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Questions involving the use of traditional convection parameterization in NWP models with a higher resolution

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ABSTRACT

Traditional schemes for parameterization of convection have mainly been developed and tested for models with horizontal resolution of the order of 100 km. Experiments are undertaken to test the behaviour of a traditional parameterization scheme for convection, designed for a coarse resolution, in a numerical weather prediction model when the model resolution is increased. It is shown that a more detailed forecast of convective precipitation and cloudiness is possible with the finer resolution and that the reason for this is a better simulation of the mesoscale circulation and therefore areas with convergence of moisture, necessary for moist convection to take place. The convergence of moisture is included in the closure assumption for the parameterization scheme and the importance of the formulation of the closure is therefore studied.

1. Introduction

Numerical weather forecast models of today are often used with a resolution of 10–20 km or even less. Therefore they give possibilities to resolve and explicitly model several mesoscale circulation systems. This implies that processes that used to be subgrid-scale and had to be parameterized now partly are explicitly treated by the model dynamics (Bougeault and Geleyn; 1989, Molinari and Dudek, 1992). Specific problems connected to the parameterization of convection in such models have been pointed out by Arakawa and Chen (1987) and Molinari (1993). The question to be dealt with in this paper concerns the application of traditional schemes for parameterization of convection when the model resolution is increased.

Parameterization of convection in numerical weather prediction models are usually based on one of three main ideas: (i) adiabatic adjustment, used by Manabe, Smagorinsky and Stickler (1965) and more recently by Betts (1986); (ii) penetrative convection (Kuo, 1965, 1974); (iii) convective mass flux, suggested by Ooyama (1971), further developed by Arakawa and Shubert (1974) and more recently applied by Tiedke (1989).

The variations in the applications of these basic ideas are several. However, they all postulate a grid size large enough to cover an area including a statistical ensemble of convective clouds in different stages of their life cycle. This is a necessary assumption since the parameterization schemes can not predict the life cycle of the convective cells and therefore not the presence of small cumulus clouds, mature precipitating cells or old, dissipating clouds. The assumption has to be that all these stages are present whenever the conditions for convection are fulfilled. The properties of the ensemble (level of cloud top and base, intensity of precipitation etc.) are functions of the large scale conditions and may differ from one grid point to the next. The assumption also ensures that, in an area represented by a grid point with convectively unstable stratification, there are convective elements transporting heat, moisture and other properties to all levels in the unstable layer. This is the case if lateral entrainment/detrainment is assumed as well as if cloud top entrainment/detrainment is assumed. It also ensures that there are mature convective cells which give precipitation in all grid points with active convection.

The horizontal scale of convection is such that a statistical population of clouds can exist in the area represented by a grid point in a model with 50–100 km grid distance. But such a population can not be expected to be present within an area represented by a grid point if the model resolution is 20 km. In a grid square of this order only a few convective cells, or just one large, precipitating cumulonimbus cloud, can be expected. The parameterization schemes postulate a statistical ensemble of convective clouds in every grid point regardless of the model resolution. This basic assumption is not realistic when the resolution is 10 or 20 km, a fact that is normally not considered when the resolution is increased. Is it then possible that such a forecast model still is able to give an acceptable forecast of convection and its interaction with the larger, resolvable scales?

At the Swedish Meteorological and Hydrological Institute, SMHI, it has been noticed that when running the HIgh Resolution Limited Area Model, HIRLAM, with 0.2° ($\approx$22 km) grid resolution (Andersson and Gustafsson, 1994), the forecast of accumulated convective precipitation compares better with observations than does a forecast with 0.5° ($\approx$55 km) resolution. The model includes one of the traditional approaches to parameterization, a modified Kuo scheme (Sundqvist et al., 1989). From the discussion above we did not expect the forecast of convection to give any large improvements in the prediction of convection when the resolution was increased. The forecast will assume a statistical ensemble of clouds in different stages in all points and this can not be the case in reality. However, a model with a finer grid resolves details in the dynamics, with a scale smaller than the synoptic scale, which will be smoothed with a coarse grid. These details are parts of the "large scale" input to the parameterization scheme and may thus influence the characteristics of the assumed statistical ensembles of convective clouds in the different grid points. A more detailed pattern of the convective activity is therefore possible in the forecast, without any modifications of the parameterization scheme, since the characteristics of convection may be different in points next to each other. But the effects of convection in every grid point is still that of a statistical ensemble.

The scale of the resolved dynamics is, in the case of a 20 km grid, of the order of 100 km, the meso-β scale, and therefore far from the scale of the convective cells. Problems may arise when the resolution is such that physical processes, which used to be parameterized, are not fully subgrid scale but partly explicitly treated. This problem was discussed by Arakawa and Chen (1987) who argued that there has to be a well defined gap in the spectral domain separating the resolvable scales from the cloud scales. If this is not the case there will be a risk that effects from processes that are handled explicitly will be included twice in the forecast if they are also parameterized. However, convection has to be parameterized not only because it is subgrid scale but also because it is a non-hydrostatic process, which can not be adequately described by the dynamics of a hydrostatic model. Therefore, convection has to be parameterized also in a finer resolution. In the case of 20 km grid, the hydrostatic part of convectively driven mesoscale systems may be explicitly treated by the model but the effects of the non-hydrostatic convective currents have to be parameterized. New parameterization schemes, applicable to different model resolutions, have been suggested (Molinari, 1993) but they will not be discussed in the present paper.

The purpose of the present paper is to show that a finer grid, in a model including a traditional parameterization scheme for convection designed for coarse resolution models, may not only give an acceptable forecast of convection but a more detailed forecast of convective cloudiness and precipitation. We will study the mechanisms which make this possible. An alternative way to interpret the assumption about a statistical ensemble will also be discussed. No resolution dependent modifications of the scheme is considered. A short description of the parameterization scheme for convection is given in Section 2. In Section 3 we will study the forecasts of convection with the two resolutions and in Section 4 we will go into more details to find the origin of the difference in the predicted convective activity. The results will lead to a discussion, in Section 5, of the importance of the formulation of the closure assumption of the parameterization scheme.

2. The convective scheme

The parameterization scheme is, as was mentioned above, a modified Kuo scheme which includes cloud water as a prognostic variable. This version of the Kuo scheme was suggested by Sundqvist and collaborators and is now a part of the complete Sundqvist parameterization scheme, which handles convective as well as stratiform condensation, clouds and precipitation (Hammarstrand, 1987; Sundqvist et al., 1989; Sundqvist, 1993). In the present paper, we will concentrate on the convective part of the scheme. The equations for the tendencies of temperature, specific moisture and cloud water are in case of convection:

$$\frac{\partial T}{\partial t} = A_{\mathrm{T}} + \xi(T_{\mathrm{c}} - t) - \frac{L}{c_{\mathrm{p}}}\xi m H, \quad (1)$$

$$\frac{\partial q}{\partial t} = \xi(q_{\mathrm{c}} - q)H + \xi m H, \quad (2)$$

$$\frac{\partial m}{\partial t} = A_{\mathrm{m}} + \frac{c_{\mathrm{p}}}{L}\xi(T_{\mathrm{c}} + T) - \xi m H - P, \quad (3)$$

$$L\tilde{A}_{\mathrm{q}} = \xi[c_{\mathrm{p}}\widetilde{(T_{\mathrm{c}} - T)} + \widetilde{(q_{\mathrm{c}} - q)H}]. \quad (4)$$

Here, $\sim$ denotes a vertical integral from cloud base to cloud top. Index $_{\mathrm{c}}$ refers to properties of the rising buoyant parcel. A_{T}, A_{q} and A_{m} are tendencies of temperature, specific moisture and cloud water from all processes other than convection. All other terms on the right hand side of (1), (2) and (3) are effects of convection. H, a function of the relative humidity, is used to determine the partitioning of moisture between heating and moistening of the environment. The rate of release of precipitation is described by the expression

$$P = c_0 m\left[1 - \exp\left(-\left(\frac{m}{bm_{\mathrm{r}}}\right)^2\right)\right], \quad (5)$$

where $1/c_0$ is a characteristic time for the conversion of cloud drops to raindrops and m_{r} is a threshold value for cloud water. The rate of precipitation at the earth surface is a function of P, integrated from the cloud top to the ground. The cloud cover, b, is parameterized by the relation

$$b = \xi\tau F_{\mathrm{cu}}, \quad (6)$$

where τ is a characteristic time scale for convection and F_{cu} is a function of cloud depth and relative humidity. The more detailed equations used by the model are given by Sundqvist et al. (1989) and Sundqvist (1993).

