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Short range atmospheric forecasts using a nudging procedure to combine analyses of cloud and precipitation with a numerical forecast model.

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Abstract

A nudging procedure is developed which combines a 3-D cloud analysis and a precipitation analysis with a numerical forecast to improve the quality of a short range prediction of cloud cover and precipitation. The method which is based on modifying the tendencies of specific humidity and cloud condensate is general and does not depend on any specific parameterization package. The tendency modification becomes automatically inactive when the model cloud cover and precipitation approaches the analysed fields. 1-D simulations of both cloud build-up and cloud dissipation show that the scheme works well and shows considerable skill in matching an analysed cloud cover profile. The experiments show that the impact of cloud cover modifications for low level cloud is sometimes 18 hours or more in situations of a weak dynamical forcing. For high clouds the lifetime of cloud cover modifications tends to be somewhat shorter. The results for assimilating precipitation intensity also show good fit to a precipitation analysis during the assimilation period. The first tests on 3-D forecast cases emphasize the complexity of the dynamical forcing in the atmosphere. The relative improvements obtained in the 3-D forecasts depend on the overall modification of the 3-D structures of the main forecast variables during the assimilation period.

1. Introduction

In the last decades the model resolution in atmospheric models used for numerical weather prediction has substantially increased. It is now possible to run operational models with a grid mesh smaller than 10 km which means that there is a potential for explicitly forecasting local weather elements such as precipitation, clouds and near surface temperature with a much higher accuracy compared to achievements in coarse mesh models.

However, to achieve this goal is difficult for a number of reasons: It is necessary to have a realistic physical parameterization package to describe the sub-grid scale transports and the microphysics associated with condensation and precipitation. It is also required that the model dynamics is sufficiently accurate. Furthermore, it is vital to have a significant amount of useful cloud related observations and an assimilation system to incorporate this information. The conventional meteorological observations measuring humidity in the atmosphere are sparse in space and time. However, in recent years satellite information can supply plentiful information which can be combined with surface synoptic reports of cloud and rain rate at a high temporal resolution. It therefore makes sense to spend efforts on developing assimilation methods which combine the new observational data related to clouds and precipitation with a high resolution numerical forecast, in order to improve the forecasts of cloud cover and precipitation.

The present report is devoted to the development of a scheme for assimilating a 3-dimensional cloud cover analysis and a precipitation analysis into a version of DMI-HIRLAM (Sass et al., 2000) which is the model used operationally at the Danish Meteorological Institute. This development is a part of a new strategy for making accurate very short range forecasts of weather parameters such as cloud cover, precipitation and near surface temperature. The methodology is briefly outlined below and is described in more detail in section 2.

The assimilation method is based on the so-called 'nudging' technique which is conceptually simple, and it has been used in limited area models already in the 1970s (Anthes, 1974). The nudging technique has been mentioned as quite promising (Harms et al., 1992). Additional terms are added to the prognostic equations to bring the forecast model in harmony with observations. The additional tendency typically involves a nudging coefficient multiplied with a difference between a model quantity and a corresponding observed or analysed quantity. In reality, an analysis rather than a local observation is needed if nudging is to be done at all grid points. Furthermore, local observations may represent local weather phenomena rather than parameter values valid for a grid square. The problem of producing analyses of clouds and precipitation intensity are however far from trivial. The present report is devoted to the method of assimilating these analyses in a model and not on how to generate such analyses. The currently used method for 3-D cloud analysis is described in Sass and Petersen (2002).

Several methods for assimilating precipitation information have been mentioned in the litterature. In most schemes specific humidity and (or) temperature is adjusted according to some principle to account for estimated (analysed) precipitation. The authors report on improved skill of various aspects of a numerical forecast, from a few hours forecast range out to more than +24 hours. In one type of approach known as 'physical initialization' (Krishnamurti et al., 1991) the convection scheme is used in the adjustment process. In another type of approach known as 'latent heat nudging' (Jones and Macpherson, 1997) the model's latent heating profiles are scaled by the ratio between observed (analysed) and the model first guess value based on the heating from the model condensation processes. Special procedures are designed to handle situations where the scaling of latent heating is not directly possible. Moreover, limitations are imposed in some schemes to avoid a too noisy forecast which may otherwise occasionally lead to model instabilities.

Here it is argued that latent heat nudging, when used as a scaling of heating rates in a single grid box air column, is potentially risky and becomes wrong when going to a high model resolution. This is because a substantial part of the condensation will often be distributed over several grid boxes upstream. The cloud water and precipitation entering the grid area where precipitation is observed has therefore in many cases heated a larger area when the grid size is small, e.g., 10 km or less. It is therefore argued that it is reasonable to introduce a nudging increment for a prognostic cloud water variable in order not to translate local precipitation directly into local heating alone.

The interest in Europe for using nudging techniques for short range high resolution limited area models has been considerable in recent years. In the UK Meteorological Office meso-scale model nudging techniques have been operational since the mid 1990s (Macpherson et al., 1996; Jones and Macpherson, 1997), using a 3-D cloud cover analysis and a precipitation analysis in the nudging procedure. The cloud analysis is converted via the model's cloud scheme to relative humidity profiles which can be assimilated by the nudging scheme. The 3-D cloud analysis using satellite information, radar data and surface reports is still under development (Watkin, 2001). Also nudging techniques have been adopted in the German Weather Service mesoscale data assimilation system, (Schraff, 1996; Schraff, 1997).

The most advanced assimilation methods used in present day numerical weather prediction is based on 4-D variational data assimilation which minimize a cost function (Gustafsson et al., 2001). One may ask why assimilation of cloud and precipitation data are not managed by this method. One reason is that simplified physics is often considered necessary in this approach. This makes it less obvious to use the 4-D variational method to high resolution precipitation forecasting where complex physics is involved. Furthermore, the variational approach requires a knowledge of forecast first guess errors and observation errors which are still rather uncertain for moisture variables. In recent workshop proceedings on methods for assimilating clouds and precipitation information (ECMWF, 2000) the nudging method is considered as a good alternative to variational data-assimilation in the context of short range predictions with limited area models.

The present nudging scheme for assimilating a 3-D cloud analysis and precipitation analysis is described in section 2. The properties of the scheme is studied in idealized 1-D tests in section 3. Preliminary experience from 3-D test runs is briefly summarized in section 4. The results of a long continuous assimilation test will be presented in a later publication. Section 5 provides a discussion and some conclusions from the present study.

2. A nudging scheme utilizing analyses of cloud and precipitation

Different strategies may be used when designing a nudging scheme. The intention is to construct a scheme suitable for very short range forecasts making the numerical forecast model (DMI-HIRLAM) able to adapt efficiently to cloud related observation data, available at a high resolution in time. The 'nudging' approach implies that the model is run forward in time while the cloud related observations or analyses are assimilated.

It is emphasized that a total moisture conservation over a limited volume of the atmosphere before and after assimilating moisture data is not guaranteed. It is thus accepted that a given part of the atmosphere is gaining of loosing total moisture without a compensating change elsewhere in the surroundings. Furthermore, in order that the scheme be efficient the 'nudging'-terms which corrects the forecast model towards the analysis state should be operating fast enough to allow that the characteristic time scale for adjustment is shorter than the time scales which are intended to be forecasted.

For the scheme to be successful, it should be shown that a subsequent forecast will gain quality as a consequence of the data assimilation. Currently the present scheme can receive input from a 3-D cloud analysis and a precipitation intensity analysis. It is intended to create a general scheme in the sense that it is independent of any particular parameterization scheme. The nudging operates by modifying the tendencies of dependent model variables that are normally involved in the determination of cloud cover. This means that the tendencies of specific humidity q, specific cloud condensate w, and possibly temperature T are involved. It is imagined that the tendency modifications operate after the dynamics and the physics have been computed, as a correction before a new time step involving both dynamics and physics is started. The equations are given below:

$$\left(\frac{\partial q}{\partial t}\right)_{nud} = \left(\frac{\partial q}{\partial t}\right)_{*} + K_{q1} \cdot q \cdot (f_a - f_p) + F_d + F_{qN} \tag{1}$$

$$\left(\frac{\partial w}{\partial t}\right)_{nud} = \left(\frac{\partial w}{\partial t}\right)_{*} + K_{w1} \cdot w \cdot (f_a - f_p) + J_w \cdot K_{w2} \cdot (w_m - w) + F_{wN} \tag{2}$$

$$\left(\frac{\partial T}{\partial t}\right)_{nud} = \left(\frac{\partial T}{\partial t}\right)_{*} + F_{TN} \tag{3}$$

In the equations above

$$F_d = J_q K_{q1} \cdot \Big(q - R_* q_s\Big) \tag{4}$$

$$J_q = \begin{cases} 1 & \text{if } f_a = 0 \text{ and } R \geq R_* \\ 0 & \text{if } f_a > 0 \text{ or } R < R_* \end{cases}$$

$$R_* = 1 - K_{q2}(1 - R_0)$$

$$F_{qN} = K_{q3} \cdot \frac{1}{M} \Big(\frac{q}{\hat{q}}\Big)^{\alpha_1} \Big(\frac{q}{q_s}\Big)^{\alpha_2} (N_a - N_p) \tag{5}$$

$$w_m = c_w \cdot f_a \cdot q_s$$

$$J_w = \begin{cases} 1 & w < w_m \\ 0 & w \geq w_m \end{cases}$$

$$F_{wN} = K_{w3} \cdot \frac{1}{M} \Big(\frac{q}{q_s}\Big)^{\alpha_3} (N_a - N_p) \tag{6}$$

Currently, in the temperature equation

$$F_{TN} = 0$$

The assumed values for the coefficients are

$K_{q1} = 5.0 \cdot 10^{-4}\ \mathrm{s}^{-1}, K_{q2} = 2, K_{q3} = 10$

$K_{w1} = 5.0 \cdot\ 10^{-4}\ \mathrm{s}^{-1},\ K_{w2} = 1.0 \cdot\ 10^{-3}\ \mathrm{s}^{-1},\ K_{w3} = 5$

$\alpha_1 = 1, \alpha_2 = 2, \alpha_3 = 4$

The values of the parameters have been determined on the basis of many 1-dimensional experiments (see next section)

On the r.h.s. of eq. (1),(2),(3) the first terms (with '*') are representing the preliminary model tendency before correction. The second term in (1) is a nudging term proportional to specific humidity q and the difference between the local values of analysed and predicted cloud cover , f_a and f_p, respectively. This implies that the tendency modification will automatically switch off as the forecasted cloud cover approaches the analysed cloud cover. It seems reasonable that the needed tendency modification should be larger for high specific humidity than for low specific humidity. It is asumed that the nudging is proportional to q. With this choice the nudging coefficient K_{q1} has the dimension of an inverse time scale.

The third term in (1) is a 'drying' term. It is to be active if the analysed cloud cover is zero while the specific humidity is moist enough to imply that the cloud scheme diagnoses clouds or is close to doing so. At this point it is assumed that a model threshold relative humidity R_0 exists, which may depend on a number of parameters in the model. The cloud scheme is assumed to generate clouds when the relative humidity gets above this value. From a statistical point of view the humidity will be lower than the threshold humidity defined by R_0 in case that no clouds are observed. R_0 may be regarded as a threshold to be used in the model in order to produce a correct volumetric cloud cover (cloud cover extends through at least one model layer in the vertical). It has been found (Macpherson et al., 1996; Walcek, 1994) that clouds in the atmosphere are observed at lower threshold relative humidities, from a statistical point of view, than the appropriate threshold for describing volumetric cloud cover in the model. This observational result is probably related to that fact that observed cloud sheets may be far more thin than the thickness of a model layer. It is argued that if clouds tend to occur in the real atmosphere at a lower relative humidity than the model threshold R_0, a reduction of model relative humidity below R_0 is justified if no clouds have been observed (analysed). The chosen formulation (4) determines a subsaturation in the nudging determined from a 'magnification' factor $K_{q2} > 1$ which increases the subsaturation below the threshold. In DMI-HIRLAM the R_0 increases as the model resolution gets higher. The formulation given by (4) will then automatically reduce the drying effect. This appears reasonable since model resolution can ultimately resolve all observations of these clouds. On the other hand, eq.4 automatically guarantees that sufficiently dry air without clouds will not suffer any drying effect by the scheme.

The last term in (1) is a precipitation nudging term which is substantially different as compared to the other terms. This is because it involves non-local effects which are indeed a characteristic feature of precipitation processes. For example, specific humidity and cloud condensate at a given level may be influenced by deep convection or a modified stratiform precipitation release at a higher elevation in the atmosphere. On the contrary, the previous terms have involved local values of parameters either analysed or forecasted. The principle has been maintained that the nudging should automatically 'switch off' when the model prediction converges towards the analysed value. In this case the model surface precipitation intensity N_p equals the analysed precipitation rate N_a. The expression for F_{qN} is used from the lower boundary up to an upper level containing a total mass of $M \mathrm{kg} \cdot \mathrm{m}^{-2}$. In practice a non-zero nudging contribution can be limited to the troposphere, e.g, up to about 200 hPa. Eq.5 contains a dimensionless nudging coefficient K_{q3}, a division by the total mass involved, two dimensionless power functions and the difference between analysed and model forecasted precipitation intensity. In the first powerfunction $\widehat{q}$ is the vertical mass averaged specific humidity over the involved depth of the atmosphere. It is argued that the largest tendency modification should be done where the specific humidity is large. This is typically in the low troposphere. The second power function involves the relative humidity. It is argued that it is most likely that the specific humidity should be substantially modified where the atmosphere is close to saturation and hence cloud cover with precipitation release. The coefficients α_1 and α_2 have been chosen after experimentation with several cases with a needed precipitation adjustment.

