# Combining a Statistical Cloud Parameterisation and Moist Conservative Turbulence scheme in the HIRLAM model.

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## 1. Introduction and Motivation

The Rossby Centre Regional Climate Model (RCA) physics package is used at SMHI within the HIRLAM NWP system for short-range weather prediction. Within this physics package there can potentially be 3 active cloud fractions in a single grid box. These cloud fractions must be combined before being used for microphysical and radiation calculations. The 3 cloud fractions are:

1. Large scale (resolved) fractional clouds
2. Shallow cumulus cloud amounts, associated with parameterised shallow convection.
3. A cloud fraction associated with parameterised deep convection.

Each of these cloud types also has an independently generated cloud water amount. This makes a consistent treatment of clouds within the model physics package a difficult challenge.

Recently, a moist conservative turbulence scheme has been introduced into the physics package (Lenderink and Holtslag 2004) this builds on the original dry, prognostic turbulent kinetic energy (TKE) scheme due to Cuxart etal (2000). A key difference between the original dry TKE scheme and the new moist scheme is the need to calculate static stability and turbulent mixing lengths taking into account that a grid box may be partially cloudy. The vertical fluxes of heat, moisture and momentum are directly sensitive to the derived mixing lengths in the TKE scheme. These mixing lengths are highly dependent on the static stability in the model (see Lenderink and Holtslag 2004 and Bougeault and Lacarrare 1989 for more details). The static stability inside a cloud may be radically different to that in the surrounding clear sky regions, mainly as a result of latent heat release. This difference directly leads to the amount of turbulence and hence vertical transport being considerably larger inside clouds than in the surrounding clear air. Including this non-linear contribution to the subgrid scale vertical fluxes is a key motivation for introducing a moist version of the TKE mixing scheme. The static stability in a partially cloudy boundary layer can be expressed as a combination of the stability in the cloud free regions and in the cloudy portion of the grid box (Cuijpers and Dunkerkye 1993).

$$\frac{g}{\theta_v}\frac{\partial\overline{\theta_v}}{\partial z} \approx N^2 = c_f\left(A_m\frac{\partial\overline{\theta_l}}{\partial z} + B_m\frac{\partial\overline{r_t}}{\partial z}\right) + \left(1-c_f\right)\left(A_d\frac{\partial\overline{\theta_l}}{\partial z} + B_d\frac{\partial\overline{r_t}}{\partial z}\right) \qquad 1.$$

where $c_f$ is the cloud fraction, $\theta_l$ is the grid box mean liquid water potential temperature and $r_t$ is the grid box mean total water mixing ratio. For the definition of the *A* and *B* terms refer to Cuijpers and Dunkerkye 1993.

The sudden formation of a cloud, or rapid increase in cloud fraction within a model grid box can lead to very rapid changes in the moist static stability and resulting vertical fluxes. Due to the central role cloud fraction now plays in the calculation of static stability and turbulent fluxes it is crucial that an accurate estimate of the cloud fraction be available in the TKE scheme. In the initial implementation of the moist TKE scheme, we used the resolved cloud fraction, diagnosed as a function of relative humidity, for calculating the moist static stability inside the TKE scheme. Due to the rapid nature of the turbulent fluxes and cloud fraction changes, this approach led to numerical instability in the model as the vertical resolution was increased. To alleviate this problem we implemented a calculation of cloud fraction (and cloud water) directly within the moist TKE scheme. The cloud fraction is estimated within the TKE scheme, using a statistical cloud approach following the original ideas of Sommeria and Deardorff (1977) and Mellor (1977). We implemented the parameterisation closely following the suggestions of Chaboureau and Bechtold (2002), where the cloud fraction and diagnosed cloud water are functionally dependent on a single variable, the normalised grid box saturation deficit $Q_1$ . The cloud fraction is expressed as:

$$C_f = \max\left\{0, \min\left[1, 0.5 + 0.36\arctan\left(1.55Q_1\right)\right]\right\} \qquad 2.$$