It is obvious from (1)–(3) that the intensity of convection is determined by the function ξ, which in turn, from eq. (4), is a function of the stratification and of the integrated moisture tendency, $\tilde{A}_{\mathrm{q}}$. If the stratification is stable or $\tilde{A}_{\mathrm{q}} \leqslant 0$ no convection will be possible. The energy available for heating and moistening by convection is equal to $L\tilde{A}_{\mathrm{q}}$. Any change of convective activity when the model resolution is changed should therefore be an effect of changes in these physical quantities. They are influenced by the dynamics of the model as well as of the surface fluxes of heat and moisture.

In the Sundqvist scheme all condensation and precipitation, that takes place when the above mentioned conditions (unstable stratification and positive integrated moisture tendency) are fulfilled, will be classified as convective activity. Stratiform condensation and precipitation is not considered as possible in any point at the same time as convection is predicted in the point. It is obvious from (6), that a convective cloud cover only exists when $\xi > 0$ and convection is active. If convection stops, the cloud water, m, produced by convection, will be evaporated in one timestep if the air in the point is unsaturated. If the air is saturated when convection ceases the clouds will be considered as stratiform and treated by the parameterzation scheme for stratiform clouds.

3. Experiments and results

Experiments have been undertaken to study forecasts of convection and the effects that determine its intensity and its variability in space and time. Several weather situations have been studied and a case study will be presented as an example.

The weather situation, 28 June 1993, with daytime convection over southern Sweden has been chosen. The convection is not homogeneously distributed over the land area, as can be seen from satellite pictures, but shows variations in space and time. Convection seems to be most active in the eastern part of the area but there is also a band of convection 60–70 km inland, parallel to the west cost, that may be an effect of sea breeze circulation. From an analysis of accumulated precipitation over the area (Fig. 1a) it can be seen that there is no accumulated precipitation connected to these clouds.

Experiments have been undertaken with the HIRLAM model, which includes Sundqvist parameterization scheme for stratiform and convective condensation and precipitation. Two different horizontal resolutions, 0.5° and 0.2°, have been used. In the following, the resolution 0.5° will be called the coarse resolution, CR, and the resolution 0.2° the fine resolution, FR. The vertical resolution, 16 levels, is the same in all experiments. The time step has been the same, 2 min, for the two resolutions to avoid possible effects of different time stepping when the results are compared. The model grid covers an area of 50×50 points for the coarse resolution and 110×100 for the fine resolution. Horizontal boundary values are interpolated from the ECMWF global forecasts for every 6 h. The area that will be more closely analysed in the present paper is a smaller area over southern Sweden close to the centre of the forecast area. The forecasts have been initiated at 00 UTC 28 June 1993 and run for 18 hours and the afternoon convection, mainly over land, has been studied.

3.1. Accumulated precipitation

12-h accumulated precipitation 06–18 UTC 28 June 1993 has been analysed from observations (Fig. 1a). Precipitation has been falling in the south-eastern part of Sweden and the maximum accumulated amounts, 5 mm, are found in the northern part of the precipitation area. A weaker maximum, 3 mm, is found in the southern part. From the model output of the 18 h accumulated convective precipitation it can be seen that the forecast with the coarse resolution, Fig. 1b, shows a maximum of more than 4 mm in one grid-point in south Sweden. Further north, west of Stockholm, there is another maximum with more than 2 mm. Between the two maxima there is a minimum with no precipitation at all. The corresponding forecast with the finer resolution, Fig. 1c, shows convective precipitation within approximately the same geographical area but with a more detailed structure. The northern maximum is here 3 mm and it is located south-west of Stockholm, close to the observed maximum. The maximum for the southernmost area is just above 4 mm. All accumulated precipitation in the two forecasts are of convective origin. Both forecasts give too much precipitation in the southern part of the area and too little in the northern part and both forecasts show a minimum in precipitation between the two maxima, which is not in agreement with observations. However, the forecast with the finer resolution is closer to the observations in amount as well as in location.

3.2. Cloud cover

Another parameter that is determined by the convection is the cloud cover. Two satellite pictures from the afternoon of 28 June 1993 are available, Fig. 2. They have been analysed for cloud top temperatures and they show that a broken cloud cover exists over southern Sweden. This broken cloud cover is interpreted as convective clouds. Cloud top temperatures down to -20°C can be observed but most cloud tops have temperatures in the vicinity of -10 to -15°C. The stratiform, mesoscale cloud area (marked by "1" in Fig. 2), off the Swedish east coast, has cloud top temperatures below -30°C.

The satellite pictures can be compared to the forecasts of convective cloud cover at different model levels. Fig. 2 shows the satellite pictures together with the forecasts for the same real times (i.e., 00 UTC $+13$ h 58 m and $+17$ h 10 m respectively) at model level 10 ($p\approx690$ hPa), where the temperatures are approximately -5°C. This level is not the level of the highest cloud tops but a level that the high convective clouds have to penetrate. The forecasts show convective cloud cover in percent. No stratiform clouds were predicted in the area this afternoon. Even if comparisons with snapshots like these may be coincidental, there are a few features that should be pointed out.

Convection over the sea is not well predicted in the present case and neither is the stratiform mesoscale cloud area (marked "1") off the Swedish east coast. We will not discuss the reasons for this in the present paper but concentrate on the daytime convection over land. The overall agreement between forecasts and observations is good and convection is predicted in a satisfactory way by both versions of the model. There is an inland cloud free area at 13 h 58 m, marked by "2" in the satellite picture, which seems to be well predicted by the FR forecast. The western boundary of this area is a band of clouds, marked by "3", parallel to the Swedish west coast. This band is partly

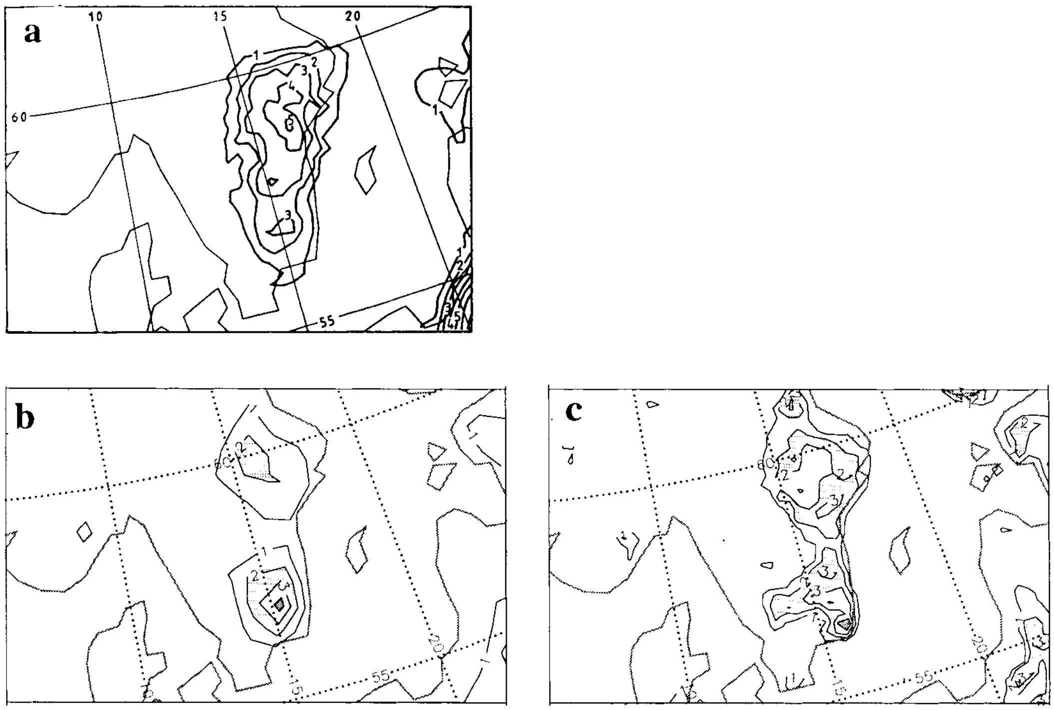

Fig. 1. Accumulated precipitation 28 June 1993. Isoline spacing is 1 mm. (a) Observed, 06–18 UTC. (b) Forecast, 00 UTC + 18 h, 0.5° resolution. (c) As (b) but 0.2° resolution. None of the forecasts had any precipitation in the period 00 UTC + 6 h.

captured by the FR but not by the CR forecast. A necessary condition for convection in a grid point is a positive integrated tendency of moisture in the point. The necessary convergence is in this perticular area provided by the rising branch of the sea breeze circulation, a mesoscale dynamic system, which thus seems to be simulated by the dynamics of the FR model. The stratification is unstable and the clouds are therefore classified as convective clouds. This is an example of details that are better captured by the finer resolution.

