Comparison of Parameterized Cloud Variability to ARM Data

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Abstract

Cloud parameterizations in large-scale models often try to predict the amount of sub-grid scale variability in cloud properties to address the significant non-linear effects of radiation and precipitation. Statistical cloud schemes provide an attractive framework to self-consistently predict the variability in radiation and microphysics but require accurate predictions of the width and asymmetry of the distribution of cloud properties.

Data from the Atmospheric Radiation Measurement (ARM) Program are used to assess the variability in boundary layer cloud properties for a well-mixed stratocumulus observed at the Oklahoma ARM site during the March 2000 intensive observing period (IOP). Cloud boundaries, liquid water content (LWC), and liquid water path (LWP) are retrieved from the millimeter wavelength cloud radar and the microwave radiometer (MWR). Balloon soundings, aircraft data, and satellite observations provide complementary views on the horizontal cloud inhomogeneity.

It is shown that the width of the LWP probability distribution function (PDF) is consistent with a model in which horizontal fluctuations in LWC are vertically coherent throughout the depth of the cloud. Variability in cloud base is overestimated by this model, however; perhaps because an additional assumption that the variance of total water is constant with altitude throughout the depth of the boundary layer is incorrect.

Introduction

Variability in cloud properties at scales smaller than those resolved by large-scale models may cause significant biases because processes such as cloud microphysics and radiation are non-linear and model calculations do not take this into account. Particularly well-known are biases in cloud albedo and autoconversion. Techniques to correct for these biases have been developed but depend crucially on the variance assumed to exist within the grid box.

One way forward might be to use a statistical cloud scheme (Sommeria and Deardorff 1977; Mellor 1977) because the PDF of total water contained in the scheme can be used to determine the PDF of cloud condensate from which domain averaged process rates may in turn be calculated. In this framework, an issue arises because of the coarse vertical resolution of large-scale models; how should one conceive of the spatial organization of the PDF so that PDFs of vertically integrated quantities such as cloud optical thickness can be determined? One assumption that could be used is to assume that horizontal fluctuations in total water are perfectly correlated at all altitudes within a single large-scale model box (Considine et al. 1997). Total water is defined as the sum of the water vapor and cloud liquid specific humidities, q and l, respectively.

In this case study of a continental nearly well-mixed non-precipitating stratocumulus observed during the March 2000 IOP of the ARM Program, we use a battery of observations to assess whether the assumption of perfect vertical correlation of horizontal fluctuations of total water is sufficient to reproduce the observed PDFs of LWP, cloud optical thickness, and cloud base altitude.

ARM Data and the March 19, 2000, Case Study

On March 19, 2000, a continental stratocumulus cloud was observed at the ARM Southern Great Plains (SGP) site in Lamont, Oklahoma. Climatological studies of boundary layer clouds at this site (Gottschalk et al. 1998) show that the conditions that accompanied this cloud are fairly typical, namely a nearly well-mixed boundary layer in the cold advection regime that follows the passage of a cold front. As this case occurred during an IOP, the clouds were observed from an assortment of platforms. Ground-based remote sensors included millimeter wavelength (35 GHz) cloud radar (MMCR), a Belfort laser ceilometer, and a MWR. Aircraft sampling was accomplished with the University of North Dakota Citation. Satellite retrievals of optical depth complemented radiosondes and surface measurements from a 60 meter tower and energy balance bowen ratio (EBBR) surface flux stations.

Figure 1 shows the cloud mask from the MMCR deduced with the method documented by Clothiaux et al. (2000). The passage of the cold front is indicated by the cessation of cloudiness in the middle troposphere around 10 Universal Time Coordinate (UTC) or 3:30 local time (LT). Following that a boundary layer cloud between ~500 and 1000 meters occurs with persistent overcast until about 17 UTC. Until 15 UTC (8:30 LT), temperatures from different altitudes on the 60 meter tower indicated that the surface layer was under stable conditions but with surface heating after sunrise convective conditions occurred. Consequently the boundary layer rapidly warmed and deepened leading to cloud breakup.

Combining measurements of radar reflectivity with the retrieved LWP from the MWR, we use the algorithm of Sassen et al. (1999) to perform a retrieval of LWC (Figure 2). Also shown in the figure are the LWP from the MWR and the best estimate cloud base from the ceilometer. Because the radar is sensitive to the sixth moment of the drop size distribution, the radar has difficulty seeing the very small cloud droplets near cloud base. The ceilometer is more sensitive and generally sees a slightly lower cloud base (Clothiaux et al. 2000).