The need to introduce a statistical cloud fraction and cloud water estimate inside the turbulence scheme, potentially leads to a fourth cloud fraction within a model grid box. In this paper we assess whether the statistical cloud fraction approach is a suitable method for parameterising all cloud fractions (large scale, shallow and deep convective) and associated cloud water amounts and if these cloud terms can be used globally throughout the model physics (e.g as input to the cloud microphysical and radiation parameterisations). If this is the case, it would be possible to have a single, consistent treatment of cloud fraction and cloud water throughout the model physics. To assess this we have integrated a single column version of the HIRLAM model for a number of case studies that include typical subtropical oceanic stratocumulus, summer season shallow cumulus clouds and deep convective clouds and compared the cloud fractions and cloud water amounts diagnosed by the combined statistical cloud, moist turbulence approach to available estimates from Large Eddy Simulation (LES) models and Cloud Resolving Models (CRMs) and where possible direct observations.

## 2. Results

The normalised saturation deficit ($Q_1$) describes the proximity to saturation of the model grid box, normalised by a measure of the subgrid scale variance of all terms (*moisture content and temperature*) contributing to local saturation conditions within a grid box.

$$Q_1 = \bar{a}\,\frac{\left[\overline{r_t} - r_{sat}\left(\overline{T_l}\right)\right]}{\sigma_s} \qquad 3.$$

$\sigma_s$ is the subgrid scale variance of terms contributing to the local variation of saturation conditions about the grid box mean value. $r_{sat}$ is the grid box mean saturation mixing ratio, evaluated with respect to the grid box mean liquid water temperature ($T_l$)

$$\sigma_s = \left[\bar{a}^2\,\overline{r_t''^2} - 2\bar{a}\bar{b}\,\overline{r_t'' T_l''} + \bar{b}^2\,\overline{T_l''^2}\right]^{1/2} \qquad 4.$$

Figure 1 shows cloud fraction as a function of $Q_1$, diagnosed using equation 2, as suggested by Chaboureau and Bechtold (2002). When the grid box is just at saturation ($Q_1$=0) cloud fraction is 0.5, at saturated conditions ($Q_1$>0) cloud fraction rapidly increases to unity and for sub-saturated conditions ($Q_1$<0), cloud fraction rapidly decreases to zero. Partial cloudiness is clearly very sensitive to the specification of the variance term appearing in the denominator of the expression for $Q_1$. In unsaturated conditions a large value of $\sigma_s$ will allow fractional

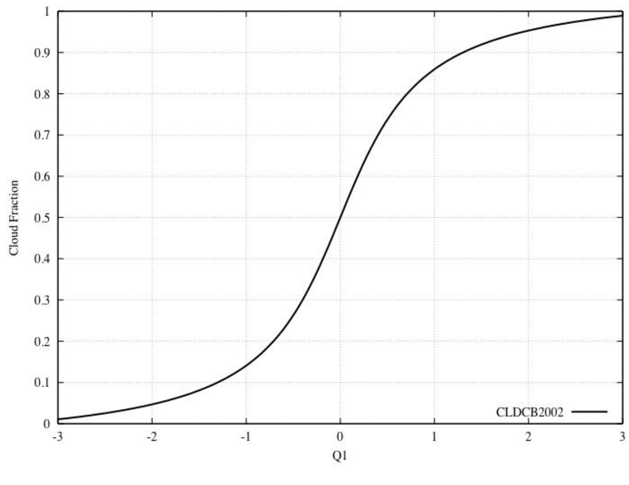


*Figure 1. Cloud Fraction as a function of normalised saturation derived From equation 2, due to Chaboureau and Bechtold (2002)*

cloudiness. Likewise, in saturated conditions a large value of $\sigma_s$ will keep grid box mean cloud fractions below unity. The key term determining the quality of simulated cloud amounts and cloud water, using a statistical cloud scheme is the representation of the variance of saturation conditions about the grid box mean value ($\sigma_s$). Here we parameterise this term as a combination of 3 assumed contributions.

1. A subgrid scale variation term associated with boundary layer turbulence
2. A term associated with convective scale variations
3. A value assumed to be related to subgrid scale mesoscale fluctuations in moisture and temperature within a model grid box.