The main differences between the two forecasts are that there are more details in FR and that the gradient of cloud cover in FR is larger than in CR. The details of FR seem to be in a fairly good agreement with the satellite observations.

4. Discussion of the resulting features

4.1. The details of the forecasts

In an attempt to understand the differences between the two forecasts we have analysed a cross section transecting the precipitation area over southern Sweden (Fig. 2). The evolution with time of convective precipitation, cloud cover and other relevant parameters have been plotted for all grid points along the cross section. The cross section consists of five points for the coarse resolution and ten points for the fine resolution. (With the chosen resolutions there is no exact correspondence between all the points in the two grids but points 1, and 3 of CR are the same as points 1 and 6 of FR.) Fig. 3 shows the precipitation rates as a function of time for the grid points of the cross section. From the figure it can be seen that convective precipitation was initiated over the area after more than ten hours forecast and that the precipitation had the highest intensity in the eastern part of the cross section. In the fine resolution a partitioning of the precipitation in two periods in time can be seen. Figure 3 shows that a more detailed precipitation pattern is not only observed in the accumulated amount (Fig. 1), but also in the precipitation rate. The precipitation events in FR have a

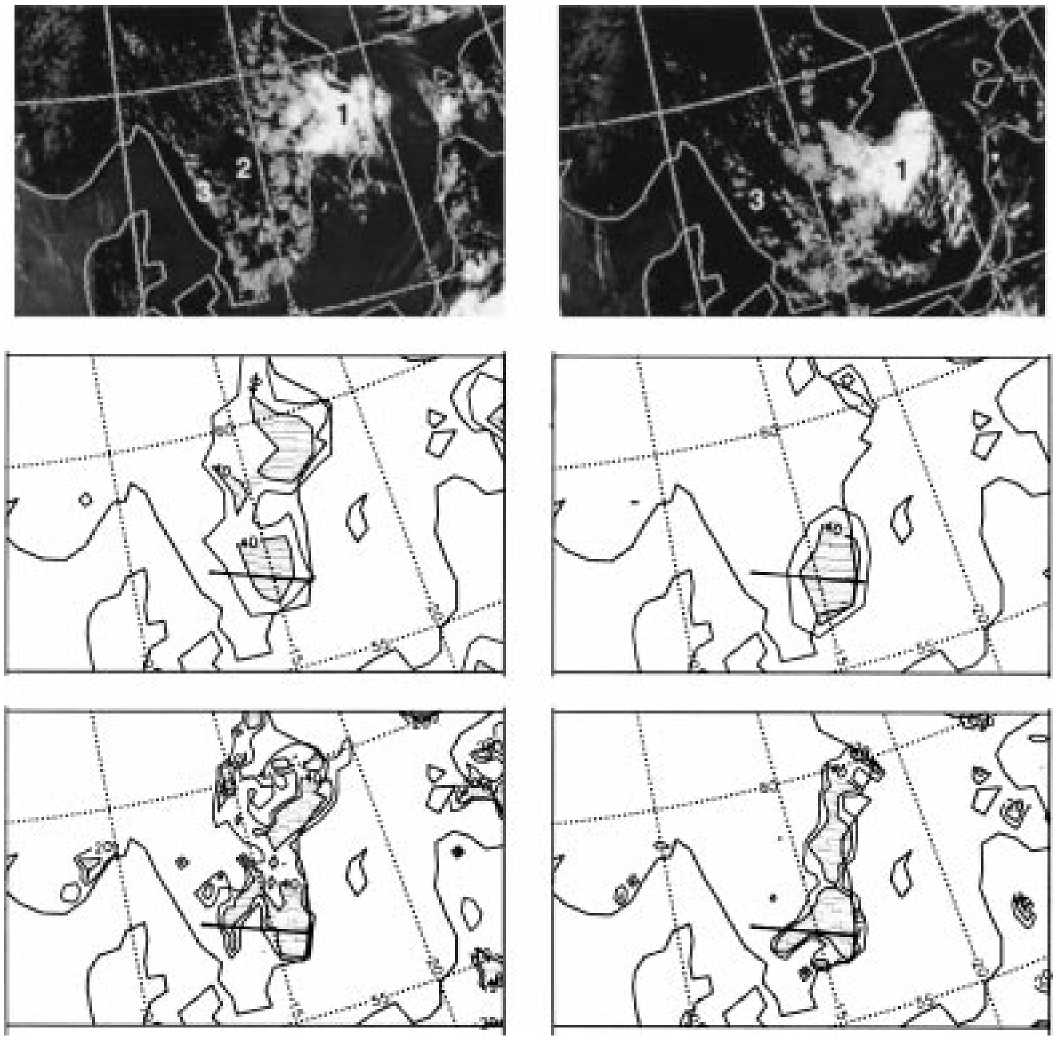

Fig. 2. Top panels: NOAA infrared satellite pictures over southern Sweden 13 h 58 m UTC (left) and 17 h 11 m UTC (right) 28 June 1993. Black areas are land and dark grey are sea surfaces. Light patches are clouds with high cloud tops and light grey areas are clouds with lower tops. (Pictures processed by K. G. Karlsson, SMHI.) The numbers, indicated in the pictures, are explained in the text. Middle panels: Forecast of convective cloud cover at model level 10, $p \approx 690$ hPa, for 00 UTC + 13 h 58 m (left) and 00 UTC + 17 h 10 m (right), 0.5° resolution. Isoline spacing is 20%. Bottom panels: As middle but 0.2° resolution. Indicated is also the cross section discussed later.

time scale of 200 min (100 time steps) and a space scale of 100 km (5 grid-distances).

The rate of release of precipitation, and thus the rate of precipitation, is strongly governed by the quantity ξ, which in turn is determined by the resolved scale flow. From (4) we get;

$$\xi = \frac{L\tilde{A}_q}{[c_p(\widetilde{T_c - T}) + L(\widetilde{q_c - q)H}]} = \frac{\tilde{A}_q}{\Delta E/L}, \qquad (7)$$

where ΔE is the sum of sensible and latent energy difference between the rising buoyant parcel and the environment in the vertical layer penetrated by the parcel, i.e., a measure of buoyancy. $\Delta E > 0$ when the atmosphere has an unstable stratification and convection is possible. The numerator gives the moisture convergence available for vertical redistribution as latent heat or moisture in the unstable vertical column. $L\tilde{A}_q$ is therefore the

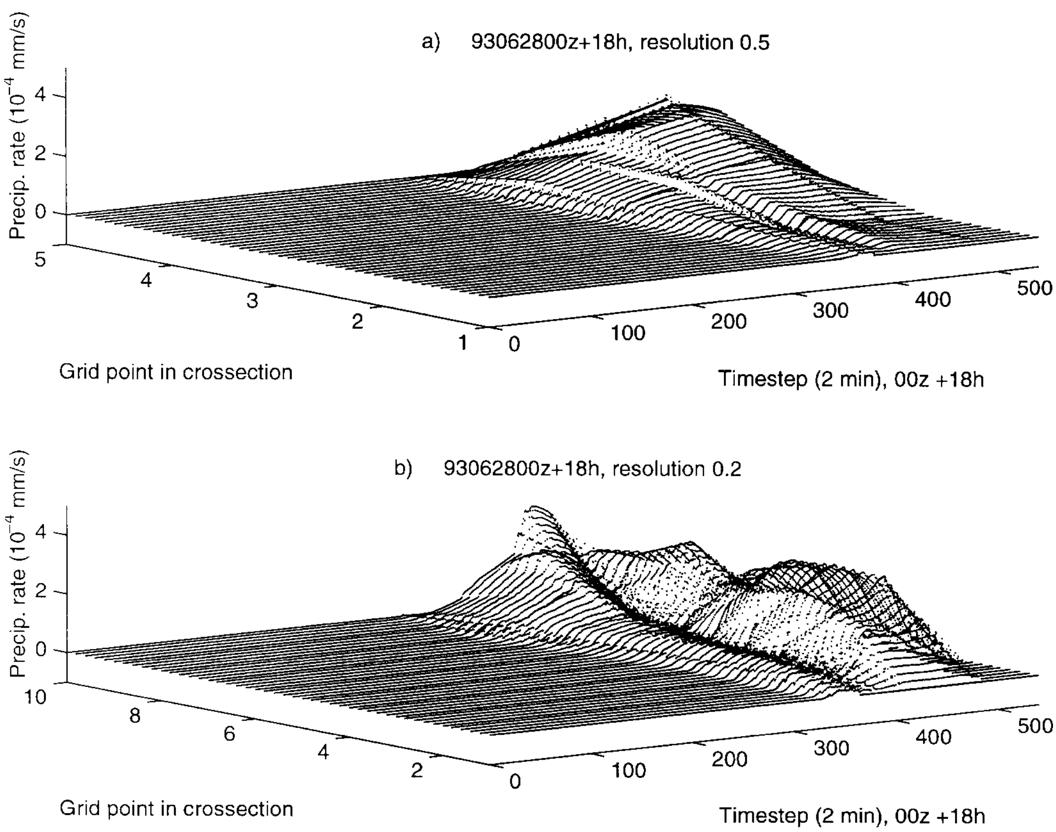

Fig. 3. Precipitation rates (mm s^{-1}) for grid-points of the cross section as functions of time plotted as a 3-dimensional surface. (a) 0.5° resolution, (b) 0.2° resolution. The grid-points are numbered from west to east.