The first nudging term in eq.2 is similar to that used for specific humidity. The nudging coefficient K_{w1} equals K_{q1}. This choice has been made on the basis of experimentation and may also be explained by the argument that the adjustment time scale for specific humidity and cloud condensate should be approximately the same when modifying cloud cover during a model run. According to this term cloud condensate will increase whenever the analysed cloud cover is larger than the model predicted one. This term, however, will be zero if cloud condensate is zero which makes it more difficult for the term to operate during the cloud build-up process. An additional term is currently used to assure that a minimum cloud condensate amount w_m is approached if cloud condensate should increase from zero or a very small value. The term is inactive for w larger than w_m. The latter is assumed to be a fraction of the saturation specific humdity q_s. The factor c_w=0.10 is estimated as an average value for mid-latitude overcast cloud fraction. Multiplication by cloud cover assures a continuous transition between cloud free and overcast analysed sky.

It seems natural in the context of precipitation nudging to use an adjustment term in the tendency equation for cloud condensate. This is because of the explicit dependence of precipitation release on the cloud condensate amount. Eq.6 is tentatively suggested. The tendency modification depending on the near saturation condition is reflected in the choice of α_3=4 in the relative humidity power function. Since the term is proportional to $N_a - N_p$ ($\mathrm{kg} \cdot \mathrm{m}^{-2} \cdot \mathrm{s}^{-1}$) the coefficient K_{w3} is dimensionless.

The function F_{TN} in the temperature equation is currently set to zero. One reason for this choice is that the nudging terms of the other tendency equations for specific humidity and cloud condensate will automatically lead to modifications in temperature through modified condensation and/or evaporation in the model's cloud scheme. No function F_{NT} has yet proven beneficial on top of the other terms already mentioned.

3. Nudging experiments

3.1. Design strategy for 1-dimensional experiments

This section is concerned with 1-dimensional column experiments which are run in order to illustrate the properties of the present nudging scheme under well defined experimental conditions. It is particularly important to see how well the vertical cloud cover profile adapts to an analysed cloud cover profile during the assimilation, and to investigate for how long the effect of the assimilated data exist in the forecast phase after assimilation. Most experiments in this section are done without specification of dynamical advections in order to evaluate a maximum potential of the assimilation procedure. Hence the nudging procedure attempts to correct the model initial state towards a state which is consistent with one particular analysed cloud cover profile. In some experiments also an analysed precipitation intensity is specified. The assimilation period is chosen to be 6 hours. When continuing a given model run in forecast mode beyond the nudging period it is not necessarily realistic to consider the specified initial analyses as 'truth' since the model processes may correctly modify the analysed state specified to be valid for the period of nudging. This should be kept in mind when evaluating the results below.

3.2. 1-dimensional model

The 1-dimensional version of the DMI-HIRLAM physical parameterizations (Sass et al., 2000) may optionally be run with dynamical forcing. The experiments are run with some recent enhancements to the subgrid scale parameterization of condensation. This allows for more variability in the threshold R_0 for onset of subgrid scale condensation. The variability of total specific humidity (the sum of specific humidity and cloud condensate) is reduced with increasing precipitation rate. In this way cloud condensate may decrease in clouds without affecting cloud amount. Such feature is potentially important in situations with nudging towards both analysed cloud and precipitation intensity. Also the convective cloud cover has been modified to better describe convective cloud cover in the upper troposphere and close to grid scale saturation (Sass, 2002).

The experiments below are carried out in a 40 model level version of DMI-HIRLAM, with 7 model levels in the lowest kilometre of the atmosphere. The settings are such that the model threshold R_0 for subgrid scale condensation varies between about 97 percent and 85 percent. The time step used is 150 s.

We denote by NU0 simulations without any nudging. Simulation experiments NU1 refer to nudging with only one basic term which is the term proportional to q. The constant $K_{q1} = 5.0 \cdot 10^{-4}\mathrm{s}^{-1}$. Simulations NU2 include all nudging terms except precipitation nudging. Finally, for an atmosphere with deep clouds where precipitation release is significant, simulations (NU3) have been carried out with all terms included.

After the assimilation period of 6 hours the forecast phase extends for another 18 hours. For simplicity, all experiments assume nocturnal conditions. Formally, the experiments start from midnight on 1 January at a latiude of 75° N. In all 1-D experiments the pressure gradient forcing is characterized by quasi-constant geostrophic wind of 10m s^{-1}. A slight vertical variation is computed in order to provide a zero temperature advection. Also the advections of specific humidity and cloud condensate are assumed negligible.

3.3. Low level clouds

It is first investigated how the nudging scheme is able to treat adjustment in low level cloud cover for stratocumulus type of situations in the low tropospere. Cloud dissipation, vertical displacement of cloud and cloud build-up are treated separately. For simplicity, the surface fluxes of sensible and latent heat are set to zero. The surface is treated as a smooth sea surface in the momentum budget.

3.3.1. Dissipation of low level stratiform cloud

At first the cloud dissipation process is investigated. We define an analysis state f_a of zero cloud cover. The initial model state before nudging is seen in figure 1 which reveals the presence of a cloud. This figure shows the liquid water potential temperature Θ_L (tetal_ini) and the specific cloud condensate w (ql_ini). The cloud cover becomes non-zero above 500 m and increases to 100 percent below 1000 m. The relative humidity increases linearly from 80 percent at the surface to 100 percent above 500 metres. For all model levels above 1000 m the relative humidity is set to 20 percent. As a consequence the model cloud cover above 1000 m is initially zero. The surface temperature is 280 K. The temperature lapse rate is $7.0 \cdot 10^{-3}$K m^{-1}. Above 1000 m the atmosphere is assumed isothermal. This situation resembles a typical stratocumulus type of atmospheric state.

Figure 1 shows also the results (w and Θ_L) of a 6-hour simulation (NU0) without nudging (curves 'ql_6h_0' and 'tetal_6h_0'). As expected the cloud is subject to some cooling. The amount of cloud water decreases somewhat because there is no surface evaporation, and the cloud releases some precipitation, typically $0.5 - 1$mm day^{-1}. The total cloud cover (maximum of individual levels), however, remains at 100 percent. When nudging is switched on the result is entirely different. Figure 2 shows how the original curves of w and Θ_L are modified for simulations NU1 and NU2. (ql_6h_1 and tetal_6h_1 for NU1, ql_6h_2 and tetal_6h_2 for NU2). It is seen that both NU1 and NU2 lead to zero cloud water (cloud dissipation) and a quite modest modification of the temperature profile Θ_L which is desirable. Figure 3 shows how the relative humidity develops when choosing the three different options NU0, NU1 and NU2, respectively. For NU0 the relative humidity stays high where clouds are present. When nudging is active there has been a substantial reduction of relative humidity to almost 60 percent in the upper part of the original cloud. The results of NU1 and NU2 are quite similar in this respect.

Figure 4 shows the evolution of maximum cloud cover deviation, computed from the analysed value and each model level below 800 hPa. The nudging period of 6 hours stops at time step 144. The rest of the integration covers the 18 hour forecast phase. As seen previously, the case of no nudging (NU0) has a cloud cover close to 100 percent which equals the deviation in the present situation with no clouds. Figure 4 shows the evolution with the NU1 -nudging, using two different values of K_{q1}. The first one ($adj1$) corresponds to a reduced coefficient ($K_{q1}= 1.0 \cdot 10^{-4}$) while the default value, being a factor of 5 larger, is used in $adj2$. In both runs there is a remarkable reduction of cloud cover in the assimilation period. As expected, the adjustment is slower when using the small nudging coefficient. In order to be able to adapt to significant changes from hour to hour it appears that the larger coeffficient is the most appropriate one to use. Moreover, the default value is able to prevent the cloud from reappearing during the 18 hour forecast. This is a satifactory result. It indicates that the nudging approach using the present model physics has a forecasting potential up to at least 18 hours under conditions of weak dynamical forcing. The smaller nudging coefficient gives rise to cloud cover increase beyond a forecast length of +10 hours , and a maximum cloud cover close to 100 percent is almost established after +16 hours.

It is noted that an experiment with the nudging terms for cloud condensate added (disregarding precipitation terms) leads to a very similar result as presented by the default value of the K_q term in figure 4. The adjustment towards zero cloud cover in the nudging phase is slightly quicker, and the cloud cover remains at zero in the forecast phase (not shown). Disregarding the 'drying'-term F_d has very little effect on the evolution of cloud cover for the present case. Cloud water nudging alone is however not able to dissolve the cloud layers. Only small cloud cover reductions are obtained. The successful suppression of cloud cover in these cases implies also that the precipitation intensity is becoming zero, consistent with the absence of analysed clouds.

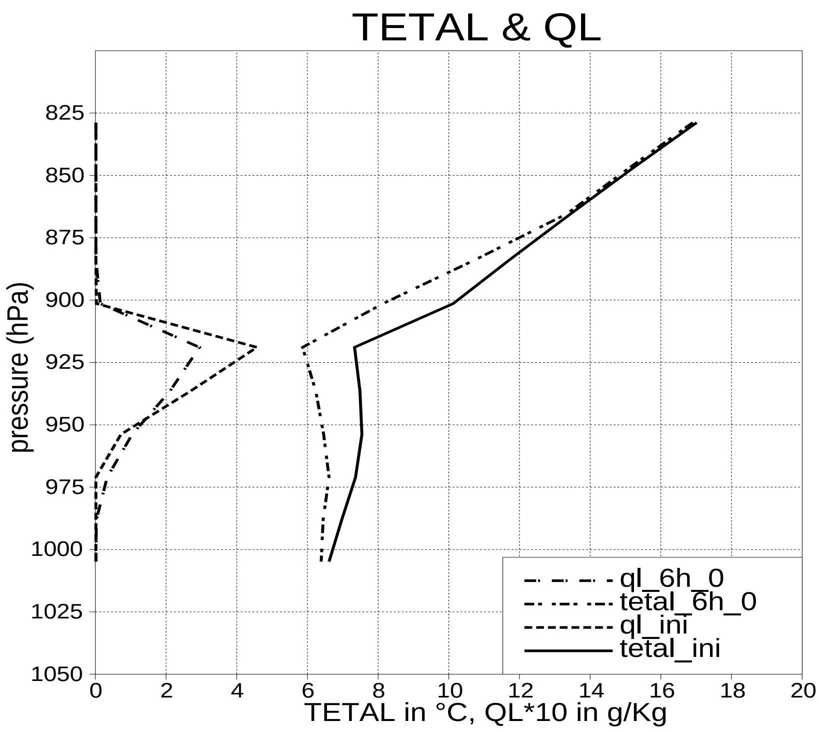


Figure 1: Profiles of cloud condensate and liquid water potential temperature initially and after 6 hours using model version NU0 in experiment starting from 100 percent stratus (stratocumulus) when no clouds are analysed (see text)

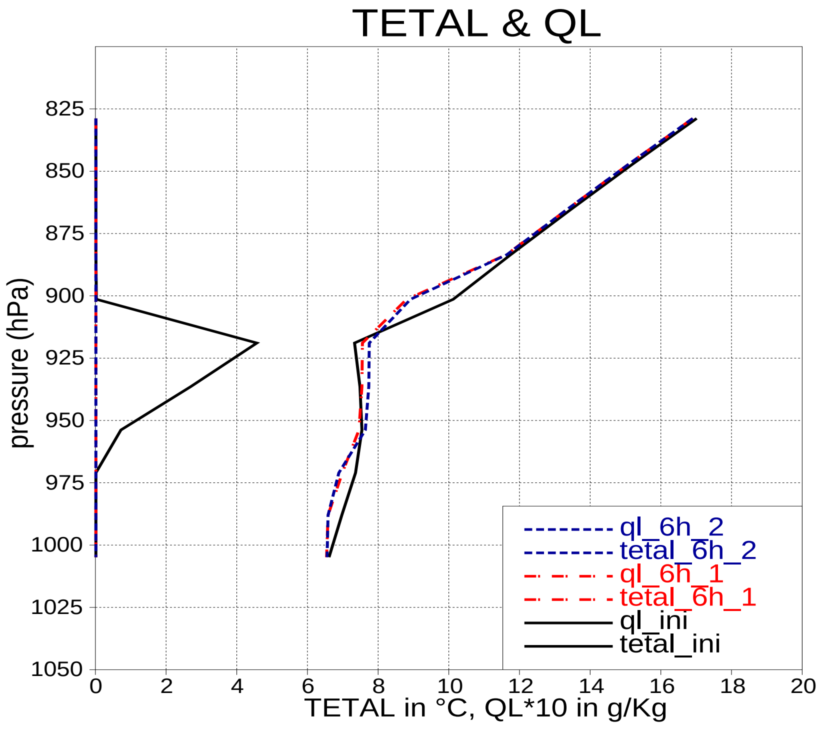


Figure 2: Initial profiles of cloud condensate and liquid water potential temperature for experiment with low clouds (as fig.1) and simulation results for nudging experiments NU1 and NU2 after 6 hours (see text).