## 2.1 Stratocumulus boundary layer clouds

Term 1 is parameterised in a manner analogous to the representation of down-gradient subgrid scale vertical transport in the model.

$$\sigma_{s_{turb}} = l_{tke}\left(\overline{a^2}\left(\frac{\partial \overline{r_t}}{\partial z}\right)^2 - 2\overline{a}\overline{b}C_{pm}^{-1}\frac{\partial \overline{h_l}}{\partial z}\frac{\partial \overline{r_t}}{\partial z} + \overline{b^2}C_{pm}^{-2}\left(\frac{\partial \overline{h_l}}{\partial z}\right)^2\right)^{½} \qquad 5.$$

where $h_l$ is the grid box mean moist static energy and $l_{tke}$ is the diagnosed (moist) mixing length from the turbulence scheme. In this manner the diagnosed cloud fraction and cloud water amounts are directly linked to the amount of simulated turbulence.

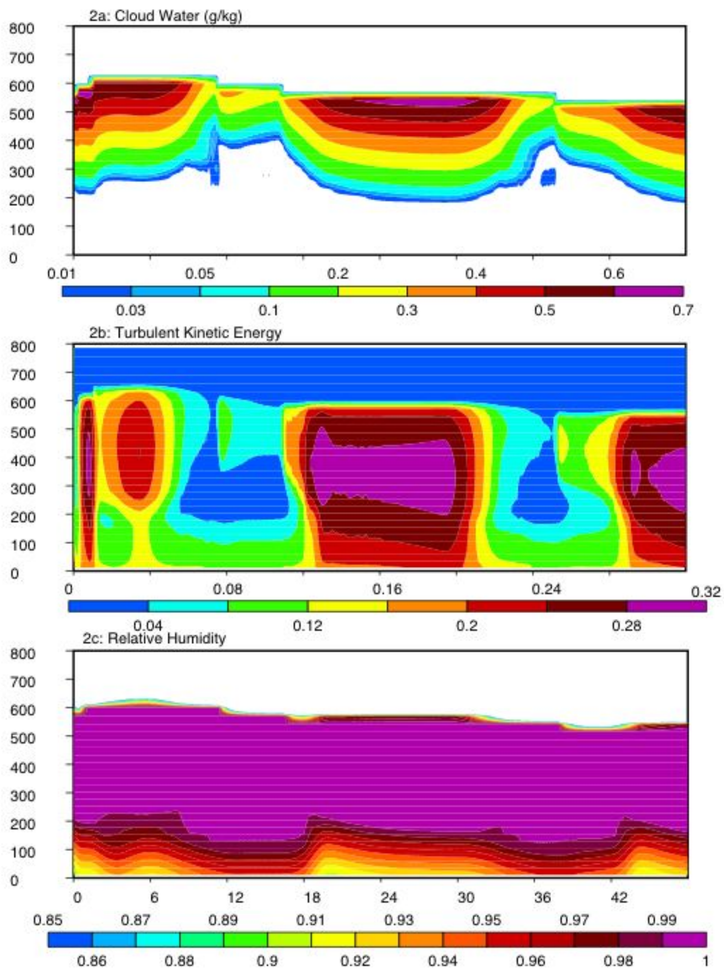


*Figure 2. Time-height cross-section of the HIRLAM SCM simulated diurnal cycle of FIRE subtropical, oceanic stratocumulus clouds. X-axis shows local time with the model simulation beginning at local midnight. Y-axis is height in metres.*

In a non-convective boundary layer, this estimate of the subgrid scale variation of saturation state appears sufficient to accurately simulate the evolution of this type of cloudy boundary layer. Figure 2 shows the simulated diurnal cycle of oceanic stratocumulus clouds, using the SCM version of the HIRLAM model incorporating the statistical cloud and moist TKE schemes. This case is based on a 2-day period of oceanic subtropical stratocumulus observed off the coast of California in 1987 during the FIRE campaign (Albrecht etal. 1988). It constituted a case study within the EUROCS project (EUROpean Cloud Systems Project, see Grabowski and Kershaw 2004), whereby a number of LES and SCM models simulated this diurnal cycle using a common set of large scale, external forcing terms. Results of these simulations can be found in Duynkerke etal (2004) and Chlond etal (2004). Figure 2 illustrates time-height sections of the simulated cloud water amounts, TKE and relative humidity for the case, using the moist TKE and statistical cloud scheme. The HIRLAM SCM was integrated with a vertical resolution of ~30m in the boundary layer.