energy available for convective redistribution. For convective heating and moistening to take place, there has to be a positive moisture tendency in the point, that is a convergence of moisture into the column. Thus both $\tilde{A}_q$ and ΔE have to be >0. $\Delta E/L$ and $\tilde{A}_q$ have been plotted as functions of time and grid-point of the cross section and for the two different resolutions (Figs 4 and 5). $\Delta E/L$ is a smooth function which is positive from the late morning and all afternoon when convection over land due to incoming solar radiation can be expected. The maximum value is about the same for both resolutions. A decrease in buoyancy towards the end of the forecast period can be seen in the westerly grid-points but not further east. The shape of these buoyancy surfaces can not explain the variability of precipitation in time. Fig. 5 shows the moisture tendency integrated over the cloud layer, $\tilde{A}_q$. This variable has more variations in time with FR than with CR and it is also split into two periods. These periods obviously result in the two precipitation periods with FR. For CR in the present cross section, the moisture tendency is almost as smooth as the buoyancy and no splitting in time is observed.

A_q is the local moisture tendency, from all processes other than convection, and $\tilde{A}_q$ is this tendency integrated over the depth of the cloud. If the specific humidity, q, and the horizontal and vertical velocity components, V and ω, are decomposed into mean and eddy components, this local moisture tendency can be written:

$$A_q = \frac{\partial q}{\partial t} = -V_p \cdot \nabla_p q - \omega \frac{\partial q}{\partial p}$$

$$= -\bar{V}_p \cdot \nabla_p \bar{q} - \bar{\omega} \frac{\partial \bar{q}}{\partial p} - \overline{V_p' \cdot \nabla_p q'} - \overline{\omega' \frac{\partial q'}{\partial p}}, \qquad (8)$$

$$\text{I} \qquad \text{II} \qquad \text{III} \qquad \text{IV}$$

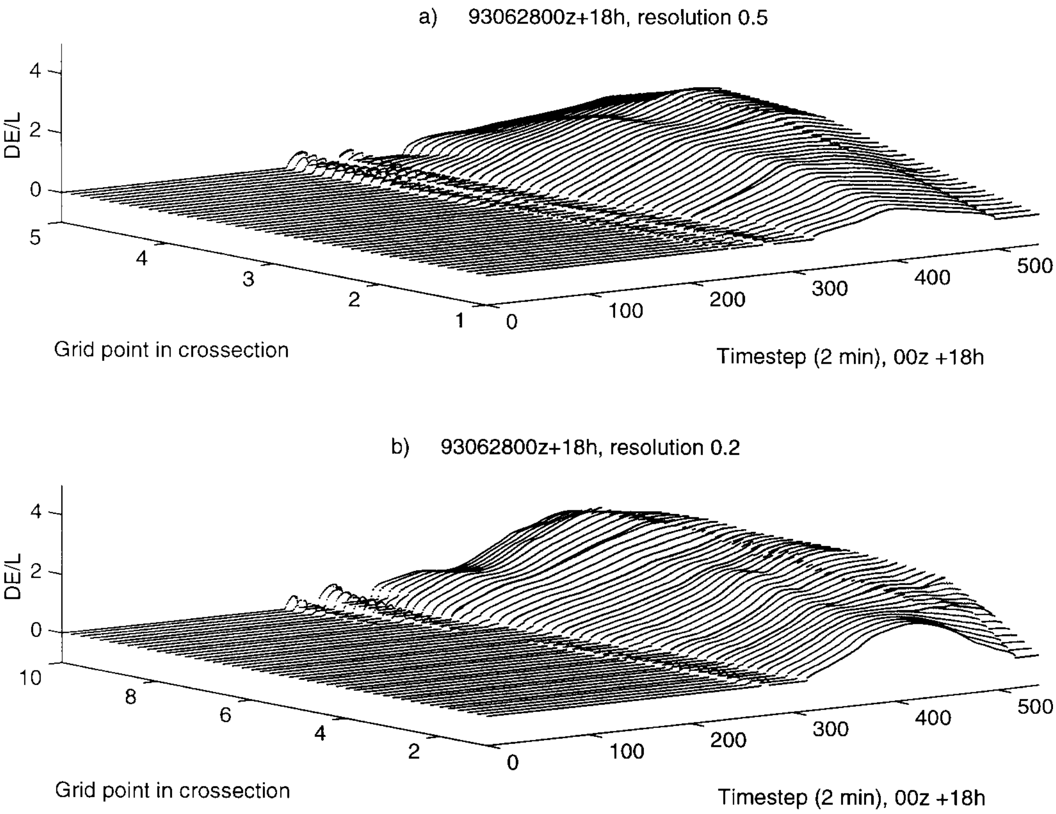

Fig. 4. $\Delta E/L$ (vertically integrated buoyancy) as a function of time and gridpoint. (a) 0.5° resolution, (b) 0.2° resolution.

where terms I and II are horizontal and vertical advection by the resolved scale and terms III and IV are the effects of horizontal and vertical eddy diffusion. For CR as well as FR the level with the largest moisture tendency, A_q, is the lowest level within the cloud layer, in this case the layer centred at level 12 at approximately 850 hPa. The higher levels give contributions to $\tilde{A}_q$ of decreasing magnitude and the highest cloud levels, from level 9 at approximately 590 hPa, give partly a negative contribution. Let us study the contribution from the different terms of (8) to the energy available for convection, LA_q, in a point in the centre of the cross section. We have chosen to do this for the vertical layer 12, centred at level 12, where the largest moisture tendency was found. A source for the vertical advection and diffusion of moisture to layer 12 is the subcloud layer. The fluxes in this layer will therefore be briefly discussed. There are vertical fluxes of latent and sensible heat to the subcloud layer from the earth's surface. These fluxes are shown in Fig. 6. It is obvious from the figure that large heat fluxes from the surface take place in the morning. These fluxes are the reason for the formation of a convectively unstable layer, taking place after sunrise at 02 h 30 m UTC until the onset of convection later in the morning. When convection and cloud formation have been initiated the surface fluxes decrease. Since the surface fluxes depend on the energy input from the sun, it is reasonable that the fluxes decrease when convection starts and the cloud cover is increasing. Also shown in Figure 6 is the effect of the vertical eddy diffusion, term IV in (8), to the latent energy tendency in the subcloud layer, here called LIVdpSC. This term is, as could be expected, strongly correlated to the surface flux of latent heat. In the lowest layer within clouds, layer 12, the total contribution, LA_q, to the energy available for convection, is called LAqdp12 and is also