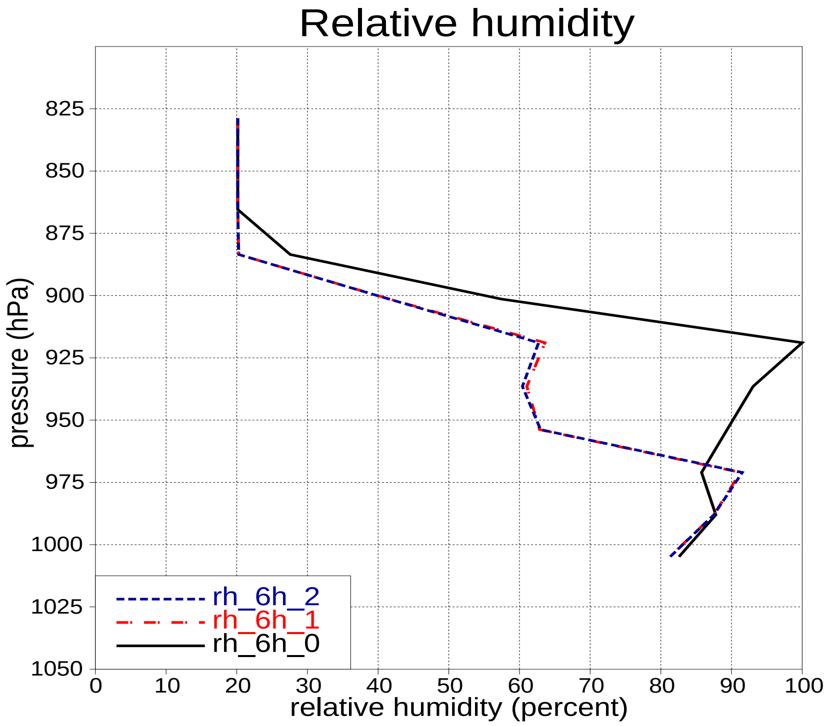


Figure 3: Relative humidity after 6 hours for simulations NU0, NU1 and NU2 starting from 100 percent stratus (stratocumulus) when no clouds are analysed (see text).

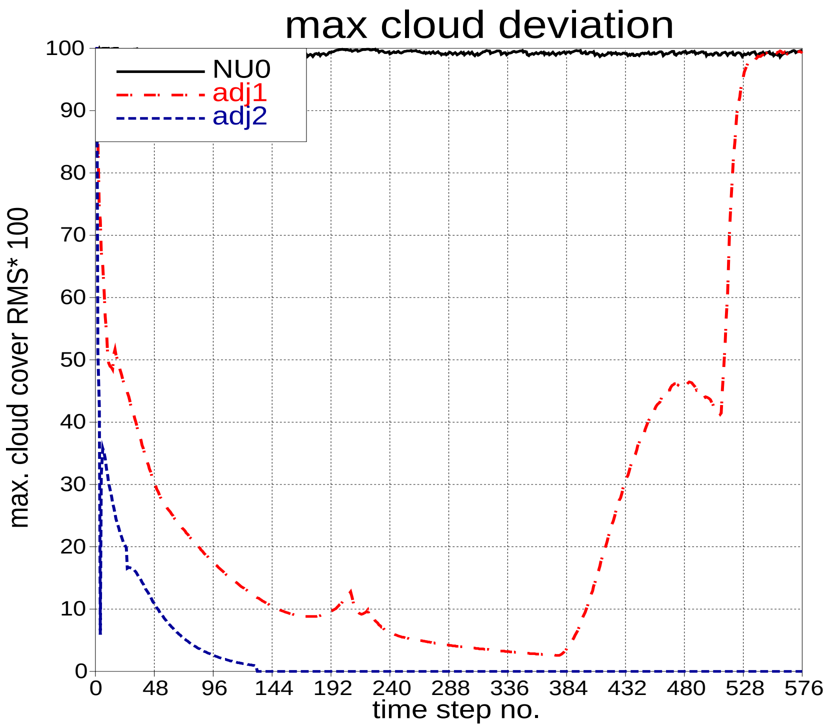


Figure 4: Time evolution of maximum vertical cloud cover deviation for low level cloud dissipation in the case of no nudging (NU0). Curves $adj1$ and $adj2$ apply to NU1 type of nudging using a small and a larger nudging coefficient, respectively (see text).

3.3.2. Vertical displacement of low level cloud

It will next be assumed that a total cloud cover of 100 percent is analysed. However, it is assumed that the analysed cloud is only one model layer thick and is situated on top of the cloud cover initially present. This turns out to be a demanding situation. Figure 5 shows that after 6 hours both nudging simulations NU1 and NU2 have done a reasonably good job since the cloud top has been moved up by one model level, although the cloud is not limited to one level on top of the original cloud. Figure 6 confirms that the nudging has worked rather well, because the relative humidity has been strongly reduced where there were originally a cloud. However, when inspecting the evolution of the maximum cloud cover deviation for the entire period of assimilation plus forecast (figure 7) it is clear that this experiment is a challenge. For both nudging experiments there are transient problems during the assimilation period. It turns out that in both NU1 and NU2 simulations the scheme first removes existing clouds efficiently, but the new cloud layer is built up somewhat later causing a cloud free atmosphere for some time. Later both NU1 and NU2 reproduce very well the 1-level cloud cover displacement, but the natural physical processes tend to spread out the cloud to some extent. This causes the nudging to become active again. When the forecast begins, a transient cloud cover change starts again, reflected in a cloud cover decrease temporarily. For the nudging version NU2 the transient period is shorter than for NU1. It seems clear that the one layer thick cloud cover surrounded by substantially lower relative humidity both at top and bottom is difficult from a numerical point of view. It is noted that a doubling of the resolution of the cloud layer when repeating NU2 leads to a better result for maximum cloud cover during the assimilation period and a shorter transient period with cloud cover reduction in forecast mode. These results indicate that single cloud layers with 100 percent cloud cover should be avoided in the data assimilation if the cloud layer is thin.

3.3.3. Building up low level stratiform cloud

Instead of removing clouds between 500m and 1000m we may consider the situation that a 100 percent cloud cover is analysed between these levels. With the present model resolution this involves three cloud levels in the model. The initial cloud cover prior to assimilation is set to zero throughout the atmosphere. To be consistent with moisture, the specific humidity in the lowest kilometre is reduced such that the relative humidity becomes 80 percent initially. Again the results of the simulations NU0, NU1 and NU2 are investigated.

In simulation NU0 it may be investigated whether clouds are formed during assimilation (6 hours) and later during the subsequent 18 hour forecast. Figure 8 shows the profiles of liquid water and liquid water potential temperature initially and after 6 hours of simulation. A slight cooling of the temperature profile occurs (as expected), but the cloud condensate remains at zero implying no cloud formation.

The results of cloud condensate w and Θ_L for experiments NU1 and NU2 are shown in figure 9 along with the initial profiles (solid lines). The adjustments appear reasonable. Both runs have managed to produce cloud in the three model levels, and the amount of cloud condensate (up to about $7 \cdot 10^{-4} \cdot \mathrm{kg} \cdot \mathrm{kg}^{-1}$) are within observational limits

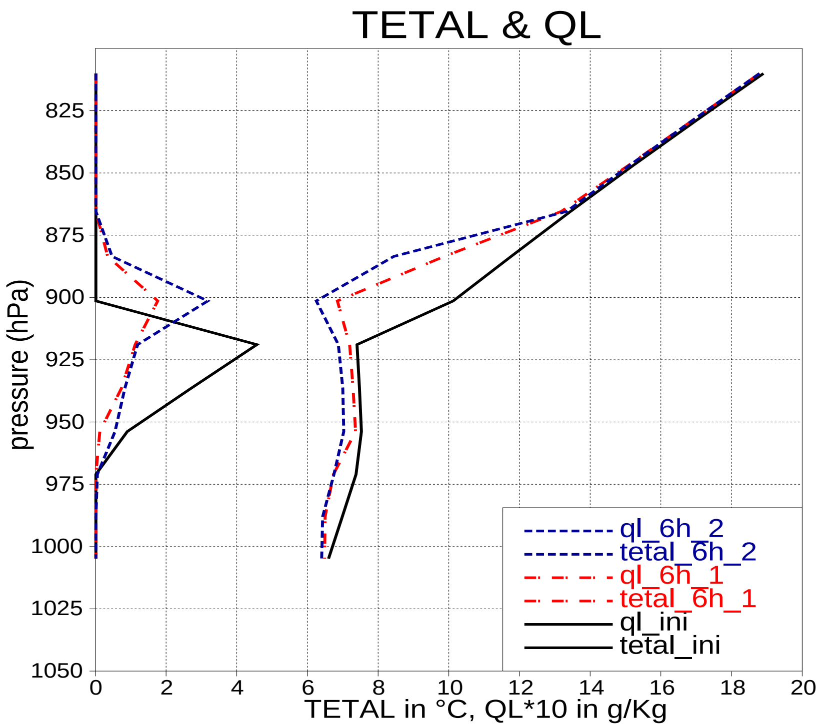


Figure 5: Initial cloud condensate and liquid water potential temperature in low stratocumulus experiment (solid lines) and corresponding profiles after 6 hours when analysed cloud is 1 layer thick on top of existing cloud. Results are shown for nudging experiments NU1 and NU2 (see text)

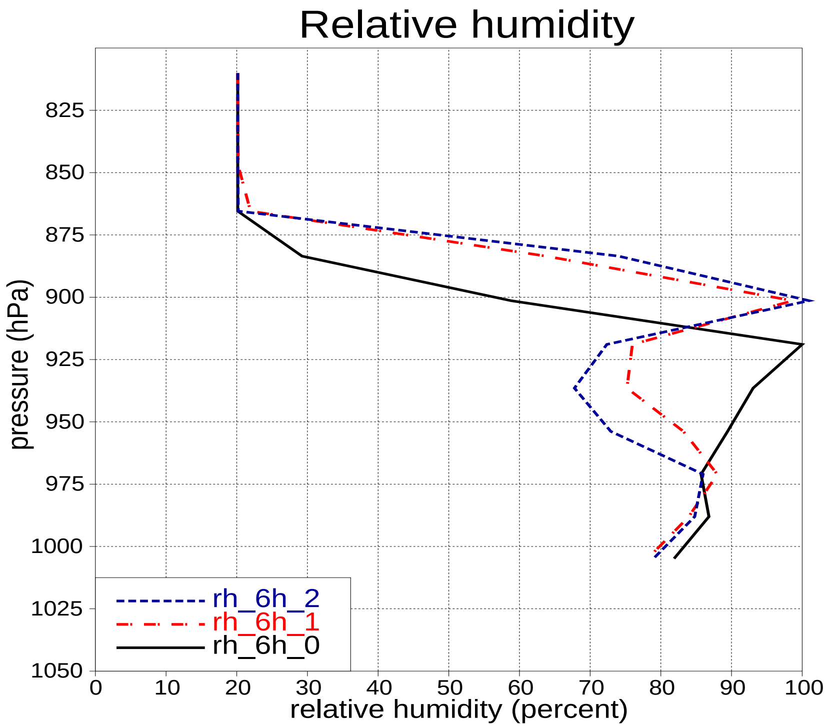


Figure 6: The relative humidity after 6 hours in low level cloud build-up experiment when analysed cloud cover is 1 level thick on top of existing clouds. rh_6h_0 applies to NU0, and rh_6h_1, rh_6h_2 show results for simulations NU1 and NU2, respectively.

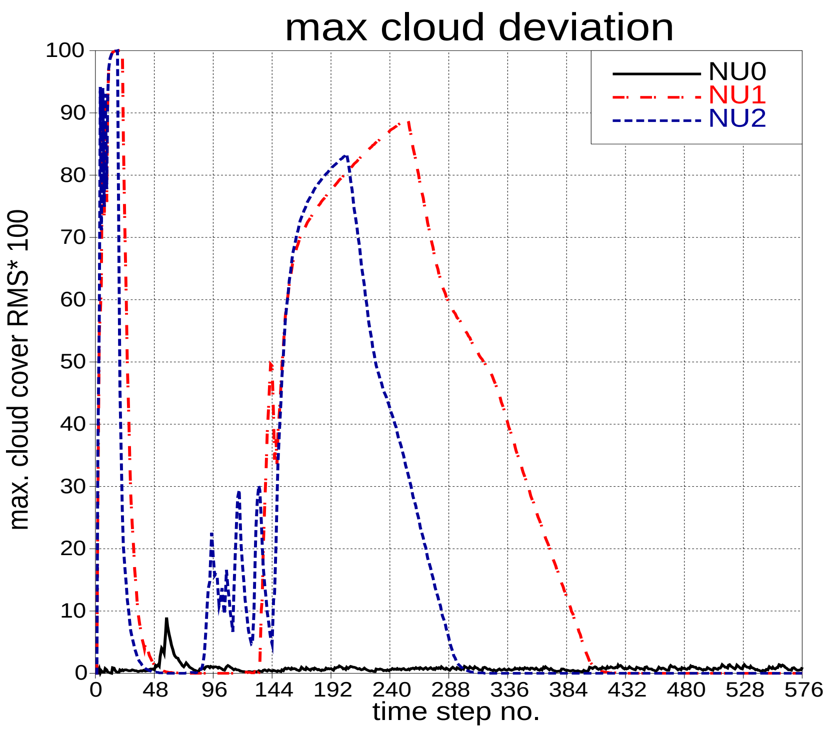


Figure 7: The evolution of maximum cloud cover deviation (error) for experiments NU0, NU1 and NU2 in the situation that low analysed cloud cover is displaced vertically by one level (see text).

found for stratocumulus clouds on mid-latitudes. The Θ_L profile has become less varying with height between top and bottom of the cloud layers, especially in simulation NU2. This is a chracteristic feature of stratocumulus clouds which one may claim to have simulated during the assimilation period. The specification of a transition from 0 to 100 percent cloud cover over a single model layer at the bottom is often awkward for the model to accomodate and it contributes to a somewhat high liquid water amount in the 3 layers. This is reflected in the precipitation intensity at the ground reaching about $2\ \mathrm{mm} \cdot \mathrm{day}^{-1}$ which is somewhat high for stratocumulus. If the more natural choice is adopted that analysed cloud cover increases gradually from zero to 100 percent through the considered 500 metres of the atmosphere a quasi-linear increase of cloud condensate with height is achieved and a reduced peak value at cloud top to about $5 \cdot 10^{-4} \cdot \mathrm{kg} \cdot \mathrm{kg}^{-1}$ which is more typical for stratocumulus. Also the precipitation intensity is reduced to 0.5 - 1 $\mathrm{mm} \cdot \mathrm{day}^{-1}$. Use of the precipitation nudging terms on top of the other terms can reduce the original intensity of rain somewhat (and the cloud water in the cloud) provided that a lower analysed precipitation rate is specified (not shown).