Cloud fraction is simulated to be unity throughout the simulation, in agreement with LES models and observations (see Duynkerke etal 2004). Simulated cloud depth decreases during local afternoon, as do the cloud water amounts. This is a result of absorption of solar radiation within the cloud, leading to evaporation of cloud water. The heating, associated with the solar absorption within the cloud also leads to the development of a relatively stable layer close to the cloud base. As a result turbulent mixing is radically reduced (evidenced by the local minimum in TKE just below cloud base in the local afternoon) and the vertical flux of water from the surface required to maintain the cloud layer against depletion through solar absorption and subsidence is greatly reduced. By night, unbalanced long wave cooling generates negative buoyancy at cloud top and increased turbulence. This increases the vertical flux of water from the surface into the cloud layer and increases the cloud depth and cloud water amounts during the local night. Turbulence is simulated to be a maximum inside the cloud layer at night and the values of simulated TKE are in good agreement with LES simulated values (see Chlond etal 2004, their figure 8.). It is worth noting that during the local afternoon the relative humidity in the lowest model layer can reach 95% (see figure 2c), but no cloud is simulated by the statistical cloud scheme. This is in agreement with both observations and LES models, where a cloud base at ~300m is observed. The original relative humidity based cloud parameterisation would have placed a cloud in the lowest model layer given these relative humidities and thus would have (incorrectly) simulated the stratocumulus layer extending to the sea surface. Cloud-free conditions below 300m are simulated by the statistical cloud scheme during the afternoon, even with a grid box mean relative humidity of 95% ($r_t$-$r_{sat}$ *slightly negative (unsaturated) in equation 3*), because the local static stability is very high and thus $\sigma_s$ is small in the denominator of equation 3, leading to a large negative value of $Q_1$ and zero cloud amounts from equation 2.

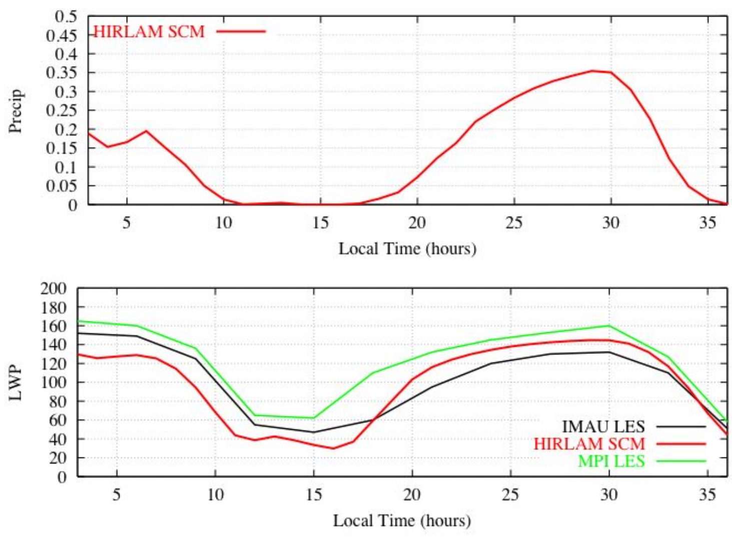


*Figure 3. HIRLAM SCM (in red) simulated precipitation (mm/day) and Liquid Water Path (LWP) in mm, for FIRE stratocumulus case. Also shown are 2 ssimulations of the FIRE LWP (in Black and Green)*

Figure 3 shows a time series of precipitation and integrated liquid water path (LWP) from the HIRLAM SCM simulation. LWP values agree quite well with typical LES values for the same case. A diurnal cycle of drizzle is also simulated by the model with zero precipitation in the local afternoon and maximum rates of ~0.25mm/day at local night-time. Stevens etal (2003) observed frequent drizzle at a similar rate, from nocturnal oceanic stratocumulus clouds off the coast of California. The cloud water and cloud fraction diagnosed from the statistical cloud scheme were used as input into the cloud microphysical scheme, indicating that a smooth interaction between moist turbulence, statistical clouds and precipitation is feasible.