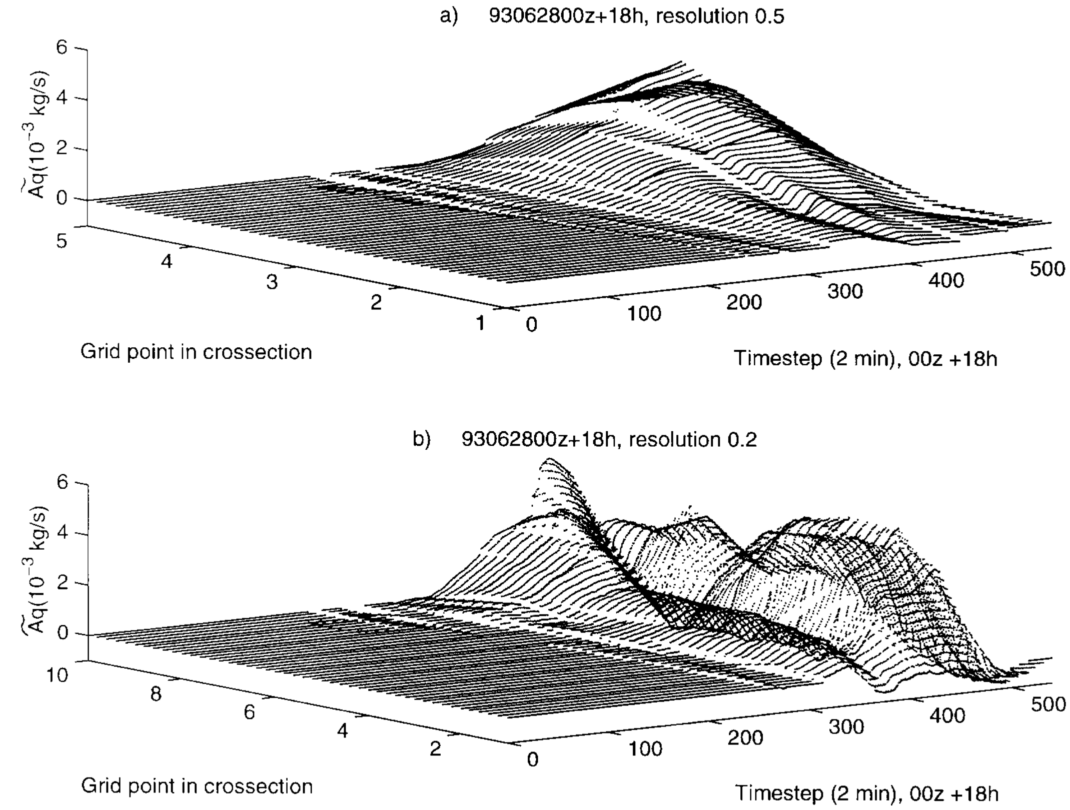

Fig. 5. Moisture tendency, integrated over the depth of the convective layer, as function of time and gridpoint. (a) 0.5° resolution, (b) 0.2° resolution.

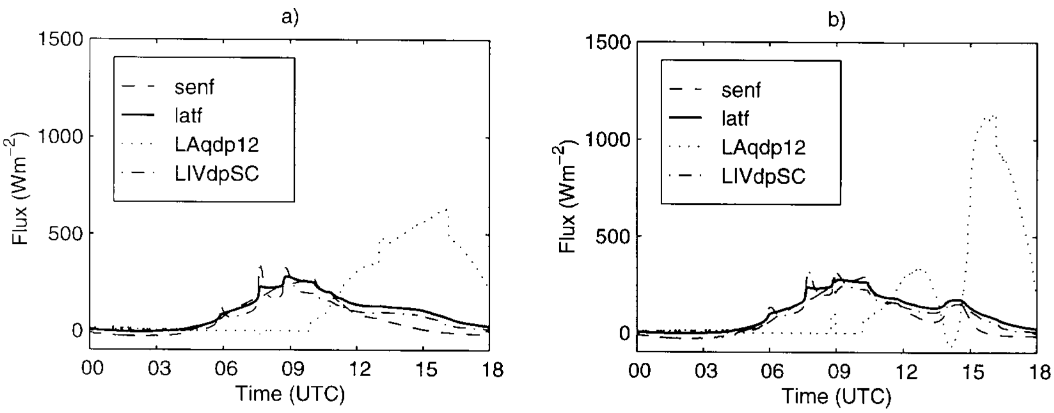

Fig. 6. Fluxes, in units of W m^{-2}, of sensible heat, senf, and latent heat, latf, from the earth's surface to the atmosphere in a grid point in the centre of the cross section. The moisture tendency due to vertical diffusion, term IV in (8), integrated over the subcloud layer and multiplied by latent heat, LIVdpSC, and the total moisture tendency multiplied by latent heat, LA_q, integrated over the lowest level within clouds, level 12, LAqdp12 are also shown. (a) 0.5° resolution, (b) 0.2° resolution.

plotted in Fig. 6 as a function of time. There is no obvious correlation between this energy and the fluxes from the surface.

This analysis suggests that the surface fluxes in a point are not primarily responsible for the variations with time of the energy available for convective activity in the same point. Neither can the surface fluxes in a point explain the magnitude of the energy available for the convection in that point, a fact that becomes obvious if the areas under the curves in Fig. 6 are compared. The energy available for convection, integrated over forecast time, has about the same magnitude for CR and FR, and is more than twice the total flux of latent heat from the surface in the point. Therefore we have to study other possible sources of latent heat than direct surface fluxes and vertical eddy diffusion in the subcloud layer of the point.

The top panels of Fig. 7 show the contributions to the moisture tendency in layer 12 (lowest layer with cloud) for the same grid point as before. The curves represent the total humidity tendency available for convection, A_q, and humidity tendencies as results of the resolved circulation (from terms I and II in (8)), and horizontal and vertical eddy diffusion (from terms III and IV respectively). The vertical eddy diffusion is important for the available moisture but the contribution from the dynamics is larger in both forecasts. The tendencies from the dynamics also show the variations with time that we have already noticed in the moisture convergence and in the precipitation rate. The dynamic tendencies result from horizontal as well as vertical advection as shown in the bottom panels of Fig. 7 and it is obvious that the vertical advection gives the largest contribution at level 12 and also the characteristic shape of the curve for FR. At higher levels within the clouds the dynamics are even more dominating for the convergence of moisture. The conditions are similar in the other points of the cross section even if the intensity of convection differs in magnitude and variability from one point to the next. The results therefore indicates that important transports of energy takes place as horizontal and vertical advection which redistributes moisture to grid points and vertical layers where the conditions for convection are fulfilled. The original source for this moisture is likely to be the surface fluxes in a larger area.

The above investigation leads to the conclusion that the large difference in the characteristics of convection between the two forecasts mainly depends on the difference in the dynamics between the fine and the coarse resolution models. The fine resolution predicts mesoscale areas with convergence and vertical motions that are poorly resolved by the coarse resolution. This results in areas with more intense convective activity in FR than in CR with scales of the order of five gridpoints (100 km) and 200 min (3 h). Thus the experiments show that with the fine resolution the model dynamics yields considerably better simulation of mesoscale areas with conditions favourable for convection. The FR forecast of convection is therefore able to give more details in agreement with the observation.

The convective heating and moistening influence the dynamics of the resolvable scales. The surface pressure falls in areas where the air is heated and with FR this may create a positive feedback to the mesoscale circulation systems that are responsible for the convergence of moisture. Such feedback is necessary for the development of convectively driven mesoscale systems in the model. In the present case study it is obvious from the surface pressure pattern that the mesoscale circulation is well developed in the afternoon and weaker in the morning and evening. To what extent this amplification of the mesoscale circulation in the afternoon is influenced by the convection has not been further investigated.

When spatial mean values, over 50–100 km, are studied there is a tendency for the differences between CR and FR forecasts to disappear. The reason for this can be seen in the cross section if the location, of the precipitation minimum of the fine resolution is studied. The minimum in precipitation lasts for less than one hour and the phase shift of the minimum is approximately 3 hours between the last 8 points of the fine resolution grid. If a mean value of the precipitation rate is taken over two or three points in the eastern part of the fine grid, the minimum will be smoothed and less obvious. Such a mean value should correspond to the CR precipitation. In the western part of the cross section the phase shift is less obvious in FR, and a small minimum can be observed also in CR.

4.2. The statistical ensemble

We also want to understand the meaning of the assumption about a statistical ensemble of con-