The associated profiles of relative humidity after 6 hours are shown in figure 10 for the control experiment NU0 (solid line) and for the simulations NU1 and NU2, respectively. The figure confirms that the original simulation with no nudging still has a relative humidity around 80 percent in the lowest kilometre while the simulations NU1 and NU2 obtain an increase of relative humidity with height, to about 100 percent in the upper part of the lowest kilometre of the atmosphere.

The evolution of maximum cloud cover deviation is shown in figure 11 . It correponds to figure 4 computed for cloud dissipation. Again the control run NU0 stays at value close to 100 percent throughout the period of 18 hours forecast. This means that the forecast remains cloud free. Apart from small fluctuations in total cloud cover, the results of NU1 and NU2 stay with an overcast sky. This is again a satifactory result which indicates a potential impact of nudging out to 18 hours or more.

3.4. High level clouds

It is of some relevance to carry out assimilation experiments for high clouds corresponding to those for low clouds described in the previous paragraphs. It is important to realize that high clouds are often associated with very low amounts of moisture. An accurate computation of the condensation then becomes more difficult due to the small humidity amounts involved. Moreover, the condensation issue becomes more problematic due to microphysical questions related to the availability of ice nuclei. When deep convection occurs the situation may be quite different due to transports of cloud condensate from the low troposhere to high elevations. However, in order to forecast this source term the convective activity needs to be adequately forecasted which is a challenge due to the rearrangements of moisture over deep layers.

In the two paragraphs below we consider again cloud dissipation and cloud buildup under the condition of no direct moisture advection from dynamics and zero surface energy and moisture flux imposed. The presence of analysed clouds or initial cloud specification involves model levels between 6500 m and 7500 m above the surface (2 levels). The initial temperature at the lowest model level is 280 K and the temperature lapse rate

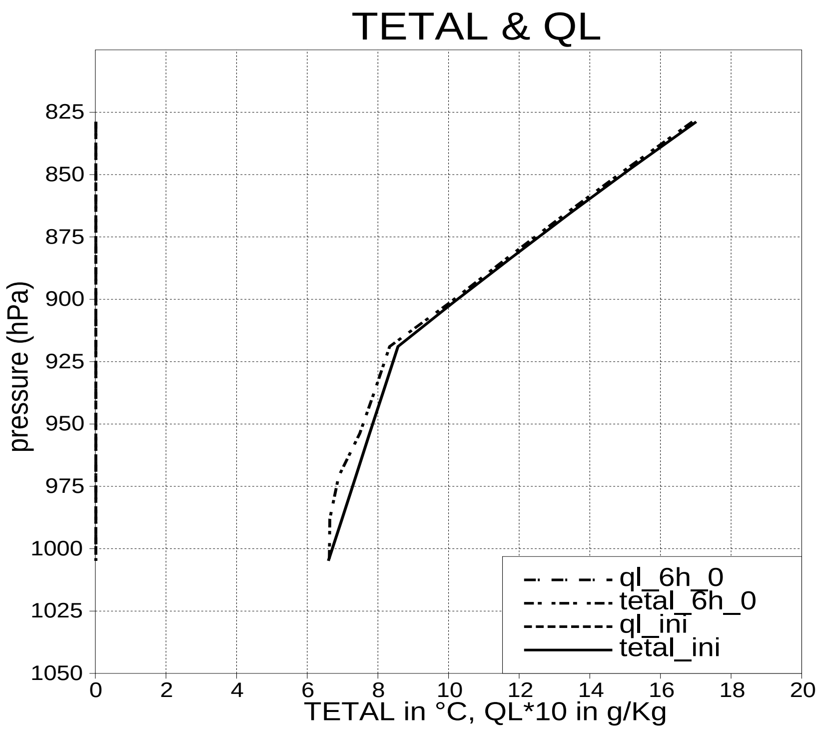


Figure 8: Cloud condensate and liquid water potential temperature profiles initially and after 6 hours in simulation NU0 for the low level cloud build-up simulation (see text).

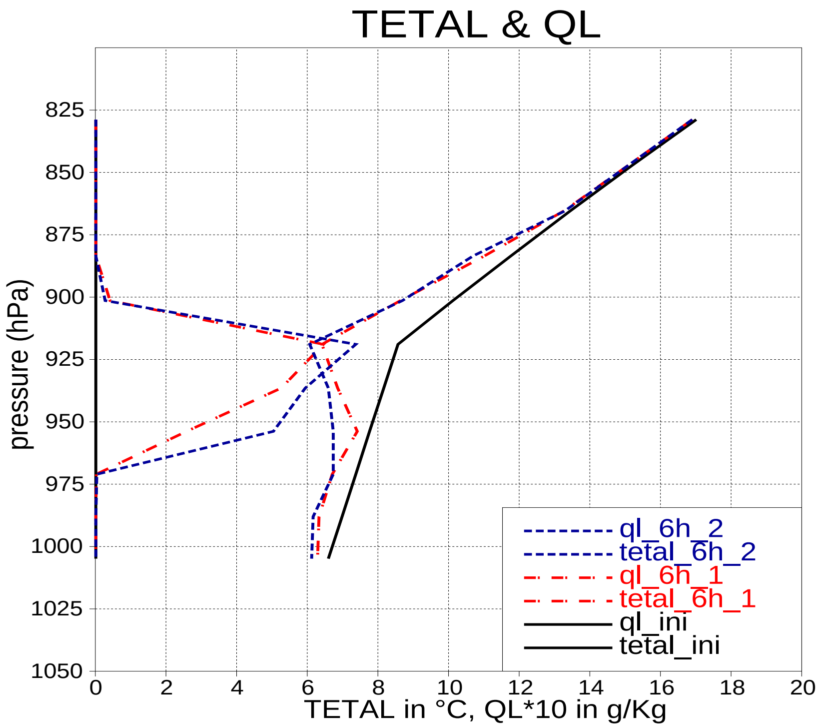


Figure 9: Initial profiles of cloud condensate and liquid water potential temperature after 6 hours assimilation in experiments NU1 and NU2 for the simulation investigating low level cloud build-up (see text).

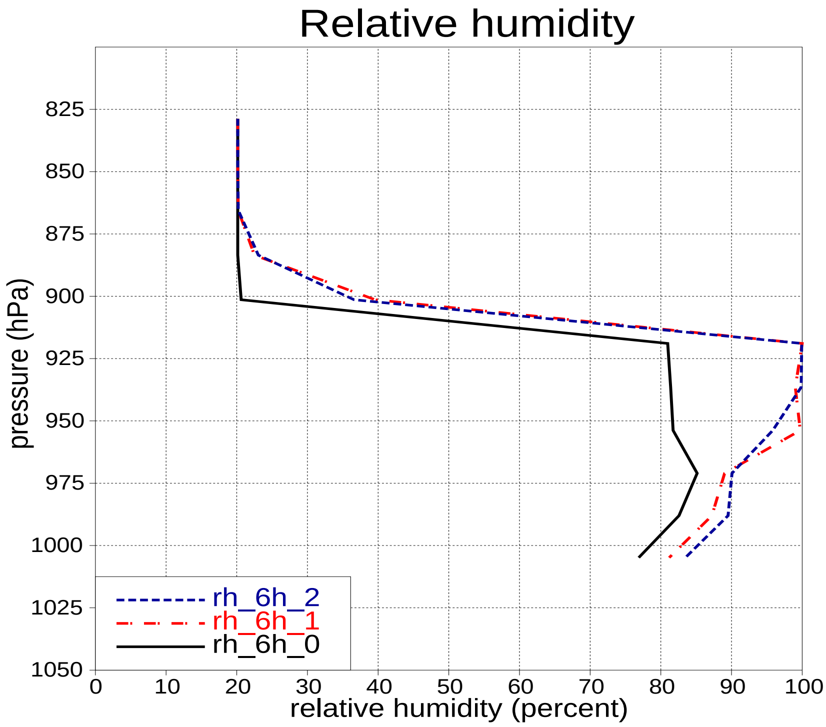


Figure 10: Relative humidity rh_6h_1 and rh_6h_2 at +6 hours for the assimilations NU1 and NU2, respectively, in the experiment investigating low level cloud build up. The corresponding relative humididity at +6 hours for experiment NU0 is also shown (solid line)

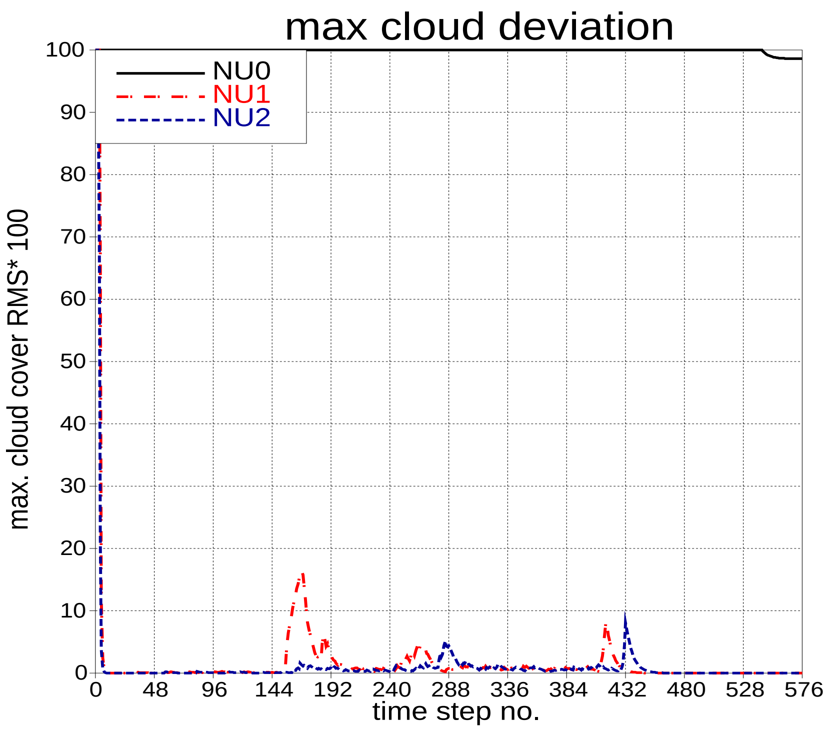


Figure 11: Maximum cloud cover deviation as a function of time for simulations NU0, NU1 and NU2 (low cloud build-up experiment).

up to 7500 m is $7. \cdot 10^{-3}$ K $\cdot$ m^{-1}

3.4.1. Dissipation of high level clouds

The initial description of relative humidity is similar to that for the low level cloud dissipation experiment. The relative humidity increases linearly from 80 percent at the ground to 100 percent above 6500 m. The cloud condensate amount is specified to increase linearly at a rate of $1 \cdot 10^{-7}\text{kg} \cdot \text{kg}^{-1} \cdot \text{m}^{-1}$. This gives a maximum possible value of $10^{-4}\text{kg} \cdot \text{kg}^{-1}$ at 7500 m (for a model level placed at this elevation). Above 7500 m the atmosphere is initially isothermal with a relative humidity of 20 percent.

Figure 12 shows the results of a reference run without nudging during the 6 hour period. The amount of cloud condensate w decreases primarily due to precipitation release. The profile of Θ_L is againg cooled by at most 1.5 K. For the nudging experiments NU1 and NU2 the cloud condensate is almost completely removed and the modifications of the Θ_L profile are small compared to the NU0 run. Figure 13 shows the evolution of relative humidity during the runs. The original cloud top level is close to 420 hPa. The nudging experiments have substantially reduced the relative humidity at this level, as expected. At lower elevations the run NU2 including the 'drying'-term F_d has adjusted to a somewhat reduced relative humidity. This turns out to have some consequences for the subsequent forecast of cloud cover shown in figure 14. This figure shows again the maximum cloud cover deviation in the vertical which reflects well the error of a total cloud cover. The run NU0 remains with a deviation close to 100 percent throughout the forecast. The two runs with nudging manage to remove the two cloud layers almost completely during the assimilation (144 time steps) but the cloud cover adjustment is different in the two runs. It is seen that the cloud cover builds up again after 9 hours in NU1 while the cloud cover stays below 100 percent in the NU2 run.