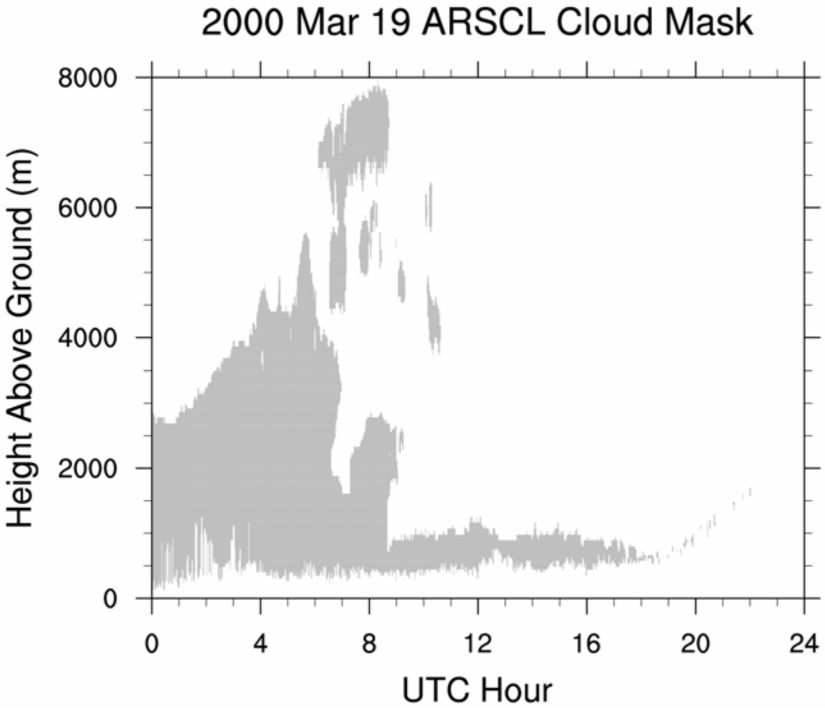

Figure 1. Cloud mask for March 19, 2002. This mask is derived from cloud radar and ceilometer measurements following the algorithm of Clothiaux et al. 2000.

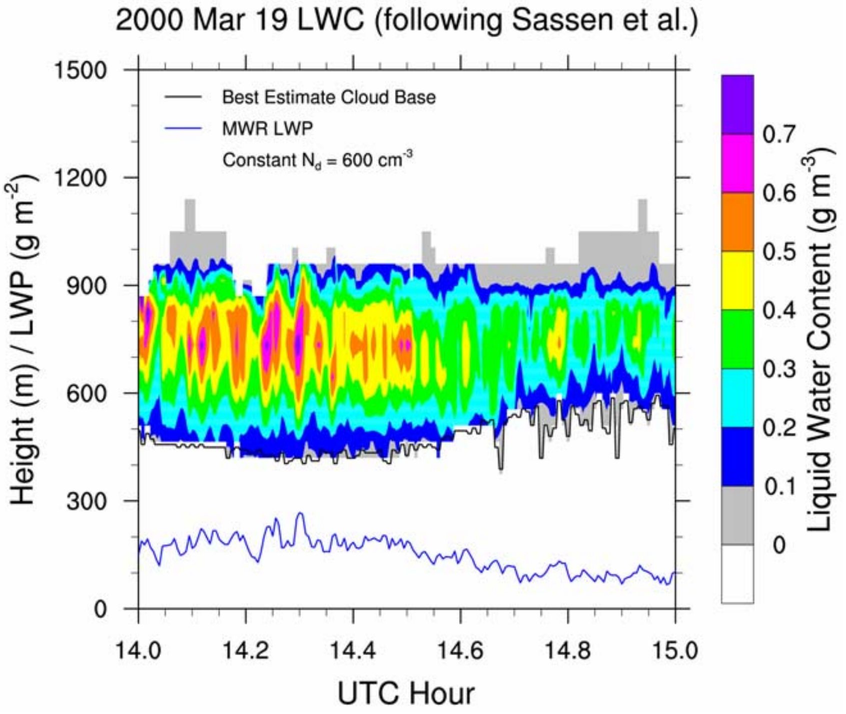

Figure 2. Radar retrieved LWC, MWR LWP, and ceilometer cloud base from 14 to 15 UTC.