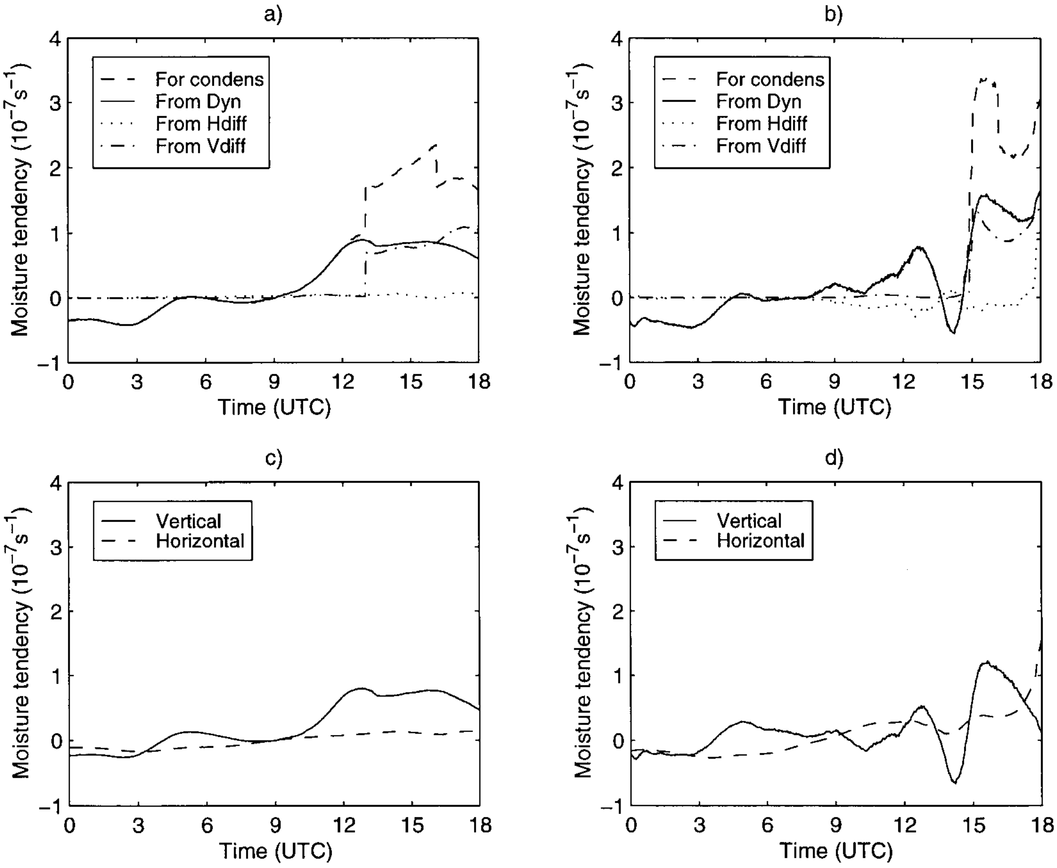

Fig. 7. Top panels: Tendency of specific humidity in the convective scheme (condens) at level 12 and the contributions to it from the model dynamics (Dyn), horizontal (Hdiff) and vertical (Vdiff) diffusion as functions of time for (a) 0.5° resolution, and (b) 0.2° resolution. Bottom panels: Tendencies due to vertical and horizontal advection of relative humidity by model dynamics at level 12 as functions of time for (c) 0.5° resolution and (d) 0.2° resolution.

vective elements in the area represented by a grid point in case the resolution is too fine to make it a realistic assumption. It was shown in the previous section that the mesoscale dynamic circulation gives an important input to the convective scheme in the forecast model. This is the case also in reality, where the mesoscale circulation will have an impact on convection and convective elements mainly will be initialised where there is a dynamically driven convergence. In such an area convective cells will undergo their life cycle, from small cumulus clouds to large precipitating cumulonimbi but, if the area is small, there will not be a statistical ensemble of clouds present at every moment. The precipitation will therefore not be continuous over the whole convective time period but be concentrated to 10–15 min, the typical precipitating period of a cumulonimbus cloud. The total life time of a convective cloud is about one hour. Some time will also pass between the dissipation of one convective cell and the initiation of a new one at the same location. But, if the conditions are favourable for convection for a few hours in a point, convective cells will pass through their life cycle in the area represented by the point and convective precipitation will fall for a minor part of this time period. We can interpret this as if a statistical ensemble of convective elements is present in the area if it is observed over a time period long enough to include the full life cycle of convection in the area. This should be compared to the forecast where the precipitation is assumed to be continuous over the whole convective period since a statistical ensemble of convective clouds is assumed to be present all the time. Therefore, the forecast can not predict the details of convection but rather the mean value of the convective precipitation over a time period long enough to cover the life cycle of a convective cell and the time between the initiation of convective cells in a point. If, in reality, a period with convective activity, governed by the larger scale circulation, is long enough the mean value of convective precipitation over the period should agree with the forecast value. The corresponding is also valid for other effects of convection such as cloudiness and heating by condensation.

The time scale of the mesoscale area, with intense convection in FR, is in the present case about 200 min and therefore long enough to cover a full life cycle of a convective cell. If a mean value of the observed convective activity, or accumulated precipitation, is taken in a point over approximately 3 h, a statistical ensemble of clouds may have been present. The basic assumption of the parameterization, saying that a statistical ensemble of convective clouds has to be present, can therefore not be regarded as fulfilled in every single time step, but over such a time period. Forecasts interpreted in this way, will give precipitation patterns, which are averaged in time but show mesoscale variations in space. They can therefore show smaller scale features than is possible with a coarse grid. However, a picture of the cloud cover, or precipitation, in a specific time step of the model, should not be expected to show the details, such as specific cumulonimbus towers, of a satellite picture.

The conclusion so far is that a finer resolution of the dynamics, giving a mesoscale pattern of the convergence of moisture, will lead to a realistic forecast of convective precipitation including its mesoscale properties. It is possible to get such a forecast with the traditional parameterization schemes, designed for a coarse grid. The assumption about a statistical ensemble of convective cells present in every grid point is not fulfilled with a resolution of the order of 10 km. But if the convective period is of the order of a few hours the assumption may be fulfilled in time but not in space. Thus, the assumption should be that convection is studied over time periods long enough for a statistical ensemble of convective elements to develop in a point.

5. Alternative formulation of the closure

It has been demonstrated that the effect of the finer resolution on convection in the model is mainly channelled through the convergence of moisture by the dynamics. This means that the formulation of the closure for the model, including the convergence of moisture into a grid point with unstable stratification, is important. Such a closure is not unique to the Kuo scheme but is also used by mass flux schemes (Tiedke, 1989), which therefore also depend on the model resolution in the way demonstrated above. The sensitivity of the forecast cloud and precipitation to the formulation of the closure has therefore been studied.

In the Sundqvist formulation of the convection scheme, $\tilde{A}_q$ is the tendency of moisture integrated over the depth of the convective layer, from cloud base to cloud top. But it is obvious from the experiments in the previous section that this moisture tendency can be negative or zero in the cloud layer even if there is a positive tendency in the subcloud layer (Fig. 6). The original Kuo-scheme (Kuo, 1965) considered the moisture convergence in both the subcloud and convective layer as an input of available moisture for redistribution by convection. The assumption that all moisture converging in the boundary layer is transported up to the convective layer means that the moisture content in the subcloud layer is not allowed to change with time, due to convergence by the resolved scales, as long as convection is active. Such an assumption is supported to some extent by observations of the marine tropical PBL where the moisture content changes little with time since the net convergence is close to zero. This difference in closure formulation can be expected to influence the results of the forecast since the moisture tendency can be different in the subcloud layer and in the cloud layer.

In order to examine the sensitivity of the parameterization scheme and the forecast to the formulation of the closure assumption we have rerun the experiments with $\tilde{A}_q = \tilde{A}_{q+\mathrm{PBL}}$ which is integrated from the earth's surface to the cloud top. This approach will be referred to as the Kuo formulation. The only change compared to previous runs is the formulation of $\tilde{A}_q$, everything else is identical to the Sundqvist formulation of the previous runs. The results with FR for 18h accumulated precipitation and for cloud cover at 00 UTC + 13 h 58 m and + 17 h 10 m can be seen from Figs 8, 9. There are large differences if Figs 8, 9 are compared to Figs 1c, 2, bottom panels, in the location and amounts of clouds and precipitation. With the Kuo formulation precipitation is close to zero in the southern part of the area and has a maximum of less than 3 mm in the northern part. The cloud cover at level 10 ($\approx$690 hPa) is less with the Kuo formulation but there are more clouds at lower model levels. Around noon, the total cloud cover (not shown) is larger than with the Sundqvist formulation but it decreases in the afternoon. This can partly be explained by looking at the development with time of the convective parameters in a grid point (Fig. 10). After approximately 7 h 15 m forecast time there is a period with unstable stratification, $\Delta E/L > 0$, in a shallow layer predicted by both formulations. For convection to be initiated there also has to be a convergence of moisture, $A_q > 0$, which is not the case with the Sundqvist formulation. This can also be seen from Fig. 6, where the moisture tendency due to vertical diffusion, integrated over the subcloud layer, is positive in the morning but the moisture tendency in layer 12 is zero. But with the Kuo formulation, the convergence in a deeper layer, including direct flux from the earth's surface, is considered and in this case the requirements for convection are fulfilled. Clouds and some precipitation are therefore formed in the morning with the Kuo formulation. The clouds have a direct influence on the radiation and therefore also on the surface fluxes and on the energy balance at the surface. Fig. 11 shows the surface fluxes of energy in a grid point as a function of time for the two closure versions. The flux from the surface to the boundary layer is, with the Kuo formulation, smaller than the corresponding flux with the Sundqvist formulation for almost three hours in the morning. In the Kuo case, there is also a flux of heat and moisture from the boundary layer to the free atmosphere due to convection (not shown in the figure). The subcloud layer will therefore keep more energy in the Sundqvist case and the vertical profiles of temperature and specific humidity will become different in the two cases.