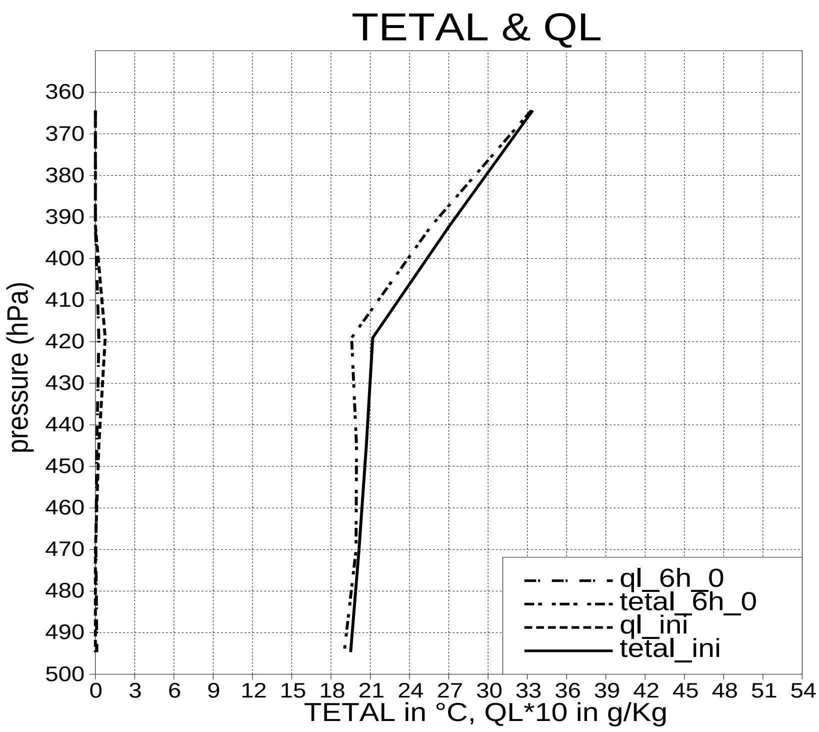


Figure 12: Results of cloud condensate and liquid water potential temperature at 0 hours and 6 hours for NU0 simulation in experiment with high clouds present initially (see text)

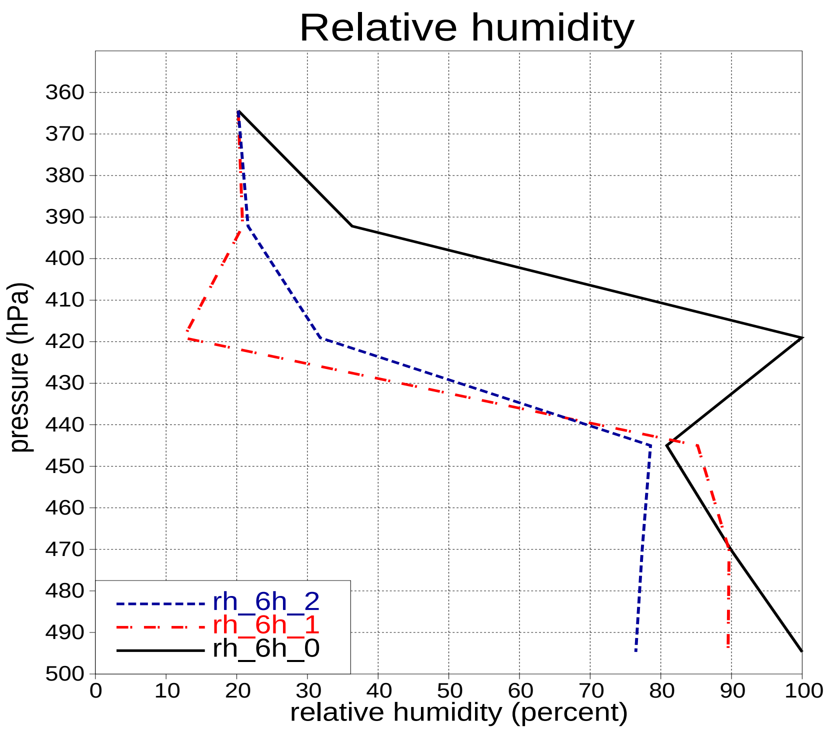


Figure 13: Relative humidity rh_6h_0, rh_6h_1 and rh_6h_2 at 6 hours for assimilations NU0, NU1 and NU2, respectively, in experiment with high clouds initially (see text).

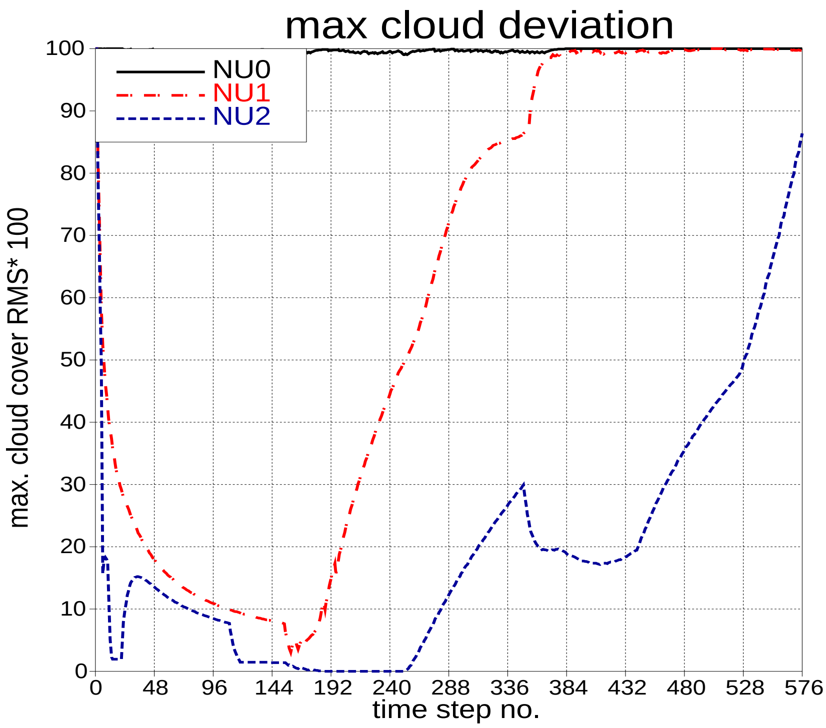


Figure 14: Time evolution of maximum cloud cover deviation for simulations NU0, NU1 and NU2 in the experiment investigating the dissipation of high clouds (see text).

3.4.2. Building up high level clouds

In this experiment the build-up process is investigated. The model initial state for levels below 7500 m is specified to have 80 percent relative humidity. Above 7500 m the atmosphere is still isothermal with a relative humidity of 20 percent. Figure 15 shows that both standard nudging tests NU1 and NU2 have adjusted the Θ_L profile in a modest way after the assimilation, with a similar coling above cloud top as was seen in the NU0 run with cloud present initially. Figure 16 shows the modifications of the the relative humidity profile after the 6 hours assimilation period. Also in this case, the results appear to be reasonable. The relative humidity in NU0 has only been modified slightly while effective moistening has taken place at the two model levels between 6500 m and 7500 m in simulations NU1 and NU2. The simulation NU1 has produced a slight supersaturation at the lowest cloud level, emphasizing that convergence of the saturation computations at low temperatures (and humidities) may require several iterations. The subsequent 18 hour forecast phase is somewhat different in this case, because after 6 hours of integration in forecast mode the maximum cloud cover deviation in NU0 starts to decrease. By the end of the 18 hour period the deviation has gone down to 47 percent. This may be explained by the continued cooling leading to a start of the cloud condensation process. The forecast of NU1 stays without cloud dissipation while NU2 starts to dissipate cloud after about 7 hours. However, the cloud amount is larger than that of NU0 out to +15 hours where the cloud cover in both NU0 and NU2 starts to increase in almost the same way (deviation from analysis decreases).

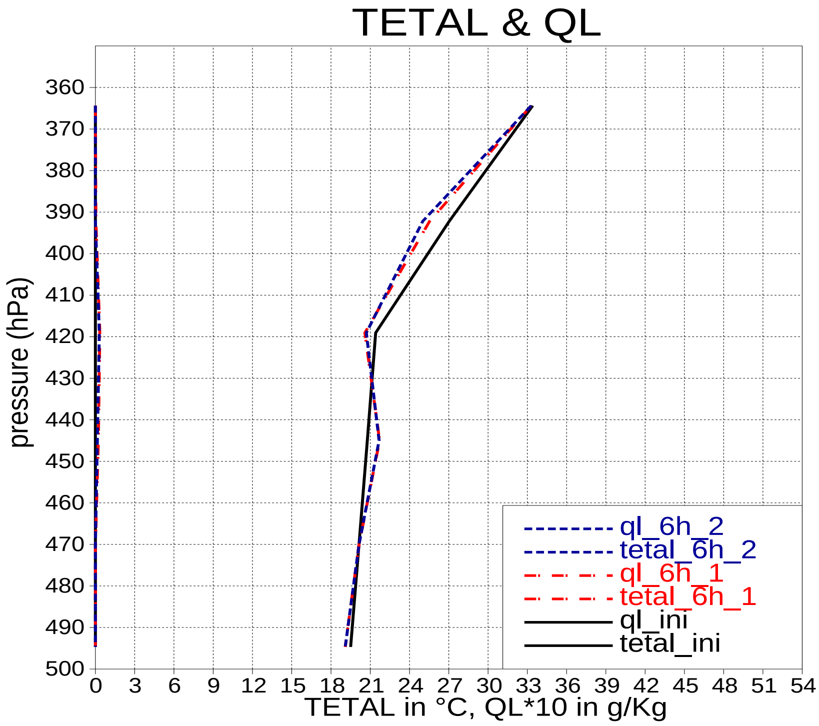


Figure 15: Profiles of cloud condensate and liquid water potential temperature in cloud build-up experiment for high clouds. The solid lines apply to initial profiles. *ql_6h_1* and *tetal_6h_1* are valid for NU1, *ql_6h_2* and *tetal_6h_2* apply to NU2 (see text).

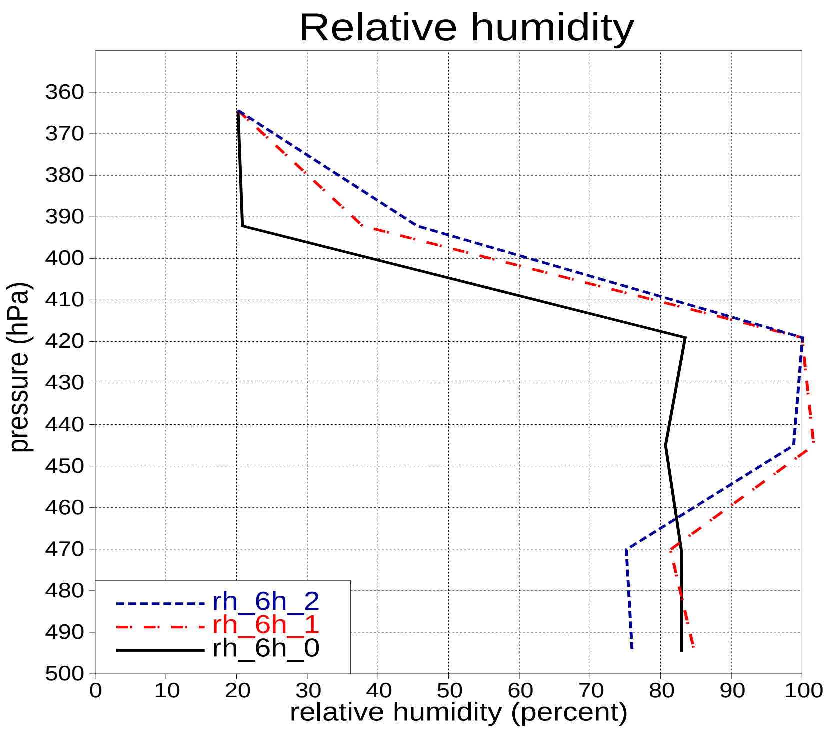


Figure 16: Relative humidity adjustment at 6 hours for simulations NU0, NU1 and NU2, respectively, in experiment examining build up of high clouds (see text).

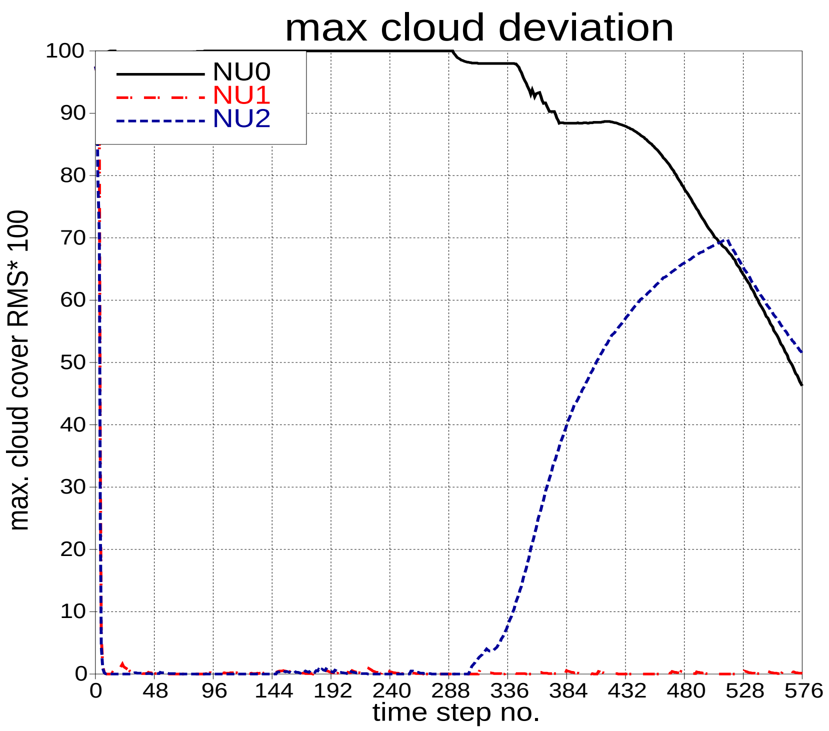


Figure 17: Time evolution of maximum cloud cover deviation in simulations NU0, NU1 and NU2, respectively, valid for the high cloud cover build up experiment (see text).

3.5. Deep clouds

3.5.1. Stable stratification

The problem of satisfying a cloud- and precipitation analysis is more demanding when deep cloud layers are considered in the atmosphere. One reason is that precipitation release at a given level is affected by precipitation coming from levels higher up. For example, the precipitation release is affected through collision/coalescence effects (in the case of rain) or aggregation of snowflakes (in the case of snow). Furthermore, phase changes and latent heat release associated with precipitation generated at other levels make the situation more complicated. First, the situation involving a stable temperature lapse rate is considered, where the problems of 'non-localness' are less severe as compared to an atmosphere which is convectively unstable.

