Fig. 8 As Fig. 7, for the following experiments: exp1 (*full line*), exp4 (*dashed*), exp5 (*dotted*), exp6 (*dash dotted*) and exp7 (*dash dot dotted*). Additional explanations may be found in the Table 1 and text

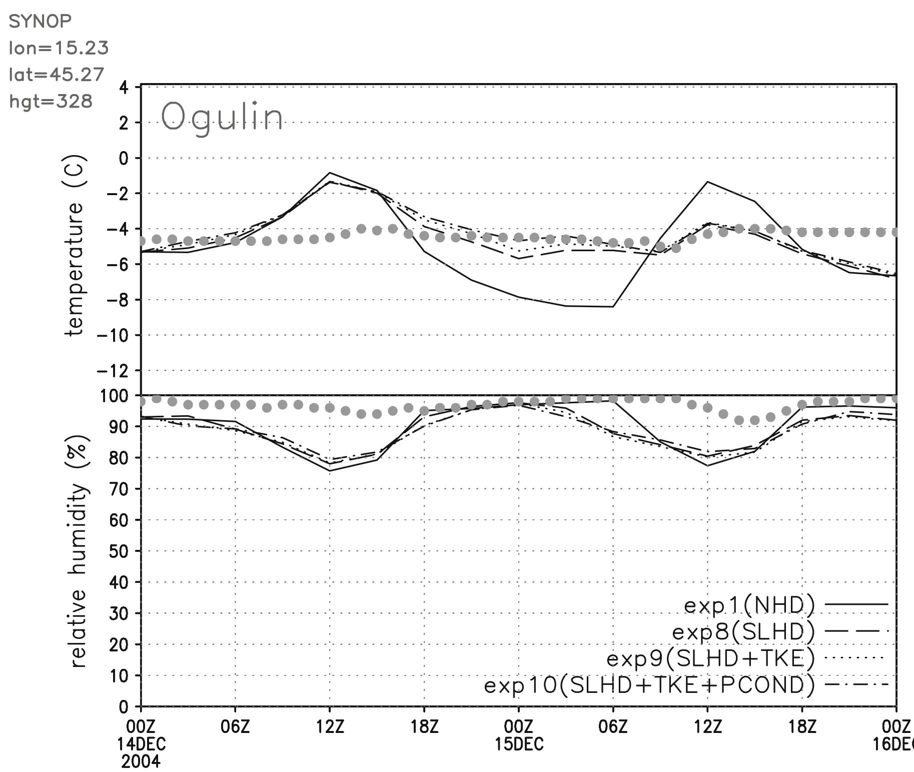

Fig. 9 As Fig. 7, but for Ogulin SYNOP station and the following experiments: exp1 (*full line*), exp8 (*dashed*), exp9 (*dotted*) and exp10 (*dash dotted*). Additional explanations may be found in the Table 1 and text

of cloudiness. This does improve the forecast of fog and low stratus as well as the 2m temperature, especially in the valleys when combined with the SLHD (Fig. 6f). These modifications have a positive but small influence. Impact on the 2m temperature and relative humidity forecast (Fig. 9) is small. It is interesting to note that although the 2m temperature improves, the 2m relative humidity is slightly lower and further from the measurements.

3.4 Impact of orography representation and vertical resolution

All the model runs described so far used mean orography. When envelope is introduced in the model, the valley floor in the model is raised significantly above the real valley bottom, while the peaks in the model become higher, closer to the real mountain peaks. As a consequence, certain areas rise above the real fog layer observed in the atmosphere, especially where the hills and mountains are too narrow to be properly resolved. A fog layer becomes much thinner in valley since the bottom of the valley is elevated and so the valley is shallower. When modelled data are compared to the measured 2m temperature, the results are worse for the SYNOP stations close to the valley bottom (Fig. 10), but better for those positioned on local peaks.

In this experiment (exp12), the model was run with Xu-Randall cloudiness, random overlap, sub-inversion cloud scheme, RG90 radiation scheme, SLHD, prognostic TKE and condensates on 73 levels. Higher vertical resolution not only increases the low-level cloudiness but also the boundary layer temperature. The 2m temperature is higher and the relative humidity is lower (Fig. 10). Similar effect can be seen in the measured and forecast vertical profiles (Fig. 11) for the Zagreb-Maksimir station. The 73 level temperature forecast is higher than measured in the entire layer below the temperature inversion. This result suggests that the parameterization schemes need retuning when the vertical resolution changes significantly.

4 Conclusions

The numerical weather prediction model ALADIN had difficulties in predicting correctly the low stratus and fog. During the first half of December 2004, low stratus and fog covered the valleys in inland Croatia. These clouds were not predicted by the operational ALADIN forecast. Since this was not an isolated incident of the model failure in such a weather situation, it was important to find out if there is a model set-up that would predict the development of low stratus and fog.