Soundings were launched every three hours and the sounding for the hour shown in Figure 2 indicates nearly well mixed conditions (Figure 3). Included in the figure is the mean LWC profile averaged during the hour centered on the sounding launch. At this time a well-mixed layer occurs up to about 700 meters, midway through the cloud. The soundings at 1130 and 1730 UTC and 2030 UTC are similarly well-mixed but in the 1730 and 2030 UTC soundings, no layer is saturated in the mean, consistent with cloud breakup.

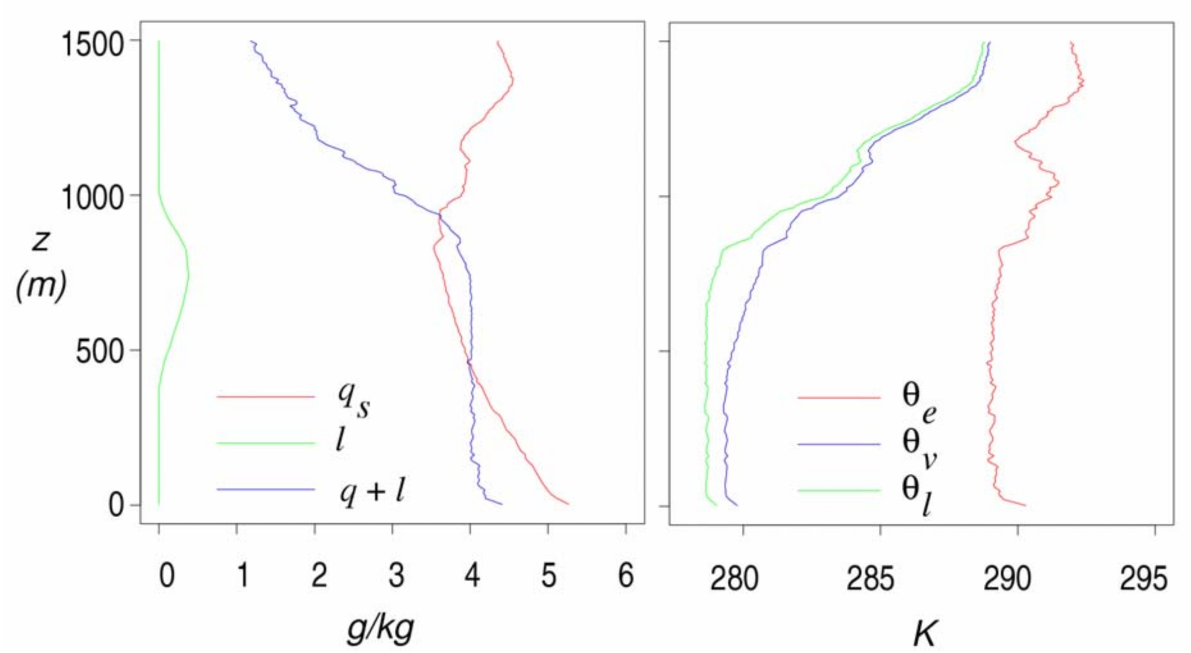

Figure 3. Sounding from 1430 UTC. The left panel shows the saturation specific humidity q_s, the MMCR retrieved liquid water l averaged over the period 14-15 UTC, and the vapor plus liquid specific humidity $q + l$ computed from the sounding vapor and MMCR liquid. The right panel shows the equivalent, virtual, and liquid water potential temperatures, θ_e, θ_v, and θ_l, respectively. The liquid water virtual potential makes use of the MMCR retrieved liquid.

A Model for Cloud Inhomogeneity

The model of Considine et al. (1997) assumes that fluctuations in total water are gaussian distributed in the horizontal direction but perfectly correlated in the vertical. Additionally the boundary layer is assumed to be completely well-mixed so that liquid water content increased adiabatically with distance above cloud base. Finally, a horizontally flat top boundary layer top results in the maximum LWC located just beneath inversion base. With these assumptions, the Considine model successfully predicts that LWP or optical thickness would have a quasi-lognormal distribution were the boundary layer overcast but a quasi-exponential distribution for partly cloudy boundary layers.

In applying this model to large-scale models, some issues arise such as that the boundary layer may be represented by several layers of the large-scale model and that not all boundary layers are well-mixed. For example, the soundings of the case study presented here indicate some degree of well-mixedness but generally the cloud top is not flat and the maximum in time-averaged LWC falls some distance beneath the top of the cloud. Because of these differences, the Considine model is generalized so that the assumption of well-mixedness is removed.