The situation of a deep stable atmosphere between the surface and 7500 m has been studied. The initial lapse rate is assumed to be $4 \cdot 10^{-3}$ K $\cdot$ m^{-1}, and the relative humidity is 80 percent. Above 7500 m the atmosphere becomes isothermal with a relative humidity of 20 percent. Assumptions for the geostrophic wind are unchanged from the previous experiments, and the surface fluxes of sensible and latent heat are still assumed to be zero. The cloud analysis tentatively imposed is that the cloud cover should be 100 percent at all levels between 500 m and 7500 m. The results of simulations through a 6 hour nudging period is studied for the model versions NU0, NU1 and NU3, respectively. NU3 replaces NU2 due the specific effects of precipitation release in the moist atmosphere over a large depth.

Different analysed precipitation intensities are studied (20 mm $\cdot$ day^{-1}, 60 mm $\cdot$ day^{-1} and 100 mm $\cdot$ day^{-1}). For each analysed precipitation intensity it is reasonable to impose a dynamical forcing through advection of moisture. For each intensity a constant advection tendency of humidity is imposed for all model levels having an analysed cloud cover of 100 percent. A precipitation intensity of 100 mm $\cdot$ day^{-1} corresponds approximately to $2 \cdot 10^{-7}$kg $\cdot$ kg^{-1} $\cdot$ s^{-1} of moisture supply for a steady state where moisture supply generates precipitation. This total humidity forcing has been used throughout the 6 hour period, using equal contributions from advection of specific humidity and cloud condensate. For the other experiments with smaller precipitation intensity, the forcing from humidity advections has been reduced in proportion to the fractional reduction in analysed precipitation rate. The posssible effect of the specific assumptions for these experiments are discussed below.

Table 1 shows the mean RMS cloud cover error (percent) during the 6 hour simulation period, computed for model levels below 200 hPa, weighted according to the thickness (Pa) associated with the model level. Table 2 shows the mean precipitation intensity (mm $\cdot$ day^{-1}) during the 6-hour simulation.

It is seen from table 1 and table 2 that there is a considerable skill of the nudging simulations NU1 and NU3 to reproduce cloud cover. The fit to analysed precipitation is clearly best in the scheme NU3 applying all nudging terms including terms with precipitation intensity. The overestimation of precipitation in the case of analysed precipitation intensity = 20 mm $\cdot$ day^{-1} may be due to the deep overcast cloud layer (7 km) considered. The run NU0 without nudging has problems to reach an accurate level for both cloud cover and precipitation intensity which is substantially too low in the three experiments.

One may ask to what extent these results are dependent on the actual magnitude of the imposed dynamical advection for specific humidity and cloud condensate. It is noted that the nudging scheme NU3 has an almost unaffected skill for the three experiments mentioned above, even if zero explicit dynamical advections are imposed in the experiments. The nudging terms can still provide very good agreement with analysed cloud cover and precipitation intensity (better agreement for low precipitation case and worse for high precipitation intensity). In this event the experiments using NU0 and NU1 provide one specific result each since these runs are unable to distinguish between different analysed precipitation intensity during the 6 hour simulation. NU0 gives no precipitation and stays almost cloud free in this case with no explicit forcing while the run NU1 gives an average intensity of 42 $\mathrm{mm} \cdot \mathrm{day}^{-1}$.

The results mentioned above apply to the assimilation phase. The impact of precipitation nudging where fairly large precipitation amounts are involved is most adequately studied in 3-D simulations. If the horizontal and vertical distribution of heating due to the assimilation of precipitation intensities gives rise to a more realistic wind field there is a chance that the impact of precipitation nudging on several model parameters will last for several hours. For example, if a low pressure system is significantly affected, there is likely to be impact on weather parameters at forecast ranges comparable to the life cycle of the low pressure system involved. On the other hand, if the modified precipitation is not well supported by the 3-D structures of the temperature, humidity and wind field, the impact of assimilating precipitation intensity may be of much shorter duration.

Table 1:
Average cloud cover RMS for levels below 200 hPa during a 6 hour simulation for an initially stably stratified atmosphere with a model state of 80 percent relative humidity below 7500 m, assuming an analysed cloud cover of 100 percent between 500 m and 7500 m and analysed precipitation intensity ('prcana') equal to 20 mm/day, 60 mm/day and 100 mm/day, respectively. Appropriate dynamical advections are imposed for specific humidity and cloud condensate (see text). The assimilation results are shown for model versions NU0, NU1 and NU3.

version/prcana	20 mm/day	60 mm/day	100 mm/day
NU0	69.8 %	41.3 %	29.8 %
NU1	9.2 %	6.8 %	5.3 %
NU3	9.8 %	4.1 %	4.3 %

Table 2:
Mean model precipitation intensity (mm/day) during a 6 hour period for an initially stably stratified atmosphere with a 80 percent relative humidity below 7500 m, but assuming analysed cloud cover of 100 percent between 500 m and 7500 m and an analysed precipitation intensity equal to 20 mm/day, 60 mm/day and 100 mm/day, respectively Appropriate dynamical advections are imposed for specific humidity and cloud condensate (see text). The results are shown for model versions NU0, NU1 and NU3.

version/prcana	20 mm/day	60 mm/day	100 mm/day
NU0	6.3 -	32.4 -	61.2 -
NU1	47.6 -	61.6 -	81.8 -
NU3	30.6 -	62.2 -	99.0 -

3.5.2. Convective clouds

The situation becomes more complex when considering nudging of cloud and precipitation information in an atmosphere where deep convection can occur. This is because of the fact that a forcing influencing cloud and precipitation generation may occur far away from the point considered at a given elevation. For example, surface evaporation and/or moisture convergence in the vertical air column may lead to a redistribution of heat and moisture throughout the depth of the convectively unstable layer. The actual processes described in the model depend on the design of the parameterization of deep convection and the related microphysics associated with precipitation release. One may expect that nudging in these situations is more difficult due to the deep layers involved and the non-local forcing.

We illustrate the impact of the cloud and precipitation nudging for rather weak specified forcing due to fixed surface latent heat fluxes equivalent of evaporation rates of 5 $mm \cdot day^{-1}$, 10 $mm \cdot day^{-1}$ and 20 $mm \cdot day^{-1}$, respectively. The surface sensible heat flux is specified to be one third of the latent heat flux which is an acceptable choice for mid-latitude sea surfaces (value not crucial for the conclusions). The surface evaporation is the only moisture source in these cases. An unstable lapse rate of $8 \cdot 10^{-3}$ $K \cdot m^{-1}$ is present initially from the surface to a height of 7500 m. The relative humidity is 50 percent. The surface temperature is 7 °C as in previous experiments. The atmosphere is isothermal above 7500 m with a relative humidity of 20 percent. Also the assumption for geostophic wind is unchanged.

The results of the nudging experiment NU3 are investigated. A 6 hour nudging period is studied followed by a continued forecast phase of 6 hours (12 h forecast length). This is compared with a forecast without nudging (NU0).

The nudging experiments need a choice for 'analysed' cloud cover and surface precipitation rate. For simplicity the analysed cloud cover is assumed to have a constant value (20, 40 or 60 percent) at all levels between 500 m and 7500 m. This cloud amount has to build up from zero in the initially rather dry, unstable atmosphere. The 'analysed' precipitation rates are chosen to be equal to the source term from the surface. This amounts to a potential steady state precipitation rate.

The result of a cloud cover root mean square error computation (RMS) averaged over 10 min. before the hour is shown in tables 3a-c. The RMS is computed as explained in the previous subsection. The values in brackets apply to experiments NU0 without nudging. The corresponding results for average precipitation rates (0- 6h) and 6h-12h are presented in table 4. The numbers in brackets apply to the NU0 experiment. A negative number means that forecast produces less precipitation compared to the 'analysed' value.

The main message from the tables 3 a-c and table 4 is that the nudging scheme adapts quite well to the imposed analysed cloud cover in the assimilation period, but the error growth becomes fairly large in the forecast phase. The results indicate just a small skill compared to the NU0 eperiment at a forecast range of 6 hours (12h in the table). This is consistent with the claim that convective clouds are difficult to control.

Precipitation rate (table 4) is handled rather well also in this situation. The precipitation rates of NU3 are in fair agreement with the 'analysed' values. The mean intensity is slightly higher during assimilation than during forecast, presumably due to the considerable rearrangement needed in the atmosphere during the assimilation period. The precipitation development without additional source terms takes more time since the surface evaporation source is to penetrate the deep, rather dry unstable layer in the atmosphere, before a significant precipitation release is realized. A considerable moistening of the atmosphere takes place first.

The results presented are considered to be fairly typical for weak atmospheric forcing in convective conditions. Qualitatively similar results are obtained if the surface moisture flux is replaced by corresponding atmospheric advections in the low troposphere.

Table 3a:
Average cloud cover rms for levels below 200 hPa during 6 hour and 12 hour simulations for a deep unstable atmosphere with a relative humidity initially at 50 percent below 7500 m subject to a forcing coming from surface latent heat flux=145 W/m2 and a sensible heat flux of 48 W/m2. Numbers in brackets apply to experiment NU0 while other numbers are results for NU3 (see text)

forecast length/cldana	20 %	40 %	60 %
6h	8 (15) %	5 (32)%	11 (48)%
12h	31 (18) %	23 (27) %	24 (41) %

Table 3b:
Average cloud cover rms for levels below 200 hPa during 6 hour and 12 hour simulations for a deep unstable atmosphere with a relative humidity initially at 50 percent below 7500 m subject to a forcing coming from a surface latent heat flux=290 W/m2 and a sensible heat flux of 96 W/m2. Numbers in brackets apply to experiment NU0 while other numbers are results for NU3 (see text)

forecast length/cldana	20 %	40 %	60 %
6h	7 (22) %	10 (28) %	18 (40) %
12h	19 (28) %	27 (27) %	30 (35) %

Table 3c:
Average cloud cover rms for levels below 200 hPa during 6 hour and 12 hour simulations for a deep unstable atmosphere with a relative humidity initially at 50 percent below 7500 m suject to a forcing coming from surface latent heat flux=580 W/m2 and a sensible heat flux of 193 W/m2. Numbers in brackets apply to experiment NU0 while other numbers are results for NU3 (see text)

forecast length/cldana	20 %	40 %	60 %
6h	9 (27) %	11 (26) %	16 (34) %
12h	17 (29) %	21 (29) %	31 (37) %

Table 4:
Difference between average precipitation rate (mm/day) and analysed precipitation rate corresponding to experiments with data presented in tables 3 a-c. Average is taken from 0 - 6h and from 6 h to 12 h respectively. Numbers in brackets apply to experiment NU0 while other numbers are results for NU3 with 'cldana'=40 % (see text).

fc-length/prcana	5 mm/day	10 mm/day	20 mm/day
6h	+2.8 (-4.9)	+2.6 (-9.0)	+3.9 (-12.3)
12h	-1.1 (-4.5)	-3.0 (-6.6)	-3.5 (-7.8)

4. 3-D testcases

It is important to test the nudging scheme in real 3-D cases. The experience is so far limited to case studies. The results from the 1-D tests that model cloud cover and precipitation adjust well towards analyses in the assimilation phase is confirmed by prelimiary 3-D tests. This appears to be the case for weather conditions dominated by stratiform type of clouds as well as for convective conditions. The impact of the assimilated analyses is likely to be significantly case dependent. In the section below the presentation is limited to one specific case dominated by stratiform type of clouds. The DMI-HIRLAM system (Sass et al., 2000) is used in the 3-D model run. The cloud scheme used in this experiment does not include the extensions (Sass, 2002) mentioned above in the context of the 1-D model. The results, however, still indicate a good skill of the assimilation method. The model integration area used is shown in figure 18. The number of vertical model levels is 31, and the horizontal resolution is 0.15 °.

4.1. Anticyclonic case

The case studied is from 13 December 2001. On this day the operational DMI-HIRLAM did not forecast cloud cover well over Denmark. The observed clouds are mainly of the stratiform type which might provide favorable conditions for the nudging scheme.

The assimilation starts at 00 UTC 13 December and continues for 6 hours until 06 UTC using hourly analyses (Sass and Petersen, 2002) of cloud and precipitation information. The start condition of the forecast is the model state after 6 hours of assimilation. The results of total cloud cover for the experiments are shown in figure 19. The lables 'NUD' and 'REF' refer respectively to experiments with nuding and without. The forecast length (+006, +009 and +012) are specified relative to the intial time of the assimilation. The corresponding synoptic weather charts with surface reports of wind, weather and cloud information valid at 06 UTC, 09 UTC and 12 UTC are shown in figures 20, 21 and 22, respectively.

The synoptic situation on 13 December 2001 is dominated by high surface pressure in Northern Europe, with several high pressure peak values of more than 1040 hPa, north of Scotland, over Southern Norway and in the Baltic states, respectively.

Towards the south of the large high pressure area, that is, in the southern parts of the Baltic sea, Scandinavia and the North Sea, soundings have been measured with a structure of the low troposphere typical of stratocumulus. This means that a low relative humidity has been measured in a stable layer on top of a cloudy layer approximately between 900 and 850 hPa. It indicates that subsidence has been active.

The dominating air flow is mainly from the east and northeat and increases considerable with height. The wind speed reaches a magnitude between 20 $\mathrm{m \cdot s^{-1}}$ and 35 $\mathrm{m \cdot s^{-1}}$ between levels of approximately 800 hPa and 500 hPa. This implies a potential for strong advective effects across the area during the studied 12 hour period. In the same pressure interval some soundings show one or several layers with very high relative humidity indicating the presence of more cloud layers over parts of the region. Such feature is not uncommon in the atmosphere, but it makes the prediction of total cloud cover more complicated.