At the end of this period the stratification in the Kuo case has become stable again, the convection stops and the clouds evaporate. Fig. 12a shows that at noon, the dew point temperature, T_d, and the temperature, T, are lower at all levels in the subcloud layer in the Kuo case compared to the Sundqvist case. A consequence of this is

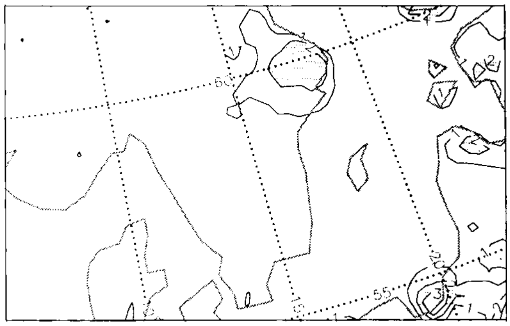

Fig. 8. Accumulated precipitation 00 UTC + 18 h 28 June 1993 with the original Kuo formulation of the closure and 0.2° resolution.

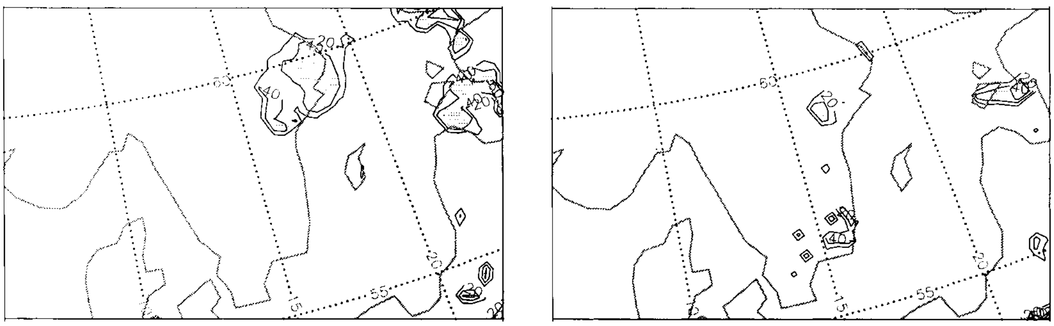

Fig. 9. Forecast cloud cover at model level 10, $p \approx 690$ hPa, for 00 UTC + 13 h 58 m (left panel) and 00 UTC + 17 h 10 m (right panel) with the original Kuo formulation of the closure and 0.2° resolution.

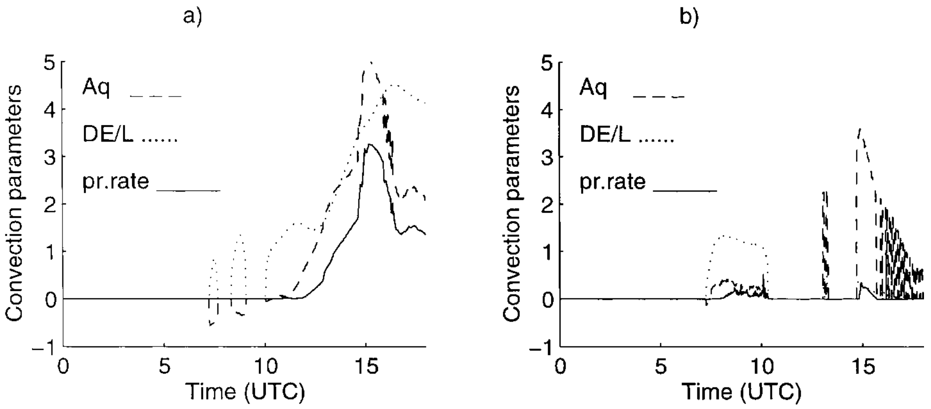

Fig. 10. Moisture tendency, A_q, integrated buoyancy, $\Delta E/L$, and precipitation rate in a grid point in the eastern part of the cross section, (a) with Sundqvist formulation of the closure, and (b) with the original Kuo formulation of the closure. (All parameters are dimensionless in the figure.)

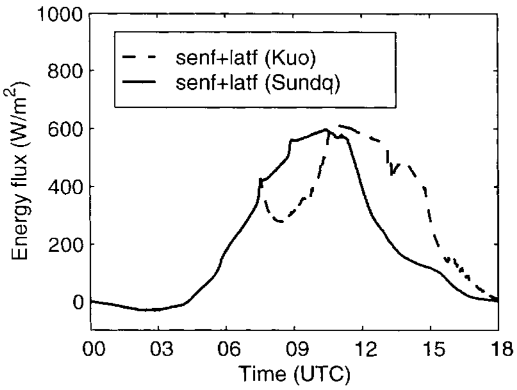

Fig. 11. Surface fluxes as functions of time, with the two different closures, in a point in the eastern part of the cross section.

that the cloud base and the cloud temperature, T_c, calculated as the temperature of a moist adiabatic ascent from the cloud base, differs in the two cases. With the Kuo closure $T_c < T$ at the condensation level and no convection is possible at noon. In the case with the Sundqvist closure $T_c > T$ at the condensation level and the buoyancy is positive in a layer just above this level. This unstable layer is first observed after 10 h forecast time and after another hour the moisture convergence becomes positive in the unstable layer and convection starts.

In this case, the moisture increases in the subcloud layer during the afternoon and the cloud base therefore sinks, which makes the buoyancy even larger. The convection lasts all afternoon with varying intensity in spite of the effect of the clouds on the surface fluxes. Fig. 13d shows that the cloud top level reaches approximately 400 hPa. The Kuo formulation gives a much weaker convection in the afternoon (Fig. 13a, b). The energy flux to the higher levels is therefore lower and the temperature in the subcloud layer becomes higher in the late afternoon (Fig. 12b). With the Kuo formulation the moisture in the subcloud layer is not allowed to change due to convergence of moisture and the cloud base therefore rises to a somewhat higher level when the temperature increases. The buoyancy of the unstable layer is just on the limit to what is necessary for convection to take place and oscillations can therefore be noticed in the forecast (Fig. 10b). In this example it seems as if Sundqvist's formulation of the closure gives a better agreement with observations of cloudiness and accumulated precipitation. The example also demonstrates the importance of the formulation of the parameterization schemes used. The difference in results between two applications of the same basic parameterization scheme can be just as large as if two difference principles for parameterization of convection have been used. Qualitatively the same results could be expected if a mass flux scheme was tested with the corresponding changes in the formulation of the closure. The results also point to the importance of the formulation of the boundary layer fluxes and the vertical diffusion.

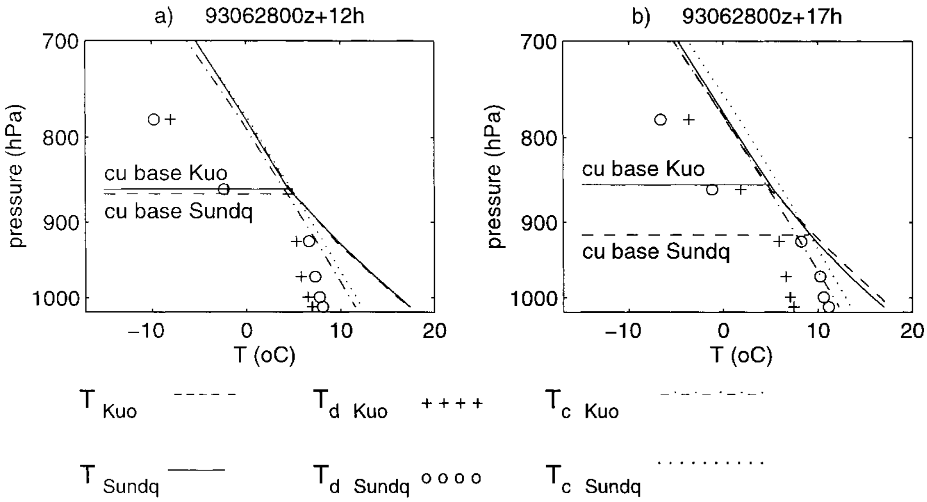

Fig. 12. The vertical profiles of temperature, T, dewpoint, T_d, and temperature inside possible clouds, T_c, with the two different formulations of the closure assumption. Cloud base levels in the two cases are also indicated. (a) 00 UTC+12 h, and (b) 00 UTC+17 h 10 m 28 July 1993.