Specifically, the vertical profiles of total water specific humidity $q + l$ and liquid water potential temperature ϑ_l from the 1130, 1430, and 1730 UTC soundings are taken at their finest vertical resolution with two additional assumptions: first, that the horizontal variance in $q + l$ is independent of altitude, and second, that horizontal fluctuations in $q + l$ are perfectly correlated in the vertical. The horizontal fluctuations are computed using 3000 samples from a symmetric beta distribution with shape parameters p and q equal to 2. Horizontal fluctuations in ϑ_l are ignored. With this ensemble of LWC profiles, the PDF of LWP and cloud base can be diagnosed.

In this model, the magnitude of horizontal fluctuations in $q + l$ must be specified. For the 1130 and 1430 soundings, the standard deviation of $q + l$ is specified so that the standard deviation of the radar retrieved l at the levels with overcast cloud are matched. Because the radar retrievals use the MWR LWP and the ceilometer cloud base altitude, the model LWP and cloud base PDFs are not totally independent of the observations; in these cases, the assumption of perfect vertical correlation of horizontal fluctuations is the primary idea being tested. In contrast, for the 1730 UTC sounding the $q + l$ standard deviation is set equal to that computed from 4 GHz data from a nearly space and time coincident 15 minute level aircraft leg in the middle of the cloud.

Although not addressed here, questions about how representative temporal variability from a single ground based sensor is of spatial variability at a single time are being examined.

Testing the Model

Figure 4 shows the PDF of LWP and cloud base altitude calculated from the model using the sounding displayed in Figure 3. The observations are the PDF formed from all observations within the 14-15 UTC hour. Note that with 10 and 20 second sampling to the ceilometer cloud base and MWR LWP data, the corresponding spatial resolution of the data at 9 m/s cloud-level wind speed is approximately 100 and 200 meters, respectively.

The model predicts a quasi-lognormal distribution to both liquid water and cloud base altitude consistent with the Considine model for overcast conditions. While the PDF match for LWP is reasonable, the match for cloud base altitude is more problematic with the observations indicating a somewhat skewed distribution with very few observations of cloud base less than 400 m. Although the width of the modeled PDF can be reduced if temperature is assumed to be positively correlated with total water, this would result in a LWP PDF with too little variance. Additionally the assumption of symmetric total water PDF cannot yield a skewed cloud base distribution as seen here.

A more likely explanation for the difference is that the horizontal variance in total water $q + l$ is not constant with altitude. Specifically, convective planetary boundary layers are known to have maximum variance at the top and bottom of the PBL, with a relative minimum in variance near the middle of the PBL. This is logical since the source of much variance within the PBL comes from turbulent fluxes