## 2.2 Shallow Cumulus Clouds

In the presence of convection, the variation of saturation conditions at the scale of a typical NWP grid box (~20km) will increase. Localised regions of high humidity will be concentrated in the areas of convective ascent and regions of relative subsaturation in regions of convectively induced, compensating subsidence. In convective boundary layers the relative humidity is often below saturation, clouds occur as a direct result of the large variation of saturation conditions at the scale of a model grid box. To simulate partial cloudiness in a convective boundary layer it is necessary to include an estimate of the variance of saturation conditions associated with the convective scale motions. To do this we follow the suggestion of Lenderink and Siebesma (2000) and in the convective cloud layer relate the saturation variance term to the convective intensity (given by the parameterised convective mass flux) and the saturation excess/deficit of convective plumes relative to the local grid box conditions.

$$\sigma_{s_{CU}} = \left( \frac{M_{cu}\left(q_{t_{CU}} - \overline{q_t}\right) C_{dep} \dfrac{\partial \overline{q_t}}{\partial z}}{\rho w^*_{pbl}} \right) \qquad 6.$$

$w^*$ is a convective scale velocity and $C_{dep}$ is the depth of convection simulated by the convective parameterisation. In convective boundary layers, the total variance of saturation conditions is assumed to be a combination of the variance due to boundary layer turbulence and that due to convective scale variations.

$$\sigma_s = \sigma_{sturb} + \sigma_{scu} \qquad 7.$$

Figure 4 shows a SCM simulation of a typical diurnal cycle of shallow cumulus clouds over the ARM Southern Great Plains site during the summer IOP of 1997. This case has been extensively simulated by LES models (Brown etal 2002) and SCMs (Lenderink etal 2004). Figure 4 shows the simulated cloud fraction and cloud water amounts using the HIRLAM SCM with 30m vertical resolution in the boundary layer. Also shown is the simulated cloud water amount from one of the LES models contributing to the EUROCS case study of this event. The HIRLAM SCM uses the moist turbulence and statistical cloud scheme in combination with the Kain-Fritsch convection scheme (Kain and Fritsch 1990, Deng etal 2000??). The convection scheme provides tendencies of heat and moisture due to convection in regions where shallow cumulus convection is simulated to occur. At grid boxes where parameterised shallow convection is occurring heat and moisture tendencies due to moist turbulence are not communicated to the model prognostic equations. Cloud fraction and cloud water amounts associated with the shallow convection are diagnosed in the moist turbulence scheme using the combined estimate of subgrid scale saturation variation given by (7). The diagnosed cloud fraction and cloud water amounts are then used in the subsequent calculations of radiation and microphysical conversion in the same model time step. In this manner the statistical cloud fraction and cloud water are the only cloud variables being used (consistently) by all model parameterisations.

Figure 4 indicates that the statistical cloud scheme is able to simulate a reasonably good diurnal cycle of shallow cumulus cloud amounts and cloud water mixing ratios. Figure 5 shows the terms $\sigma_{sturb}$ and $\sigma_{scu}$ that contribute to the total subgrid scale variance of saturation conditions used in the diagnosis of $Q_1$ and subsequently the cloud fraction and cloud water amounts. In this convective boundary layer, parameterised shallow convection is the primary contributor to the variance of saturation conditions within a model grid box. A relative maximum in $\sigma_{sturb}$ can be seen in the shallow convective cloud layer, but the simulated cloud fraction is cleared phased with the onset of parameterised convection and the sharp increase in $\sigma_s$ due to convection. Simulations made with parameterised convection turned off failed to simulate a shallow cumulus cloud due to the low value of $\sigma_{sturb}$ and the subsequent large negative value of $Q_1$. We are presently testing using only the moist turbulence scheme for simulating shallow convection with an extra term included in the subgrid scale buoyancy flux calculation due to the non-gaussian nature of vertical transports in a partially cloudy layer (Cuijpers and Bechtold 1995). Inclusion of this contribution to the buoyancy term in the TKE equation greatly increases the simulated value of TKE in partially cloudy grid boxes. This will increase the $\sigma_{sturb}$ term and it is hoped might allow a better estimate of shallow cumulus cloud fractions directly from the moist turbulence scheme, without requiring the $\sigma_{scu}$ contribution from parameterised shallow convection.