Conclusions, about which of the two formulations that should be preferred for use in forecast models, can not be drawn from the present work. More experiments and verifications have to be undertaken to answer this question and it is possible that the answers depend on the geographical location of the experimental area. The difference between the forecasts depends on the changes of the moisture content by processes in the boundary layer that are only possible with the Sundqvist formulation. If there is no net tendency by the resolvable scales or by diffusion in the subcloud layer, the moisture tendency, A_q, in this layer will be zero also with the Sundqvist formulation. Therefore, if it is true that these moisture changes can be neglected over the tropical oceans, there should not be any differences between the two forecasts in this area.

Most of the results discussed in this section and Figs 8 to 13 are based on experiments with the fine resolution. But there are differences between the resolutions also in this case. An example is that the cloud tops are somewhat higher with FR. But the main difference between the two resolutions, with the Kuo formulation as with the Sundqvist formulation, is that there is a splitting of the precipitation in two events with FR. This is not obvious from the figures that are dominated by the large difference between the results with the two closure formulations. Thus, the forecast seems to be extremely sensitive to the formulation of the closure assumption but the qualitative difference, between forecasts with coarse and fine resolution, is the same.

6. Summary and concluding remarks

In this paper, the use of a traditional parameterization scheme for convection in models with a finer resolution has been discussed. The traditional parameterization schemes all include an assumption that a statistical ensemble of convective elements are present in the area represented by a grid point. The scale of convection is such that this assumption can not be fulfilled if the resolution is of the order of 10 km. But this resolution is still to coarse for the model to resolve the convective elements and a parameterization is therefore necessary if the effects of convection are to be included in the forecast. The question addressed in this paper is if it is possible to use the traditional schemes without loss of accuracy also when the resolution is 20 km.

A numerical forecast model has been run with two different horizontal resolutions, 0.5° and 0.2°, and the predicted convective cloud cover and precipitation has been studied. The numerical

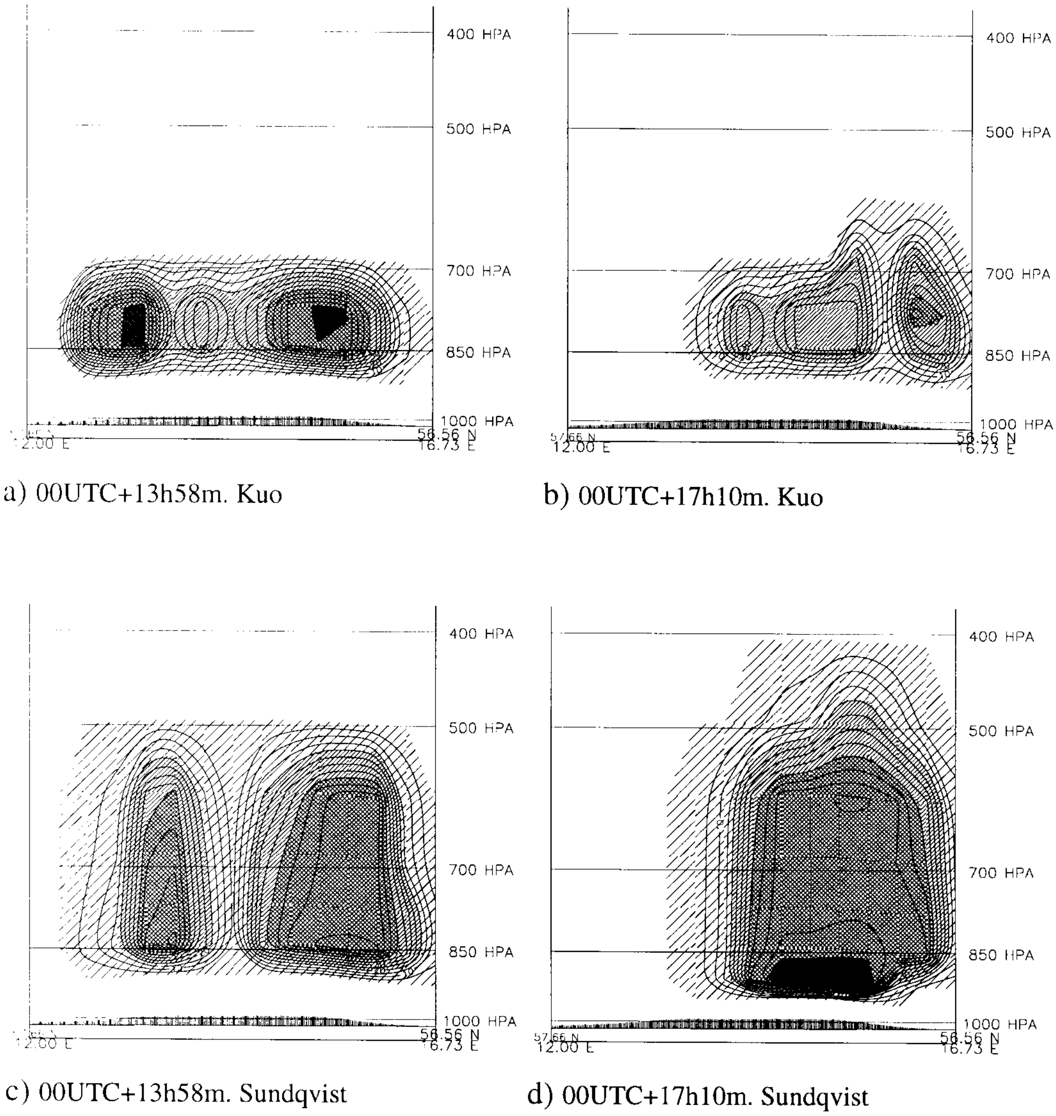

Fig. 13. Vertical cross sections showing convective cloud cover 28 June 1993. Isolines every 5%, stripes 0–20, 20–40, 40–60, shadow 60–80%. (a), and (b) Kuo closure formulation for 00 UTC + 13 h 58 m and 17 h 10 m respectively. (c) and (d). The same as (a) and (b) but with Sundqvist closure formulation.

forecast model includes a Kuo-type parameterization scheme for convection. The results show that the accumulated precipitation and the cloud cover have more detailed structures when a finer resolution is used and that the forecast agrees better with observations than does the forecast with the coarse resolution. It has been shown that this is an effect of the dynamics of the model that will describe meso-β scale circulation systems when the resolution is 0.2°. These circulation systems create mesoscale areas with convergence of moisture, which are favourable for the initiation and maintenance of convection. The fluxes of sensible heat and moisture from the underlying surface are important for the destabilisation of the subcloud layer but it is the dynamics that determines where convection is released.

The assumption about a statistical ensemble of convective clouds present in a grid square is not fulfilled with the finer resolution. But this assumption can be reformulated so that a statistical ensemble of convective clouds is assumed to be present in a point within a time period with convective activity. Thus, the assumption about a statistical ensemble in space is replaced by an assumption about a statistical ensemble in time. The time period has to be long enough to cover the time scale of convection and the forecast should be verified against mean values of the observed convection over this time period. Areas with favourable mesoscale circulation will then stand out compared to areas where convection is suppressed. If the time scale of the mesoscale circulation is shorter, of the order of one hour or less, the assumption is no longer valid.

The predicted convective activity agrees better with observations, when the resolution is finer, because the mesoscale circulation patterns are resolved and influence the forecast of convection, mainly through the convergence of moisture. The tendency of moisture is part of the closure assumptions for the Kuo-type parameterizations and also for the mass flux parameterizations. It is therefore important to see how the formulation of the closure influences the forecasts with the two resolutions.

Two different formulations of the closure, the original Kuo formulation and the formulation used by Sundqvist, have been tested. It turns out that the forecast using the original Kuo formulation gives a less intense convection in the present case. With the Kuo formulation the cloud top reaches at most 4–5 km while the Sundqvist formulation results in cloud tops at about 7–8 km. The accumulated precipitation and the areas covered by precipitation are also larger with the Sundqvist formulation. The qualitative difference, between forecasts with coarse and fine resolution, is the same with the two formulations of the closure. Therefore, the conclusion that the traditional parameterization schemes can be used and that the forecasts agrees better with observations when the resolution is finer, is valid with both closure formulations. But the experiments undertaken demonstrate clearly the importance of the formulation of the closure for the results regardless of the resolution. It is obvious that reformulating the closure may cause changes in the cloudiness and precipitation that are as large as if another parameterization scheme was used.

Resolutions of the order of 1 km have not been discussed in the present paper. With such resolutions we also have to answer the question of whether convection should be parameterized or expected to be explicitly modelled by the dynamics of the fine resolution model itself. But the circulation in convective cells is partly non-hydrostatic and can not be explicitly handled by a hydrostatic model. Therefore, the effects of this circulation have to be parameterized, independently of model resolution. Further studies should be undertaken to investigate the use of the traditional parameterization schemes and how to modify them in hydrostatic models with resolution of the order of 1 km.

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