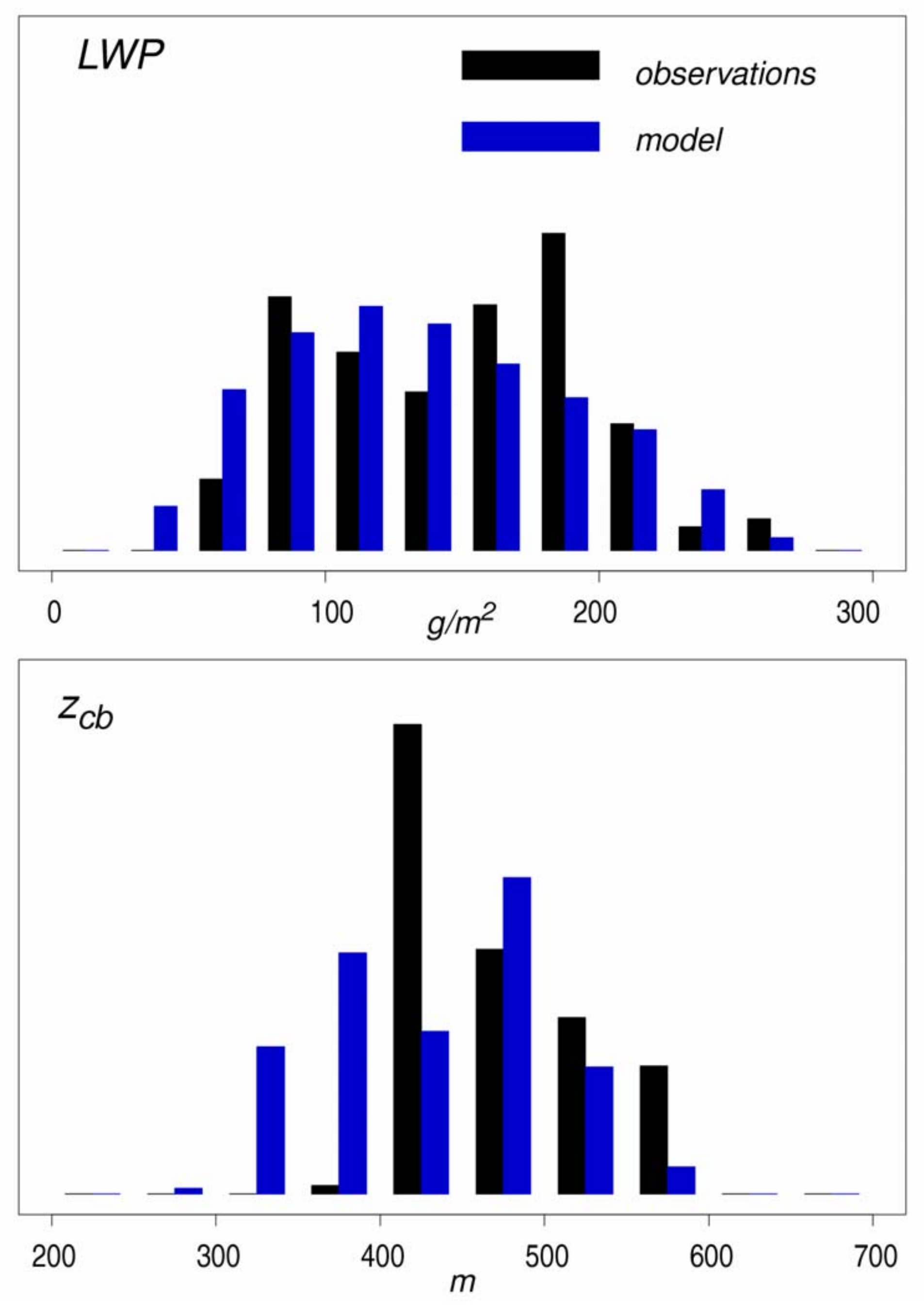

Figure 4. Histograms of microwave radiometer LWP in the upper figure and ceilometer cloud base altitude in the lower figure from observations and the model for the period 14-15 UTC.

across the top and bottom of the PBL where large vertical gradients of $q + l$ exist. If the variance in $q + l$ is at a relative minimum near the middle of the PBL, this may explain why the width of the cloud base altitude PDF is overpredicted.

The comparisons for this sounding and the other two are summarized by the results of Figure 5. This figure displays the standard deviation of LWP and cloud base altitude from the model, indicated by symbols "A," and from the observations, indicated by symbols "O." As is the case for the 1430 UTC sounding, the model can reasonably match the observed variance in LWP but overestimates the variance in cloud base altitude. Recall that because the aircraft data is used to specify the horizontal variance in total water for the 1730 UTC sounding, the comparison between model and observations is nearly independent.

A second model calculation, indicated by symbols "B," illustrates the role of the assumption of perfect vertical correlation of horizontal fluctuations in total water. In this calculation, the correlation coefficient of horizontal fluctuations between any two levels was made to decrease exponentially with the distance separating the levels. The length scale for this exponential decay was set to 50 meters so that for a typical cloud thickness of 300 meters fluctuations in total water at the top of the cloud nearly randomly overlap fluctuations from cloud base. If this were so, the variance in LWP would be considerably less than observed, although the variance in cloud base altitude is still greater than observed.

At 1730 UTC, the sun is high enough in the sky that comparison to the optical depth retrieved from 4 km satellite pixels can be made (Minnis et al. 2001). Consistent with the Considine model, the model with the further assumption of a constant droplet number specified from aircraft observations of 600 cm^{-3} predicts an exponentially shaped optical depth PDF for this partial cloudiness period (not shown).

Conclusions

If large-scale models are going to predict horizontal inhomogeneity in radiation and microphysics from a statistical cloud scheme, a method must be devised for converting the horizontal PDF of total water into the horizontal PDF of vertically integrated quantities such as cloud LWP or optical depth. With observations from a boundary layer cloud case, the assumption of perfect correlation of horizontal total water fluctuations between any two levels in the boundary layer yields a reasonable prediction of the shape and the width of the LWP PDF. The comparison at 1730 UTC when aircraft data is used to specify the variance in total water is particularly significant.