The initial and boundary conditions were obtained from the global host model ARPEGE. These contained the atmospheric state without fog and low stratus as well. There is data assimilation, but, when the model forecast is wrong, the guess is far from observations, the observations are not assimilated. Consequently, the analysis does not contain the atmospheric state details essential for the cloud formation and development. The problem persists in the consecutive operational forecast runs. This problem has inspired development of an empirical sub-inversion cloudiness scheme (Kann et al. 2009) that initiates the positive feedback of radiation flux divergence, turbulence and cloud formation. This scheme overcomes the problem of wrong initial profiles in temperature and humidity and allows for the development of stratus and fog.

This study compares influences of different parameterizations in the ALADIN model on cloudiness forecast in a fog and low stratus case. The cloud overlap assumption

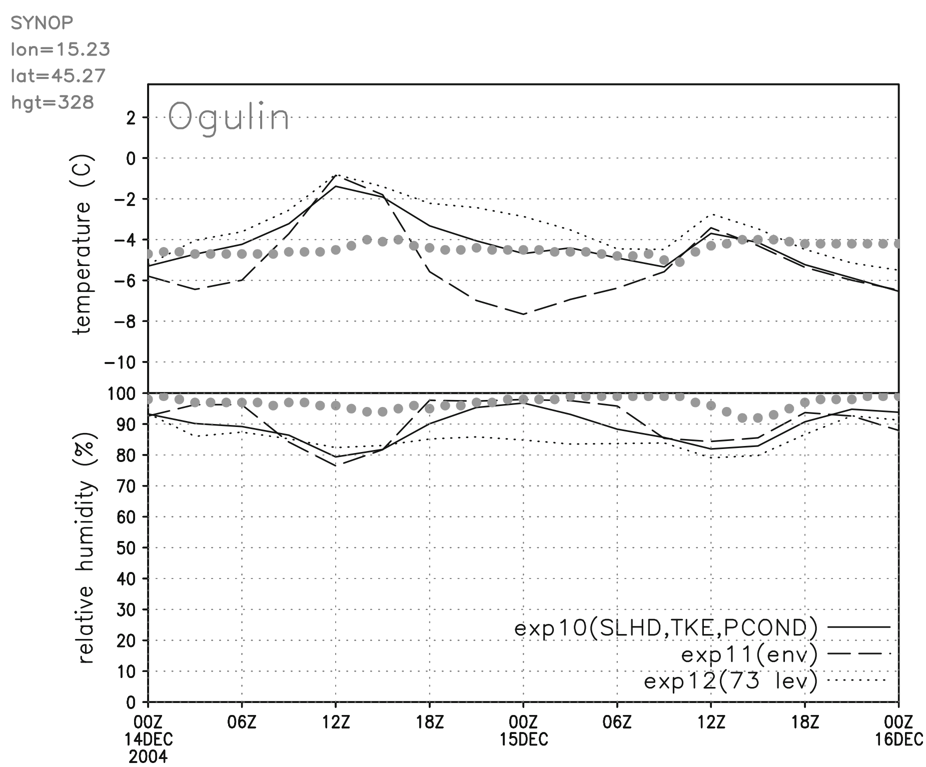

Fig. 10 As Fig. 7, but for Ogulin SYNOP station and the following experiments: exp10 (*full line*), exp11 (*dashed*) and exp12 (*dotted*). Additional explanations may be found in the Table 1 and text