Both the synoptic cloud reports and satellite pictures available for this day confirm that the cloud picture on this day is complex. Over the Baltic Sea and parts of southern and central Sweden there are elongated cloud bands separated by cloud free areas. These structures revealed on satellite pictures are not as clearly seen from the synoptic reports on figures 20, 21 and 22. If we compare the cloud information in these figures with the forecasted total cloudiness from figure 19 it may be concluded that the cloudiness forecast using nudging (left panel) is more realistic than the results obtained without nudging (right panel). Improved cloud cover using nudging can be identied over Lithuenia and parts of Polen where the cloud cover has been correctly reduced. Furthermore, substantial improvements seem to be achieved over the areas of southern Norway, Skagerrak, Jutland and in the North Sea, including the coastal regions of the Netherlands. At a forecast range of 6 hours (12 UTC on 13 December) the improvements are substantial in the United Kingdom (downstream) where a cloud cover increase has been correctly forecasted. It turns out that cloud cover improvements are still seen at a 12 hour forecast (not shown), mainly in the western part of the model domain, e.g. over the Norwegian Sea. An objective verification of cloud cover confirms these findings. The mean absolute error of the model's total cloud cover fit to the available observations in the model area is improved throughout a 12 hour forecast. The mean absolute error improvement due to nudging, shows a large value of 21 % at the start of the forecast, declining to about 7 % at 3 hours, 4 % at 6 hours and 3 % at 12 hours. A negative bias in the model predicted cloud cover has also been reduced by about 3 % in the run using nudging.

There is one rather small area around the Island of Zealand in Denmark where clouds have dissipated in the run using nudging. This was not observed. The run without nudging did not tend to dissolve the clouds already in the 3 hour forecast (9 UTC). The critical issue here is believed to be the magnitude of the subsidence effect, giving rise to warming of cloud, in combination with the amount of cloud condensate in the cloud. Output of temperature tendencies from the model run confirms that a heating does occur at the relevant low tropospheric cloud level. The subsidence in the model seems to be responsible for the significant cloud clearing over parts of the Baltic Sea and southern Sweden between 6 UTC and 9 UTC. The model run using nudging (NUD) did not produce completely overcast conditions over Zealand as opposed to REF. This implies a reduced amount of cloud condensate in NUD which makes clouds more vulnerable to dissipation. It may be noted that the cloud dissipation in the model between 6 UTC and 9 UTC in an area to the east of Gothenburg on the west coast of Sweden can also be attributed to subsidence. Observations nearby report fog while the wind is very week. This is an indication that the clouds are confined to a very shallow layer close to the ground, with a fairly cloud free atmosphere above. Such conclusion is consistent with a satellite picture which indicates few clouds approximately in the same area. The importance of subsidence for low level cloud dissipation has been stressed in some studies (Weaver and Pearson, 1990; Sass, 2001). The present study indicates that the amount of condensate in the clouds may also be of critical importance in some situations.

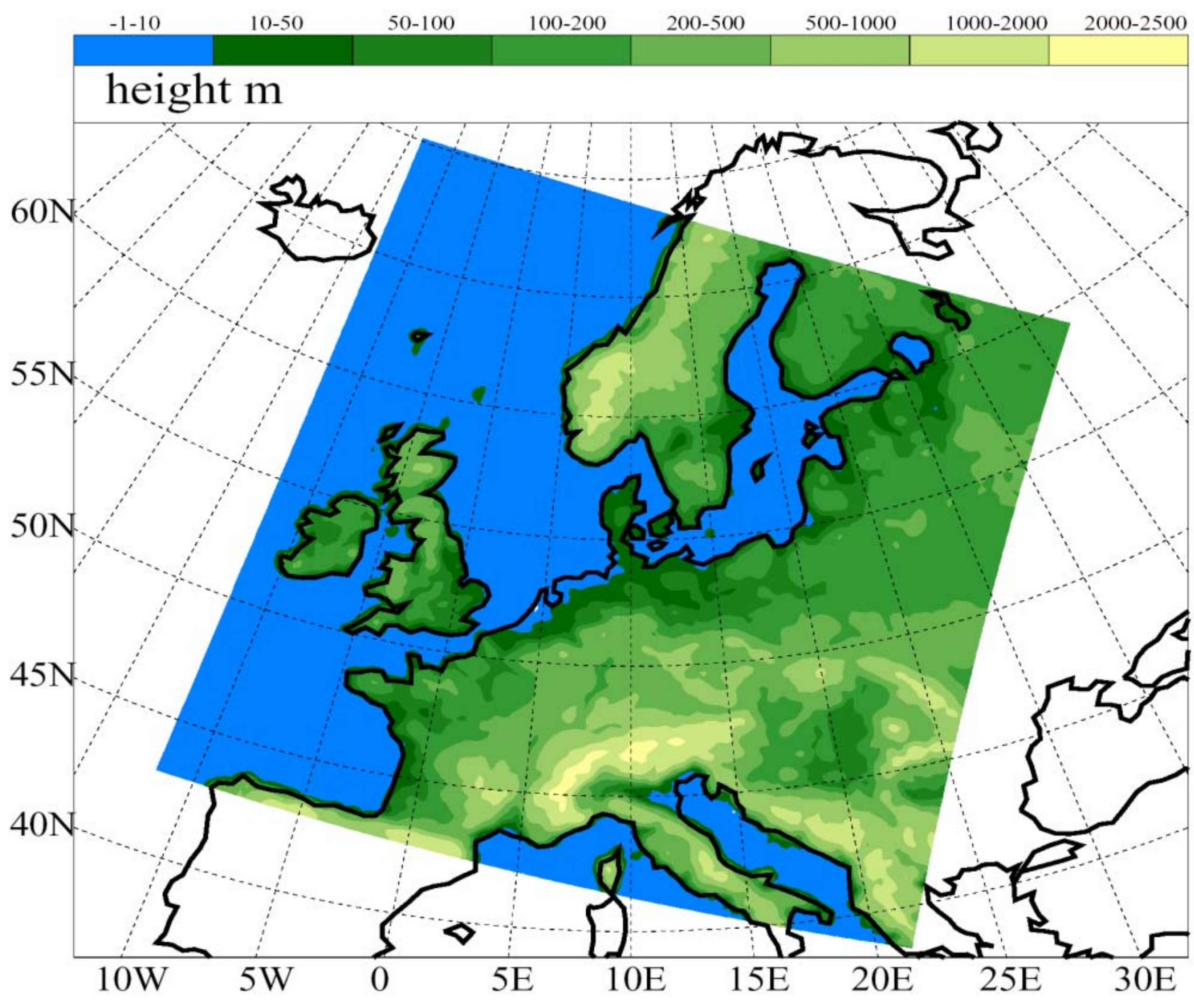


Figure 18: Model integration area for 3-D experiments (see text)

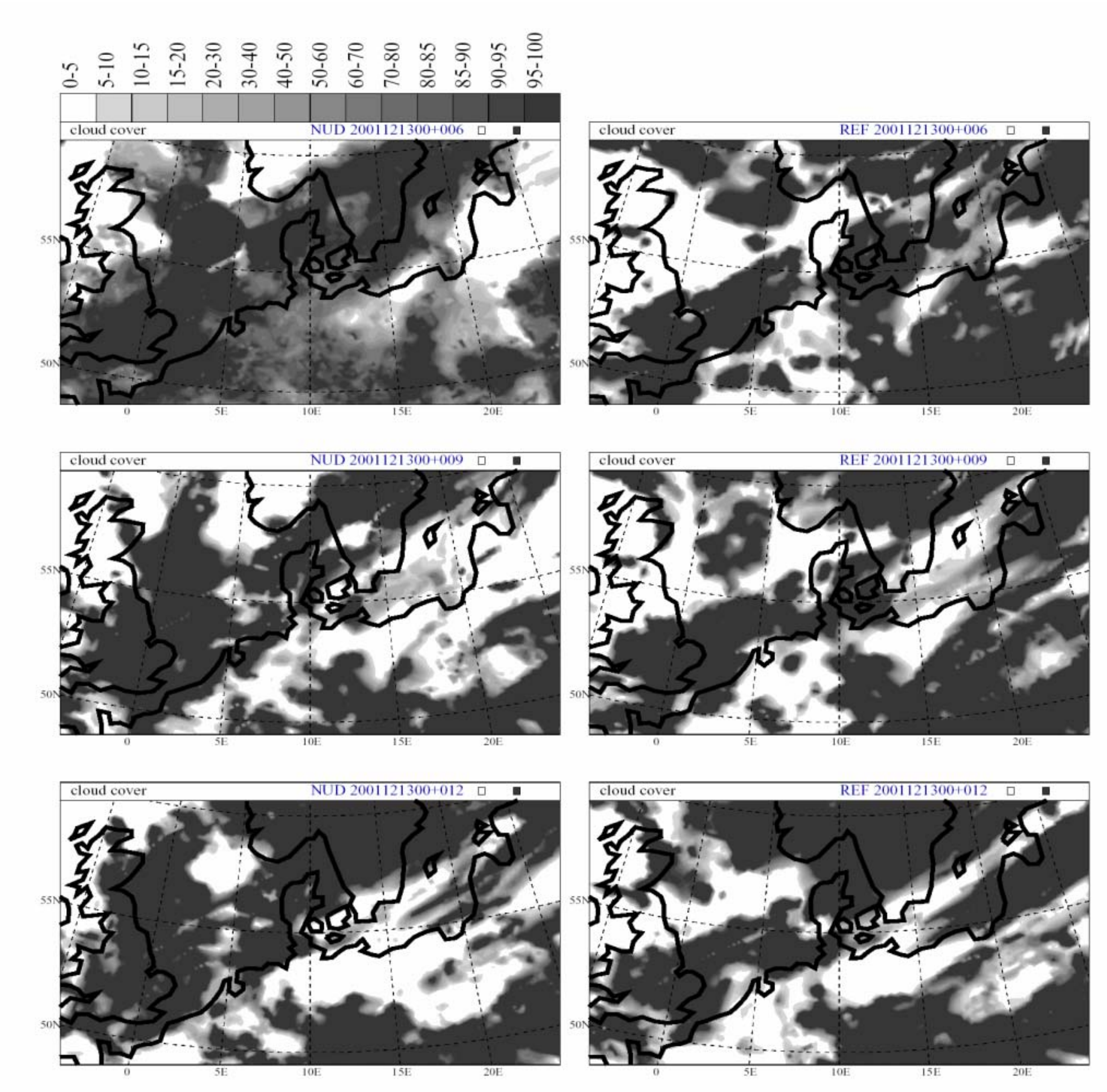
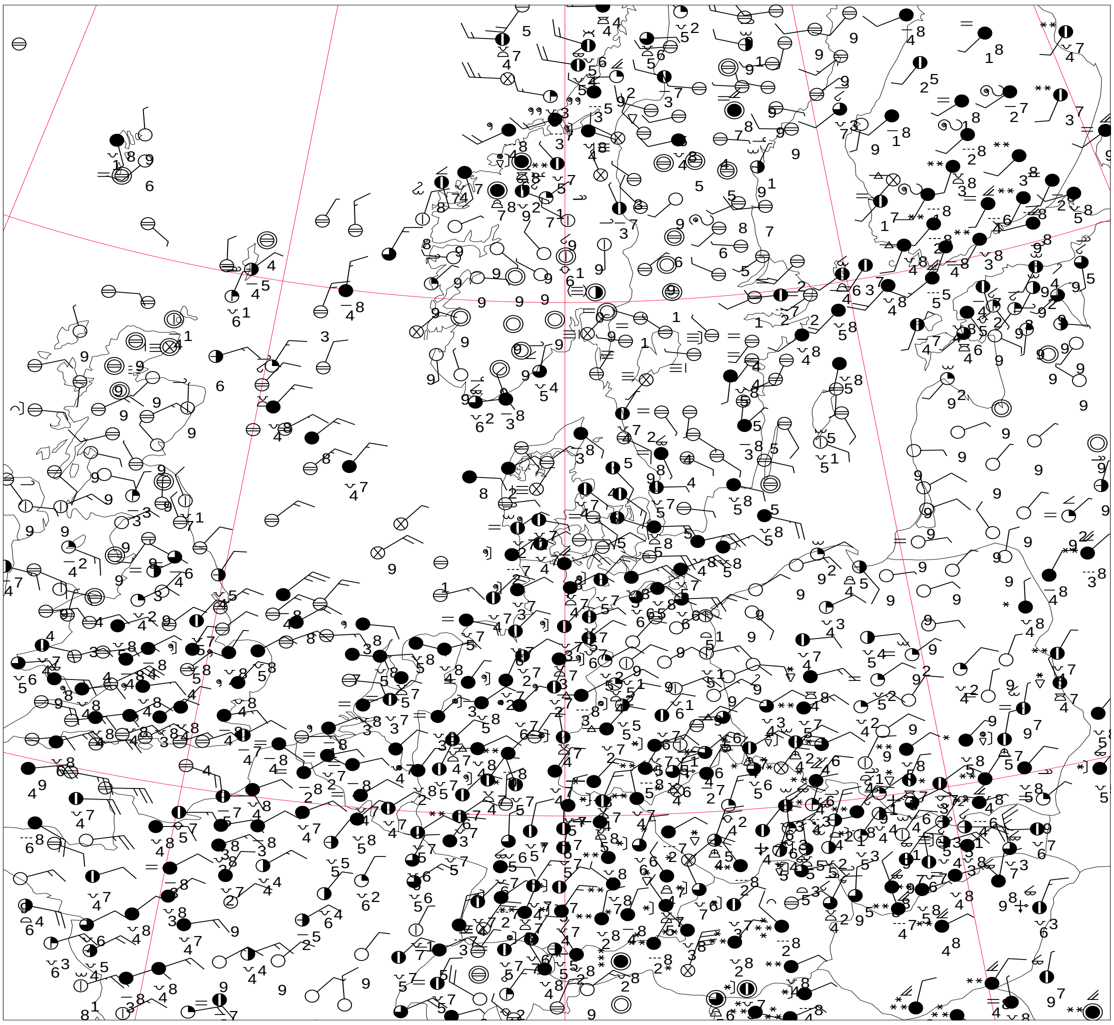
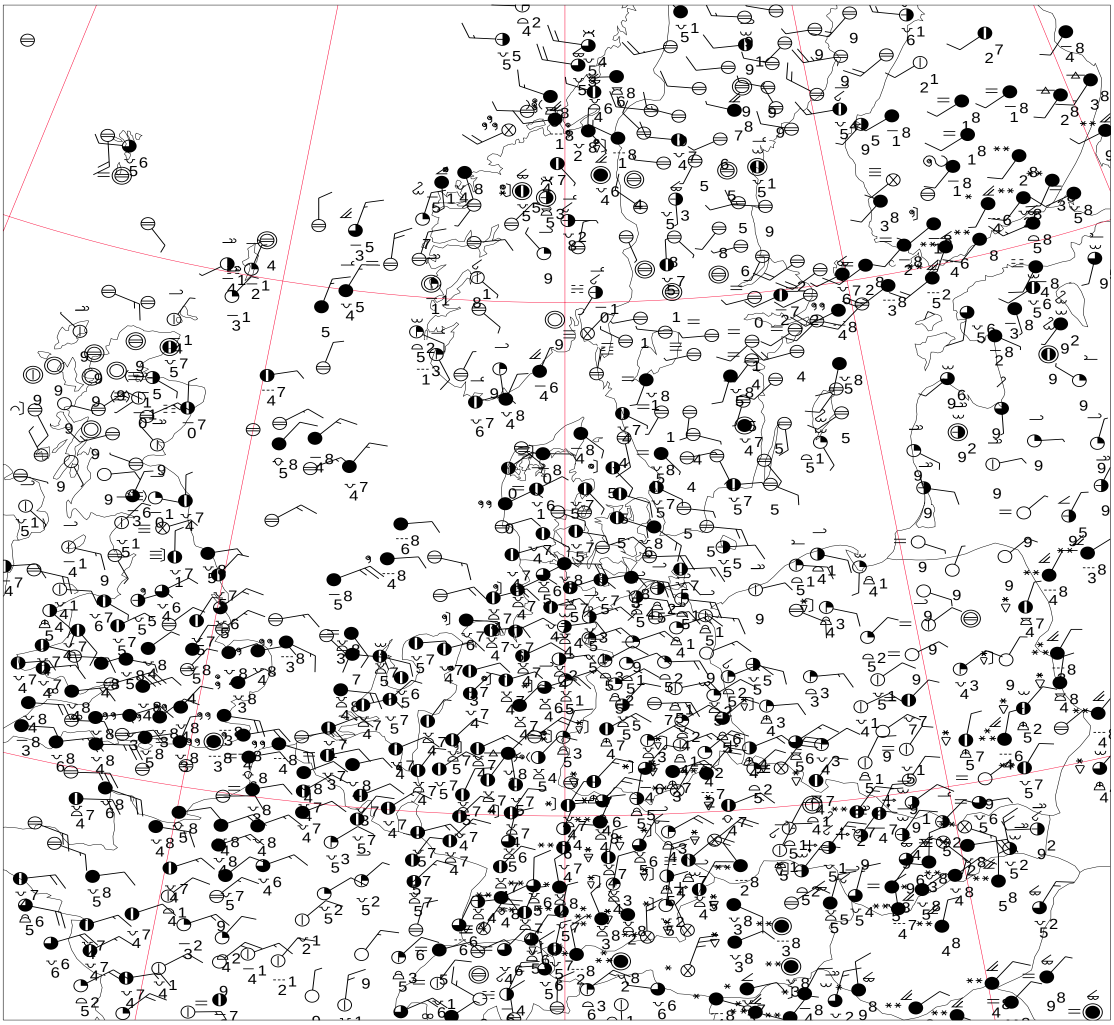