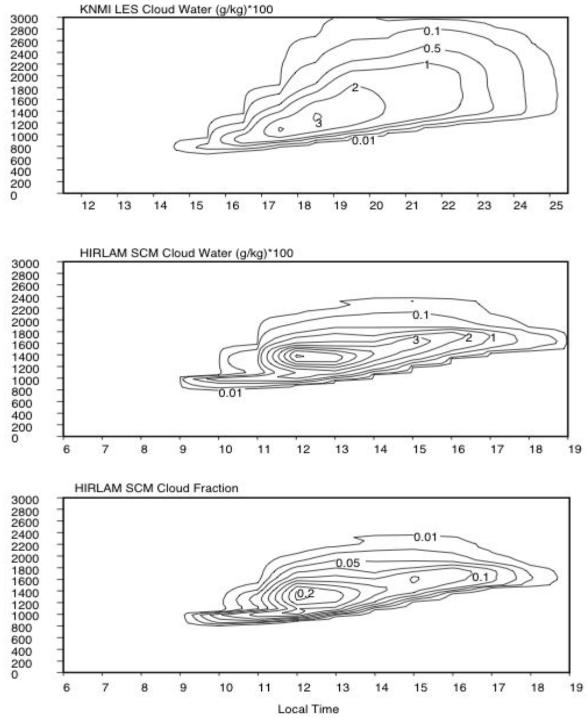


*Figure 4. HIRLAM SCM simulation of the diurnal cycle of shallow cumulus clouds observed over the ARM SGP site June 21st 1997. Also shown is the KNMI Large Eddy Simulation of the cloud water evolution for this case. X-axis shows local time and y-axis is the vertical height..*

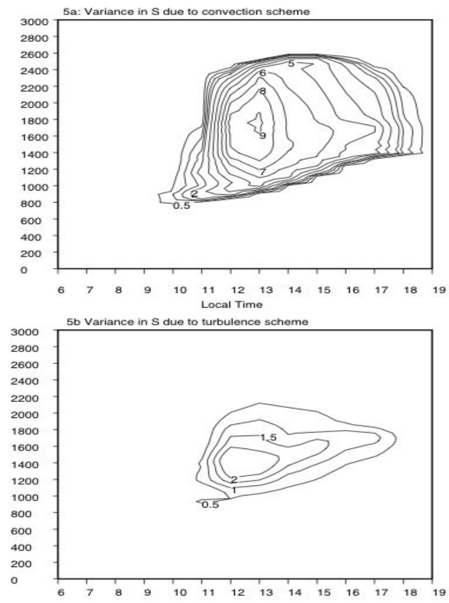


*Figure 5. Time-height cross-section showing the diurnal cycle of the variance Of saturation conditions ($\sigma_s$) about the grid box mean saturation deficit As contributed by a) the convection parameterisation and b) turbulence scheme. X-axis local time in hours.*