The comparison for cloud base is not good though in that the model significantly overestimates the magnitude of cloud base altitude fluctuations. While the cause for this difference is not clear, three other boundary layer cloud cases from the March 2000 IOP are also being examined to determine the robustness of these results.

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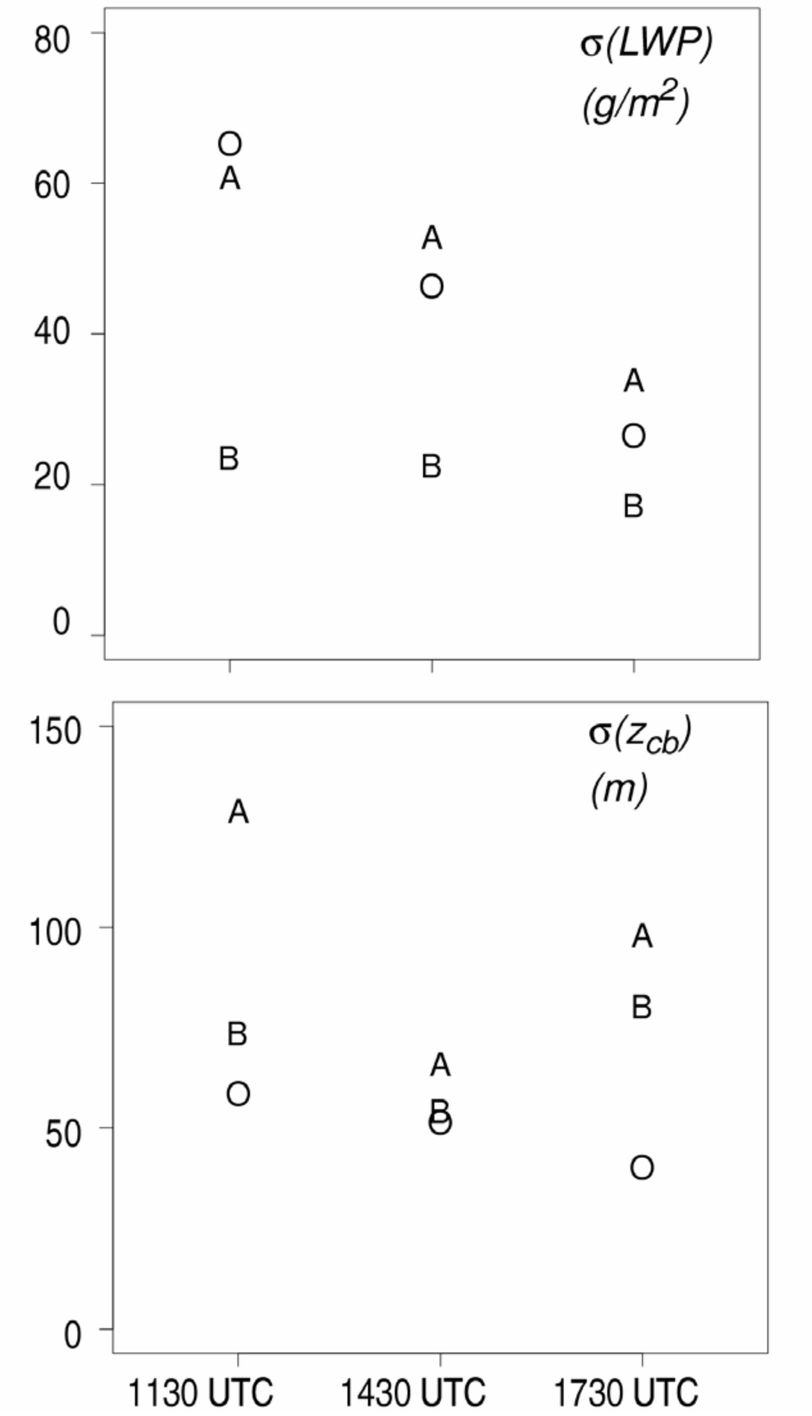

Figure 5. Standard deviations of LWP in the top figure and cloud base altitude in the bottom figure from observations ("O") and from the model ("A") for three sounding times. In addition to the standard model, a simulation is shown ("B") in which the correlation between horizontal fluctuations in total water decay exponentially with layer separation distance over a length scale of 50 meters.

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