Figure 19: Total cloud cover for 3-D case on 13 December 2001 using nudging (NUD) and without nudging (REF). The +006 applies to the end of the nudging period while +009 and +012 correspond to 3 and 6 hours effective forecasts (see text)



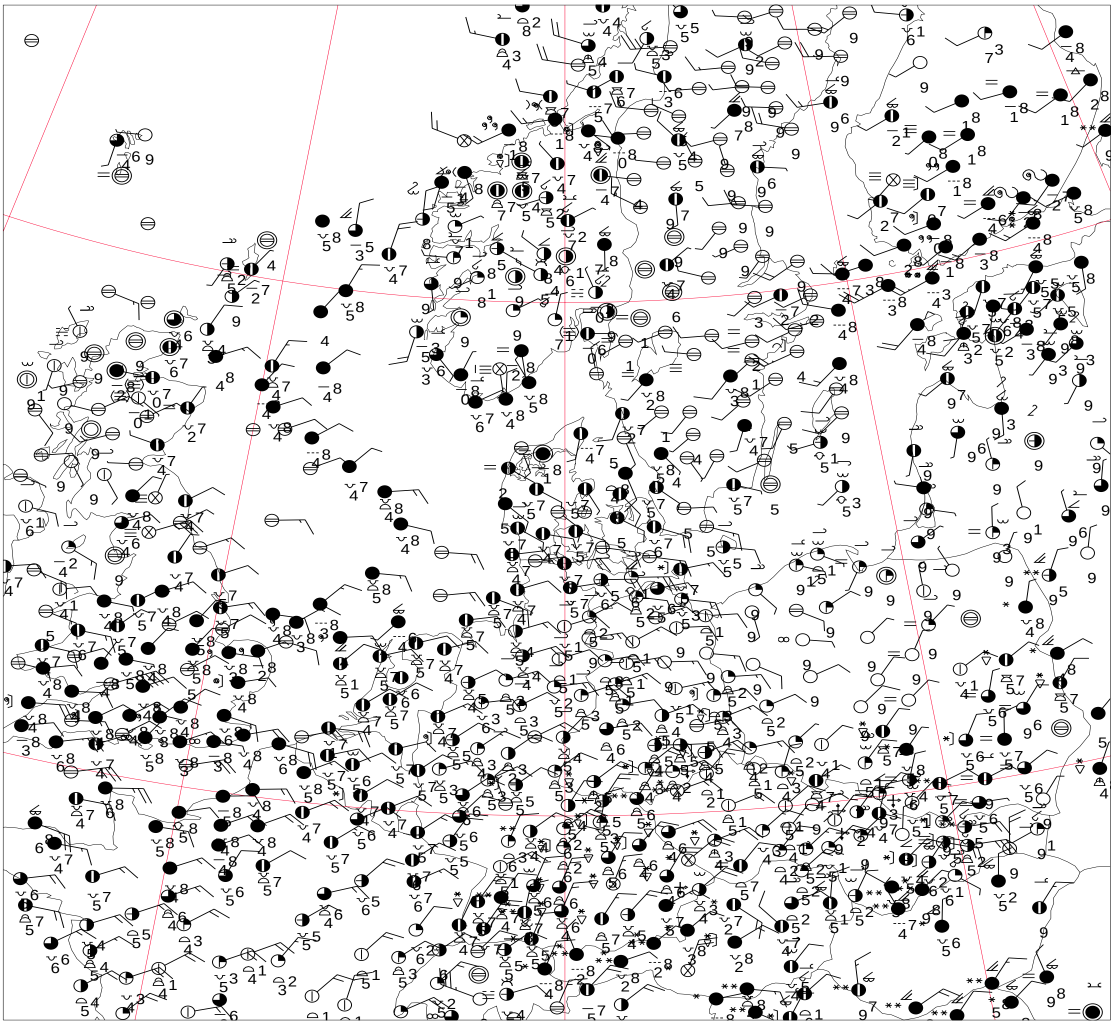
13. December 2001, 06:00 UTC
Wind, Weather, Clouds, Cloud cover

Figure 20:



13. December 2001, 09:00 UTC
Wind, Weather, Clouds, Cloud cover

Figure 21:



13. December 2001, 12:00 UTC
Wind, Weather, Clouds, Cloud cover

Figure 22:

5. Discussion and conclusions

A scheme has been developed for assimilating cloud- and precipitation data into a short range numerical weather prediction model. This information appears to be of great value since the focus of short range weather prediction is on predicting local weather parameters accurately, e.g precipitation, cloud cover and temperature. The assimilation is thought to act on top of an already existing analysis procedure for other parameters, e.g. based on variational data assimilation. In operational practice the assimilation phase may start from such pre-existing analysis. A complete restart from an existing analysis might be avoided by extending the data-assimilation to involve nudging towards pre-existing wind analyses along with the present cloud and precipitation nudging.

The scheme is general in the sense that it does not depend explicitly on any particular cloud scheme. This is apparent from the fact that the tendency modifications of the dependent model variables automatically switch off as the model approaches the analysed cloud and precipitation fields. How to actually produce these analyses has not been discussed in the present report. This task is far from trivial and involves issues of quality control of data and how to combine different data sources with a model first guess field (Sass and Petersen, 2002).

The reasoning behind the choice of a 'nudging' type of approach is that it is very simple in basic concepts. Secondly, it allows for running the full non-linear forecast model forward while assimilating observations at proper times. On the contrary, other more complicated assimilations, e.g., the very advanced 4-D variational data assimilation methods have problems to include the full model physics. It is questionable whether substantial simplifications in the model's cloud scheme should be used when attempting to make accurate prediction of local clouds and precipitation.

It is emphasized that a total moisture conservation over a limited volume of the atmosphere is in general not conserved by the scheme. The assimilated moisture data act as efficient source or sink terms not compensated for in the surroundings. For the scheme to be successful it needs to modify the atmosphere such that the time scale of adjustment is shorter than the time scales to be forecasted. In short range weather prediction this means that significant adjustments must be possible within one hour. In section 3 it has been shown that this is possible with the present scheme provided that a sufficiently short time scale is chosen for the nudging coefficients. However, it may be questioned whether the scheme can properly assimilate convective phenomena with a time scale of less than one hour. Some of the details of the nudging scheme may need to be revisited when further developing the scheme.

It should be noted that specific problems emerge when data-assimilation for increasingly high resolution is considered. For example, the precipitation rate measured at the ground has been generated further upstream. Considering the time it may take precipitation to reach the ground and taking into account typical advection speeds it may be concluded that some of the heating associated with the condensation processes should sometimes be released several tens of kilometres upstream. For high resolution models with grid sizes of 10 km or less this means that surface precipitation rate cannot be completely translated into latent heat release in the grid column above the place. Such principle which is often used in 'latent heat nudging' schemes breaks down at high model resolution. This local heating assumption is not applied in the present nudging scheme that can locally generate cloud water which is not giving rise to heating. The details connected to these issues need further studies and elaboration when developing a nudging scheme specifically for high resolution.

From the 1-dimensional experiments it has been shown in the present report that the nudging scheme can dissipate or build up cloud layers in the assimilation period. The fit to an imposed cloud cover analysis is usually very good and the structure of stratocumulus type of clouds appears to be realistic. These cloud cover modifications may sometimes last for 18 hours or more into the forecast phase provided that the dynamical forcing is small. However, if very thin cloud layers are to be assimilated at a specific height it has been detected that the data assimilation can be somewhat problematic. This feature is linked to the vertical transport processes of heat and moisture which inherently tends to move the cloud vertically or dissipate the cloud. More 'robust' clouds are achieved if it is demanded that a minimum cloud depth is used in the cloud analysis procedure.

Cloud cover changes associated with high clouds are treated in a similar way, but the life time of the adjustments appear to be somewhat smaller. This is probably related to the smaller amounts of moisture involved in cloud generation and dissipation. Moreover, the moisture source from the model's deep convection reaching high levels may also lead to the formation of high clouds. This means that high clouds are often difficult to predict and implies further that total cloud cover becomes a difficult parameter to predict when high clouds are involved. When the vertically integrated liquid water path associated with high clouds is small the practical consequences of the clouds become small for many applications. It is therefore relevant to investigate low, medium and high clouds separately when evaluating the modified skill coming from assimilating new data.

The full nudging scheme including the precipitation nudging terms is believed to be advantageous to use in most cases. The nudging scheme appears to better reproduce high precipitation amounts during the data-assimilation. Since a larger latent heating is involved in such cases there is reason to believe that the wind field is affected to some extent, provided that pressure gradients are modified as a result of horizontally varying heating rate. The modified winds will likely be connected to more significant forecast changes that last for many hours.

Experimentation with different versions of the cloud scheme indicates that the precipitation and latent heating in the assimilation phase, when building up saturation over a large fraction of the troposphere, is sensitive to the actual cloud scheme used. Such sensitivity is likely to be pronounced if the parameterization of fractional cloud cover is significantly depending on the amount of cloud condensate as a forecast parameter.

The 3-D cases studied have highlighted the complex situation associated with real forecast situations. If the 3-dimensional structures of the wind, temperature and humidity over a larger area are inconsistent with locally enforced modifications during the assimilation, the effect of the nudging will sometimes be of short duration. A positive impact on cloud cover has been demonstrated for a case on 13 december 2001, out to a forecast range of 12 hours. Continuous 3-D tests including objective verification should be carried out in the future to further diagnose benefits and problems associated with the scheme.

The treatment of convection appears to be particularly difficult to manage in a satisfactory way. It is known that currently used convection schemes have some basic problems to describe the cloud and precipitation processes at very high model resolution. Experience from the present study indicates that further accuracy in the prediction of local cloud parameters requires that efforts are spent on improving both the data assimilation procedure (including cloud and precipitation analysis) and the forecast model. Obviously the model physics behind precipitation generation needs attention. When approaching the resolution of cloud resolving models one can expect that the model's convection scheme can be replaced by explicitly resolved cloud physics.

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