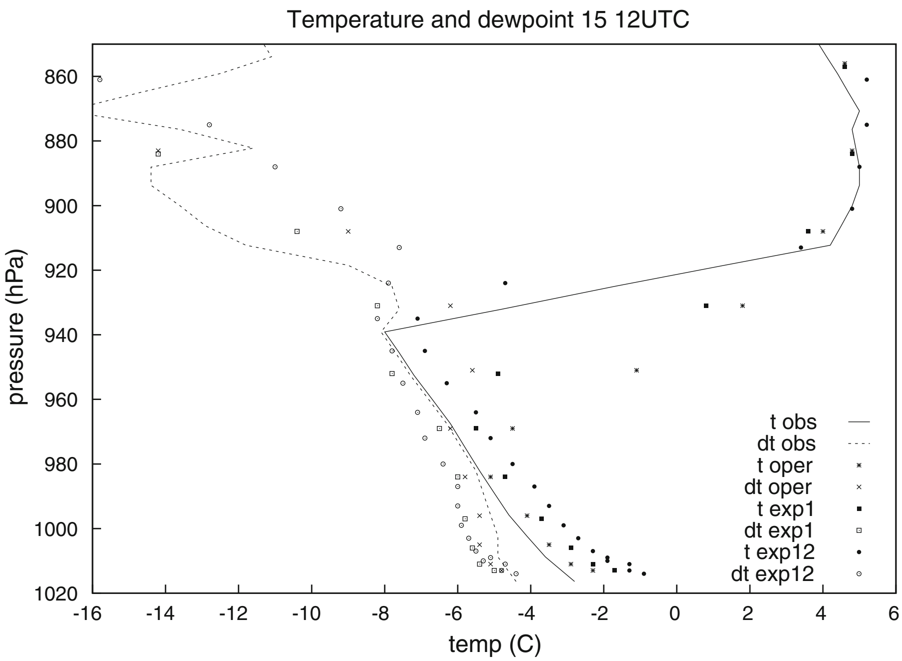

Fig. 11 Measured and forecast vertical profiles of temperature (*t*) and dewpoint temperature (d*t*). The pseudo-TEMP messages were created extracting data on the model levels for the location Zagreb-Maksimir where vertical sounding measurements are available. The model output is shown for operational run (*star* for temperature, *times symbol* for dewpoint temperature) and exp1 are run on 37 levels (*full square* for temperature, *open square* for dewpoint temperature) and exp12 that is run on 73 levels (*full circle* for temperature, *open circle* for dewpoint temperature). Measured temperature is shown as *full line* and dewpoint temperature as *dashed*

plays a very important role, as well as the formula used to diagnose cloudiness. Both are needed to establish the correct cloud input for the radiation scheme that supports further cloud development. Although fog is not a rapidly developing phenomenon, it seems necessary to compute radiation at least on an hourly basis to allow fog to develop in the model. Otherwise, "old" radiative transfer coefficients computed in a cloud free atmosphere are used. This prevents the feedback process that leads to cloud development. Other phenomena, as well as transient fog cases might require new radiative transfer coefficients more often. Infrequent calculation of radiative heating rates can produce numerical instability (Pauluis and Emanuel 2004) and degrade the forecast in cases where radiative balance between the cloud and the rest of the atmosphere is important in the cloud development.

Numerical horizontal diffusion acts along model levels that follow the terrain and consequently mix (or smooth) the model fields between the valley bottom and a mountain ridge nearby. Its intensity is the same in all weather situations. The new scheme for horizontal diffusion, SLHD, is dependent on the flow deformation field, so that the intensity of horizontal mixing is weak when the wind is low. A more physically based horizontal diffusion scheme allows the development of fog in relatively narrow valleys (for the horizontal resolution of 8 km used in this study). Introduction of prognostic condensates and TKE scheme has a positive impact in the valleys and close to the mountain slopes, but only in combination with SLHD.

The terrain complexity stresses the importance of the correct representation of the unresolved terrain height variations. Different representation of orography, with or without the envelope, can lift certain areas (in the model) within or above the fog layer (in the real atmosphere) and therefore have a significant impact on the correct forecast of the 2m temperature and humidity. The persistent fog layer in this case was thick, so increased vertical resolution has a low impact on cloudiness forecast, once the parameterizations are set to produce fog. However, increased vertical resolution improves the temperature inversion forecast.

Very high horizontal resolution has been found necessary (but not sufficient) for the correct modelling of boundary layer structure over complex terrain of some phenomena as the valley flows and foehn (for an overview see Rotach and Zardi 2007). This was not necessary for this study where both large scale and local circulations are almost non-existent and the valleys considered are wide enough to be resolved with 8 km horizontal resolution. Higher horizontal resolution would allow higher slopes and the effect of mountain shadows on solar radiation would become important. Therefore, a case of transient fog in a narrow valley would require high horizontal resolution that would resolve local flow patterns that develop due to differential heating of the slopes.

Study of other fog and low stratus cases, especially for more narrow valleys, might require higher horizontal resolution as well as the parameterization of the shadow in the valley produced by the surrounding mountains. Case studies of more transient phenomena would give better insight into the longwave radiative balance and heating by shortwave radiation. These studies would also require better initial conditions and surface analysis as well as data assimilation in higher resolution. This study has revealed which model configurations allow the prediction of fog and low stratus. Before introducing it into the operational forecast suite, one should also verify that the proposed configuration is suitable for operational use on a large number of cases covering various types of weather phenomena.

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Appendix

The cloud diagnosing scheme that was operational in 2004 diagnoses cloudiness using the formula

$$N_S = \alpha\sqrt{\frac{q_{cs}}{q_{sat}}} \tag{1}$$

where $\alpha = 0.7$, q_{sat} is saturated specific humidity and q_{cs} is condensed stratiform specific humidity computed as

$$q_{cs} = q_{c\,max}\left(1 - e^{-\beta\frac{q - r_c q_{sat}}{q_{c\,max}}}\right) \tag{2}$$

if and 0 otherwise.In this formula, $q_{c\ max}$ is the maximum sustainable water content, $\beta = 0.4$, q is specific humidity and r_c is the critical mesh averaged humidity producing a cloud.

When the model uses prognostic cloud water and ice, liquid water and ice specific contents are added to the water vapour specific humidity, so $q+q_l+q_i$ is used instead of q in the equation for q_{cs}. The alternative equation used here is

$$q_{cs} = q_{c\,max}\left(1 - e^{-\beta\frac{q+q_l+q_i - r_c q_{sat}}{q_{c\,max}}}\right), \tag{3}$$

and it accounts for the presence of the prognostic condensate species.

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