## 2.3 Deep Convective clouds

Finally we tested the ability of the statistical cloud scheme to simulate deep convective clouds and particularly upper level clouds forced by moistening due to detrainment of condensate from deep convective towers. The HIRLAM SCM was used to simulate a 4-day period of deep convection observed during the summer of 1997 at the ARM Southern Great Plains site (see Xu etal 2002 and Xie etal 2002). In the free troposphere, above the boundary layer, simulated values of TKE and associated $\sigma_{sturb}$ will often become very small. Away from regions of convection the diagnosed $\sigma_s$ term will be very small, the only contribution coming from the small $\sigma_{sturb}$ term in the free atmosphere. In the free troposphere variations of water and saturation conditions do occur on scales smaller than ~20km, that are not directly associated with active convection or small-scale turbulent motions. For example variability associated with mesoscale convective circulations, enhanced turbulence following a convective event, jet streaks and frontal circulations. Neglect of these variance contributions risks making the cloud fraction and cloud water diagnosis through $Q_1$ become and "all or nothing" scheme, with cloud fraction being either unity (in saturated conditions) or zero (in unsaturated conditions) because of the very small value of $\sigma_s$ simulated in the free atmosphere. As an initial attempt to alleviate this problem, above the simulated boundary layer we introduce an extra variance term ($\sigma_{sfix}$). This we model analogous to $\sigma_{sturb}$ using equation 5, but we replace the prognostic $l_{tke}$ by a fixed mixing length scale $l_{fix}$=250m. This is analogous to the assumption of an asymptotic mixing length used by many turbulence schemes in the free troposphere (Louis 1979). The resulting $\sigma_s$ term is modelled as follows:

$$\begin{aligned} \sigma_s &= \sigma_{sturb} + \sigma_{scu} && z \leq pblh \\ \sigma_s &= max\left[\left(\sigma_{scu} + \sigma_{sturb}\right),\left(\sigma_{scu} + \sigma_{sfix}\right)\right] && z > 2xpblh \qquad 8. \end{aligned}$$

where $\sigma_{sfix}$ uses equation 5 for diagnosing the saturation variance but with the value of $l_{fix}$ replacing $l_{tke}$. The term *pblh* is the height of the top of the model boundary layer. The two values of $\sigma_s$ are linearly interpolated across the vertical distance between *pblh* and *2xpblh*.

Figure 6 shows a time-height section of the simulated cloud fraction for the 4-day period of this simulation. Two periods of convection were observed to occur (Xu etal 2002), the timing and duration of which are reasonably well simulated by the HIRLAM SCM convection scheme. The sharp vertical spikes of cloud fraction in figure 6 show the cloud fraction simulated by the statistical cloud scheme associated with these periods of deep convection. Fractional cloud amounts are simulated during these periods due to the large variance term coming from the parameterised deep convection. During the period between hours 24 and 42 of the simulation an upper level cloud was observed to form (observed by the millimetre radar at the ARM site, *not shown here*) and to gradually thicken and the cloud base descend with time. During this period no convection was observed to be active and non was simulated by the HIRLAM SCM. This cloud probably occurred as a result of moistening of the upper troposphere by the period of deep convection between hours 14-24 of the simulation. Inclusion of the $\sigma_{sfix}$ term above the boundary layer allows this cloud layer to be reasonably well captured, with cloud fractions of 20-40% gradually descending with time. Neglect of the term $\sigma_{sfix}$ leads to the statistical cloud scheme relaxing into an all or nothing scheme in the free atmosphere and this mid to upper level cloud deck is simulated as two separate layers of 100% cloud fraction with zero cloud in between (a situation that was not observed to occur). This is due to the model atmosphere remaining sub-saturated, with high values of static stability above the boundary layer. Cloud free conditions were not observed to occur during this period and this model error is a direct result of the underestimate of the variance of saturation conditions in the free troposphere once convection has ceased and the $\sigma_{scu}$ term is zero.

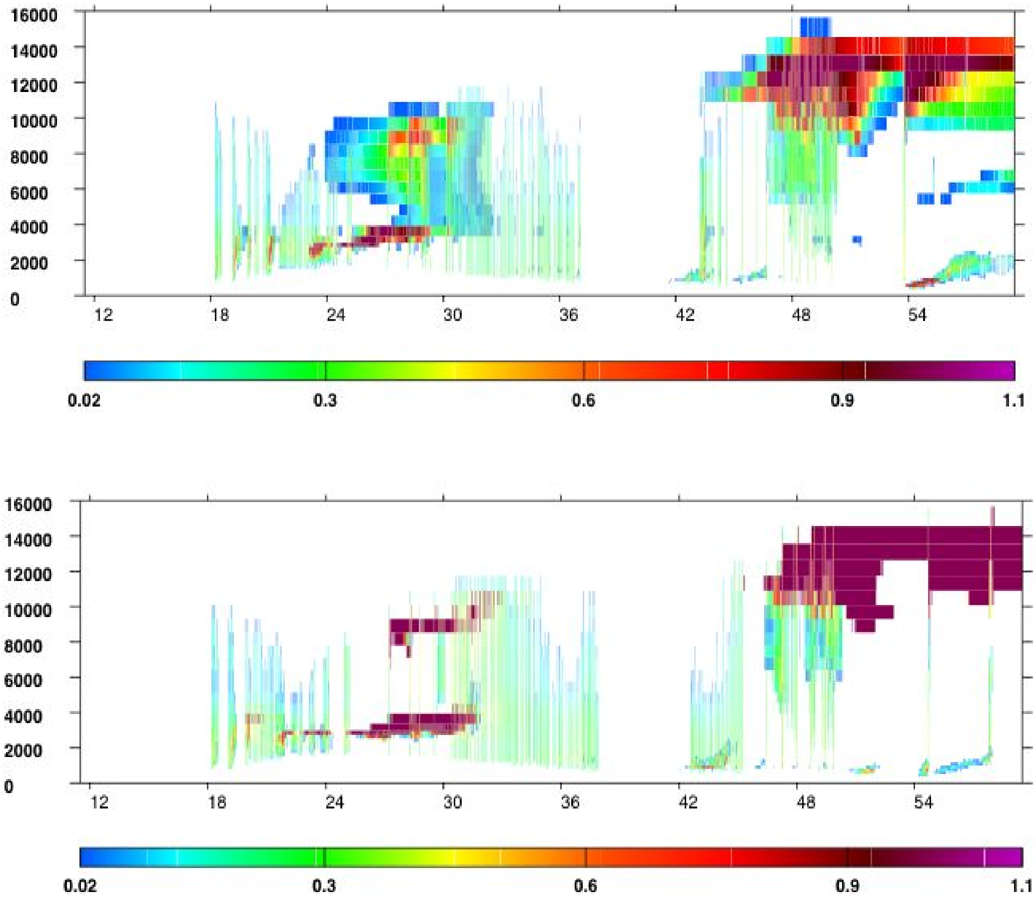


*Figure 6. Time-height cross-section of clouds fraction from a run with $\sigma_{sfix}$ included (top panel) and an indentical integration but with $\sigma_{sfix}$ equal to $\sigma_{sturb}$ (lower panel)*

For practical application of the statistical cloud scheme to represent all cloud types, an estimate of the subgrid scale variation of saturation conditions (*subgrid scale variation of total water and temperature*) resulting from processes other than convection and small-scale turbulence seems necessary. Equation 8 represents a preliminary attempt to parameterise this term.

## 3. Conclusions.

We have described the introduction of a statistical cloud scheme into the HIRLAM moist turbulence scheme. This cloud scheme is used to estimate all cloud types (*both fractional extent and water content*) in a variety of situations simulated by the HIRLAM SCM. These situations span boundary layer stratocumulus clouds, shallow cumulus and deep convective clouds. The statistical scheme links the simulated clouds to the grid box mean saturation conditions, normalised by an estimate of the subgrid scale variation of saturation conditions about the grid box mean value. The variance term has contributions from parameterised turbulence, convection and an assumed free troposphere contribution. In this manner cloud fraction and water amounts are tightly coupled to the model parameterisations of convection and turbulence. Results indicate that this approach is a promising route to simulate all cloud types by a single scheme, irrespective of their means of production. More work needs to be done to simulate subgrid scale free troposphere variations in saturation conditions. It is possible that the information on subgrid scale variation of saturation conditions might prove to be useful information for the model microphysical and radiation schemes to incorporate variability of cloud water amounts in the calculation of precipitation and cloud-radiation interaction.

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